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Review of aeronautical fatigue and structural integrity investigations in the UK during the period May 2009 – April 2011

Compiled by Dr Steve Reed

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Approved for Public Release.

Authorisation			
	Name	Signature	Date
Reviewer	Mr Ian Wilcock		18 March 2011

Executive summary

This review is a summary of the aeronautical fatigue and structural integrity investigations carried out in the United Kingdom, with a contribution from the Republic of Ireland, during the period May 2007 to April 2009. The review has been compiled for presentation at the 32nd Conference of the International Committee on Aeronautical Fatigue (ICAF), to be held in Montreal, Canada between the 29 May 2011 and 31 May 2011

The contributions generously provided by colleagues from within the aerospace and aligned industries, universities and the UK Ministry of Defence are gratefully acknowledged. The names of contributors and their affiliation are shown below the title of each item.

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1 Introduction

1.1 This review is a summary of the aeronautical fatigue and structural integrity investigations carried out in the United Kingdom, with a contribution from the Republic of Ireland, during the period May 2007 to April 2009.

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1.3 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 structural features
- Damage tolerance
- Structural ageing aircraft programmes
- Fatigue testing
- Developments in fatigue monitoring

1.4 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.

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2 Developments in fatigue design tools

2.1 Cyclic stress-strain and strain-life properties of aerospace metallic materials

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Contributor: A.C.Quilter
Affiliation: IHS ESDU, London

2.1.1 Introduction

2.1.1.1 IHS ESDU decided to approach a number of organisations in order to compile a reference source of cyclic stress-strain and strain-life properties for the benefit of the wider aerospace industry. Work began in 2006 on the collection and collation of the raw cyclic stress-strain and strain-life data points for commonly-used aerospace metallic materials. Beside the data available in the literature and other readily-accessible sources, efforts were made to encourage organisations with their own data to contribute to a database from which they would subsequently benefit. Considerable support and enthusiasm were expressed for the project and generous donations of data were received from a number of organisations. These data were combined with those gathered from public domain sources and those considered to be the most robust were retained. Cyclic stress-strain curves fitted using the Ramberg-Osgood equation were found to correlate well with the test data. The Coffin-Manson strain-life model was generally less successful but curves are provided due to their widespread use. The resulting set of cyclic stress-strain and strain-life properties of commonly-used aerospace metallic materials permits a wider appreciation of material fatigue behaviour not previously available. The results are to be published in forthcoming IHS ESDU Data Item Number 11003. Analysis of specimen geometries led to some simple design recommendations that may be useful to those considering future strain-controlled testing.

2.1.1.2 The materials covered in ESDU Data Item 11003 are given in Table I.

Aluminium Alloys	2014-T6, 2014-T651
	2024-T3, 2024-T351, 2024-T4, 2024-T42
	2124-T851
	7010-T7451, 7050-T7451, 7050-T7651
	7075-T6, 7075-T65, 7075-T651, 7075-T73, 7075-T7351
	7475-T7351, 7475-T76, 7475-T761
Titanium Alloys	Ti-6Al-4V Beta Annealed, Mill / Recrystallisation Annealed
	prEN 3354*(TI-P64001)
	IMI685 (Ti-6Al-5Zr-0.5Mo-0.2Si)
Steels	S99
	PH13-8Mo (AMS 5629)
	300M (BS S155)
	17-4PH H1150

Table I – Materials Covered in ESDU Data Item 11003

2.1.2 Example Cyclic Stress-Strain and Strain-Life Data

2.1.2.1 Figure 1 and Figure 2present example cyclic stress-strain and strain-life properties of one of the materials contained in the Data Item; 2014-T6/-T651.

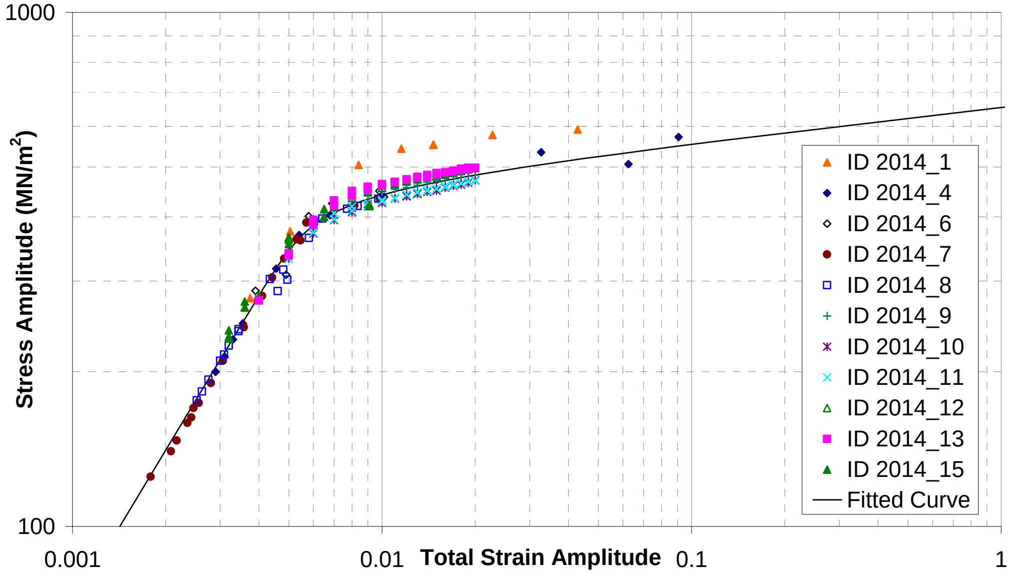

Figure 1 - Cyclic Stress-Strain Data for 2014-T6/-T651

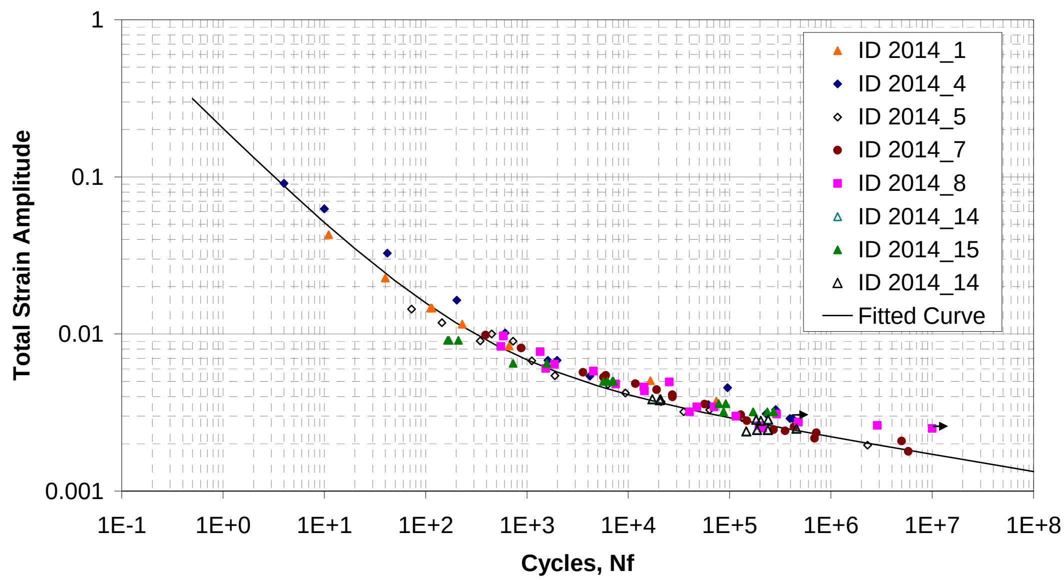

Figure 2 – Strain-Life Data for 2014-T6/-T651, R_{ε}=-1

2.1.3 Specimen Design

2.1.3.1 The vast majority of the tested specimens were generally of either machined solid-cylindrical or flat sheet (or plate), Figure 3 and Figure 4 respectively. The varying geometries of the specimens meant that correspondingly varied stress concentration factors may be present. Fine-mesh mathematical models were constructed for those specimens with dimensions available and axial net stress concentration factors, K_{TN}, were obtained.

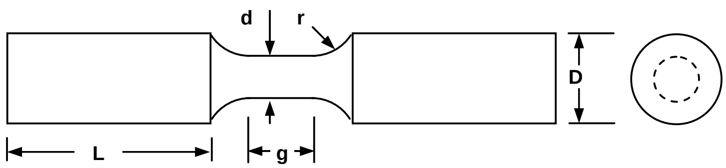

Figure 3 – Typical Machined Solid Cylindrical Specimen

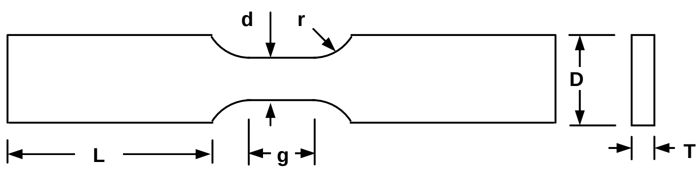

Figure 4 – Typical Flat Plate / Sheet Specimen

2.1.3.2 Analysis of the results and comparisons with published Stress Concentration data led to some suggested guidelines for specimen design which aim to keep K_{TN} beneath 1.05 (a nominally low value). Assessment of typical geometries conforming to ASTM and British Standard recommendations had led to higher K_Ts.

2.1.3.3 Table II summarises the suggested guidelines.

Specimen Shape	r/d	D/d
Flat sheet or plate	≥6.5	≥2
Cylindrical	≥4.5	≥2

Table II – Suggested Guidelines for Strain-Controlled Test Specimen Design

2.1.3.4 The design guidelines associated with effects of thickness in flat specimens and overall specimen length require further work.

2.2 Towards interactive stress analysis for fatigue calculations for solid components

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2.2.1 Abstract

2.2.1.1 The boundary element method (BEM) is presented as an alternative to the finite element method (FEM) for interactive stress analysis. Following a decade of successful usage of a 2D implementation at the industrial authors of this paper, work is in progress to take the principles behind this level of interactivity to 3D simulations. This paper summarises the application framework and some key issues for enhancing the computational performance required with a view to obtaining real-time update of stress information during dynamic geometric manipulations of the component under analysis.

2.2.2 Introduction

2.2.2.1 The last 15 years has seen an increased availability of stress analysis functionality built into Computer Aided Design (CAD) systems. Such integration of analysis and design is motivated by a general desire to bring forward in the design cycle the analysis capability that will validate the design in terms of its structural performance, and thereby to make important design decisions at this early stage. For the most part, this integration has taken the form of FEM vendors supplying analysis code that sits within the CAD system framework, ideally mimicking the look and feel of the CAD environment. Although stress analysis purists may find the increased automation troubling, the integration has met with some success and has opened up the toolbox of computational stress analysis to a wider audience.

2.2.2.2 In order to take fuller advantage of the link between geometric design and stress analysis, a different approach was proposed [1] in which the FEM was replaced by the BEM. This is a firmly established alternative computational method to the FEM [2]. The BEM brings with it an inherent suitability for use in a CAD environment because it uses a boundary representation and does not require volumetric meshing. Thus, automatic meshing becomes a more robust process that can be automated, transparently to the engineer, with greater confidence. Moreover, it became clear that other benefits accrued from the choice of the BEM, in that it adapts efficiently to a design environment in which the geometry is updating. The mesh of boundary elements can be easily and robustly modified to accommodate geometric changes, and since such modifications perturb the mesh only locally, much use can be made of previously computed matrix terms required in the stress analysis of the updated geometry. This type of analysis can be termed 're-analysis', and can lead to much improved computational performance. Research into various acceleration strategies [3] has led to the development of the *Concept Analyst software* [4] that now offers real-time update of stress solutions for small 2D simulations. The software has been in use at the offices of the industrial authors of this paper since 2001, and has proved popular with engineers there owing to its rapid, yet accurate stress analysis with a simplified user interface.

2.2.2.3 Attention is now given to the translation of these ideas to the interactive analysis of 3D solids. Under a grant from the UK Engineering and Physical Sciences Research Council (EPSRC), we are developing a 3D interactive modelling and analysis environment, and researching its potential to provide real-time response similar to the 2D code.

2.2.3 The interactive stress analysis framework

2.2.3.1 The *Concept Analyst* 3D code is developed in C++ making use of the open source solid modelling libraries *OpenCascade* [5]. The aim of the work is to provide an integrated solid modelling and re-analysis system, to investigate the possibility of real-time interactivity. We do not propose to write a fully functioning CAD system. Thus, simple solid modelling functionality has been added to be able to model features commonly found in fatigue analysis of various components, fixtures and fittings in aircraft structures, such as countersunk holes in plates and joggles for modification of the line of action of a force and interaction of geometric features.

2.2.3.2 Much use is made of the *OpenCascade* class structure, which maintains a hierarchical description of a solid object in terms of its constituent faces, wires, edges and vertices. Boundary conditions are applied to faces. Once the model is complete the analysis is initiated. This involves an initial automatic mesh (of the surface only) followed by the BEM analysis. The BEM (like FEM) is a matrix method of analysis in which (like FEM) the matrix terms are computed using numerical integration over elements, ultimately arriving at a matrix-vector expression

$$[A]\{x\} = \{b\} \tag{1}$$

2.2.3.3 Where matrix [A] is typically dense and unsymmetric, vector {b} is known and {x} contains unknowns. The equation is solved using traditional methods and stress contours may be displayed to the user. For this first analysis then, the system resembles a typical CAD/FEM integration in the user's perception.

2.2.3.4 Upon a geometric change, which is likely to be made dynamically by some mouse click-and-drag operation, the re-analysis capabilities are invoked. The modified parts of the boundary are re-meshed using our algorithm to minimise the number of elements requiring update. This has been shown [1] to have a major impact on the re-analysis time, as is illustrated in Figure 1. Since the change in geometry is likely to be of pixel order, most re-meshing can be accommodated by simple perturbations of a *small number of elements*. The corresponding terms in [A] and {b} are updated and the new system

$$[A']\{x'\} = \{b'\} \tag{2}$$

2.2.3.5 Solved using an iterative solver. Since [A’] is a good approximation to [A] we have an almost perfect preconditioner provided by the initial solution of (1), and since {x’} may reasonably be expected to be well approximated by the previous solution vector {x} we have a good starting point for the iterative solver.

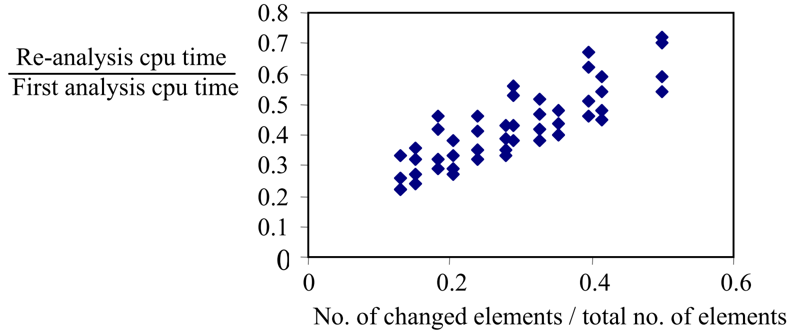

Figure 1 - Dependence of cpu time improvement on mesh perturbation (reproduced from [1])

2.2.3.6 Figures 2 and 3 show a typical example of the re-meshing when a countersunk hole in a plate is moved to a new location. The geometry of the two cases is similar since, we remind the reader, the re-analysis is being performed continuously as the hole is being moved using a graphical operation. The mesh shown in figure 3 is for a re-analysis of the problem, a short time after the analysis of the case in figure 2, with a locally perturbed mesh.

2.2.3.7 The overall effect that is the aim of this work is one of animation of stress contours as the hole is moved, giving engineers a tool that provides real interactivity through a much deeper integration of the solid modelling and analysis functionality than is present in today’s integrated CAD/FEM environments.

2.2.4 Conclusions

2.2.4.1 An integrated solid modelling and stress analysis system has been presented, which is aimed at providing stress results to engineers in real time as a design geometry evolves. The application is being developed in partnership between a university and aircraft structural fatigue specialists in industry. Use is made of open source solid modelling libraries and the underlying stress analysis method is the BEM, which lends itself well to the re-analysis of components when geometric changes are applied.

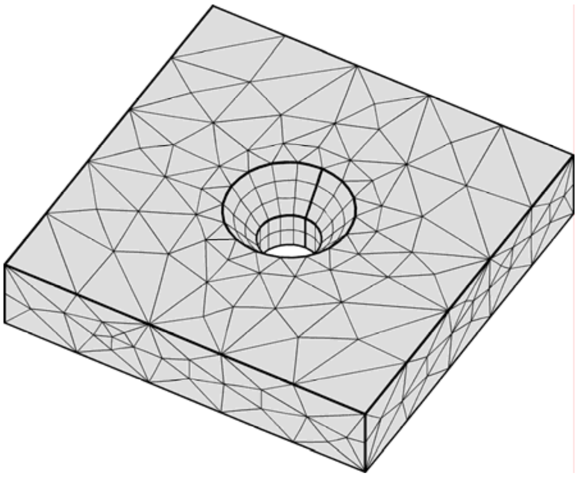

Figure 2 - Initial mesh

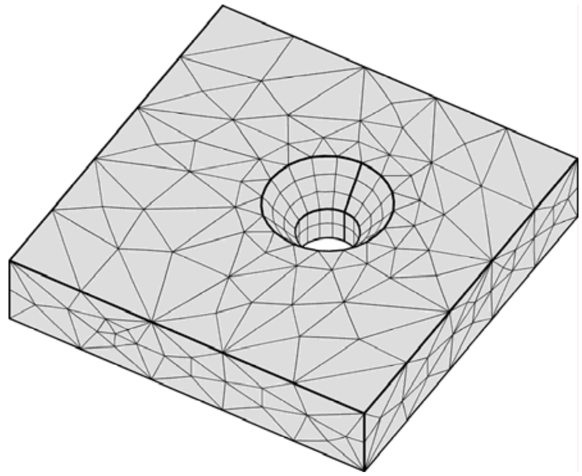

Figure 3 - Updated mesh on moving hole

2.2.5 Acknowledgements

2.2.5.1 This work was funded under grant EP/H000046/1 from the UK Engineering and Physical Sciences Research Council (EPSRC), whose support is gratefully acknowledged.

2.2.6 References

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2.3 Highly accurate stress intensity factor evaluations using an enriched dual boundary element method

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2.3.1 Abstract

2.3.1.1 We present a computational method aimed at obtaining highly accurate solutions for stress intensity factors describing the asymptotic stress conditions at crack tips in sheets. The method is based on the Dual Boundary Element Method (Dual BEM), into which we inject enrichment functions derived from analytical asymptotic displacement fields. The solutions show that the enrichment is capable of producing approximately one order of magnitude reduction in error. We believe this is the most accurate numerical method available for extracting stress intensity factors.

2.3.2 Introduction

2.3.2.1 It is well known that the stress intensity factors, K_I, K_{II}, K_{III} describe the conditions locally around a crack tip, and may be used in fracture assessments. Many fracture problems are dominated by mode I behaviour, and so consideration is limited to K_I. In other situations, K_{II} may be of importance. The rate of fatigue crack growth in metals is known to be given by fatigue crack growth laws that contain K_I. These stress intensity factors may be determined, for a given geometry (including that of the crack(s)) and loading, by a variety of numerical methods. In recent years the Finite Element Method (FEM) and Boundary Element Method (BEM) have been favoured.

2.3.2.2 The main difficulty in using the FEM and BEM for crack problems is the accurate modelling of the singular stress field. Traditional polynomial elements become cumbersome and can require very refined meshes in order to obtain sufficiently accurate solutions. This problem was initially addressed by using “quarter-point” elements [1]. Here the mid-node of the element is moved from its usual position in the middle to a position closer to the crack tip. The resulting geometric mapping automatically writes the displacement solutions in a basis containing the first three terms in the Williams expansions [2] for displacements. However, the use of these elements is limited to the elements in direct contact with the crack tip and they are not useful for curved cracks.

2.3.2.3 More recently, Moës et al. [3] developed the idea of the Partition of Unity method of Melenk & Babuška [4] to present the eXtended Finite Element Method (XFEM). Here the asymptotic Williams solutions are built into the element formulation, and as a result the XFEM offers accuracy gains over polynomial elements as well as a solution that considers crack growth without the requirement to remesh.

2.3.2.4 In this paper we present an alternative strategy based on the Dual Boundary Element Method (Dual BEM) of Portela et al. [5], in which we introduce similar enrichment to that of [4]. We consider problems of edge cracks and centre cracks in sheets, which are common simulations tackled by engineers analysing the damage tolerance of aircraft structures. The results show that the method is capable of producing stress intensity factor solutions of very high accuracy. Such accuracy is of great importance when determining fatigue lives.

2.3.3 The enriched Dual BEM formulation

2.3.3.1 The Dual BEM is based on application of the displacement boundary integral equation (DBIE) and traction boundary integral equation (TBIE), which are respectively:

$$C_{ij}(x')u_j(x') + \int_\Gamma T_{ij}(x,x')u_i(x)d\Gamma(x) = \int_\Gamma U_{ij}(x,x')t_i(x)d\Gamma(x), \qquad i,j = x,y \tag{1}$$

$$C_{ij}(x')t_j(x') + \int_\Gamma S_{kij}(x,x')u_k(x)d\Gamma(x) = \int_\Gamma D_{kij}(x,x')t_k(x)d\Gamma(x), \qquad i,j,k = x,y \tag{2}$$

2.3.3.2 where *u* and *t* are the displacement and traction fields, (*T, U, S, D*) are various fundamental solution kernels and their derivatives, *Cij* is a multiplier based on the local geometry at a point *x'*, and the integrals are taken over the boundary, Γ, of the object in question. Once the displacements and tractions are approximated using shape function interpolations, the method can proceed by collocation, taking *x'* as each node in turn, to provide a sufficient number of statements of the form (1) and (2) to enable the nodal values of *u* and *t* to be determined. Then the stress intensity factors can be evaluated using the J-integral [6].

2.3.3.3 We now write the displacement *u,* not in the usual shape function interpolated form, but with the extra enrichment functions, i.e.

$$u_j(\xi) = \sum_{a=1}^{M} N_a(\xi)u_j^a + \sum_{a=1}^{M}\sum_{l=1}^{L} N_a(\xi)\psi_l(\xi)A_{jl}^a \tag{3}$$

Where, ξ is the usual intrinsic parametric coordinate for the element, N_a is the shape function associated with node *a*, and the coefficients *A* are (unknown) amplitudes of a set of enrichment functions ψ_l which are

$$\psi(r,\theta) = \left\{\sqrt{r}\cos\left(\frac{\theta}{2}\right), \sqrt{r}\sin\left(\frac{\theta}{2}\right), \sqrt{r}\sin\left(\frac{\theta}{2}\right)\sin(\theta), \sqrt{r}\cos\left(\frac{\theta}{2}\right)\sin(\theta)\right\}^{\mathrm{T}} \tag{4}$$

Where (r,θ) is the usual polar coordinate system centred at the crack tip. Full details are given in Simpson and Trevelyan [7], and an alternative enrichment strategy is given in Simpson and Trevelyan [8]. Note that this enrichment basis automatically provides the first six terms in the Williams expansion.

2.3.4 Results

2.3.4.1 The first simulation considers mode I behaviour of an edge crack in a square plate. We run both Dual BEM and the new enriched Dual BEM solutions and compare accuracy for different mesh densities. The error norm plotted is:

$$Error = \left| \frac{K_I - K_I^{\text{exact}}}{K_I^{\text{exact}}} \right| \times 100\% \qquad (5)$$

2.3.4.2 The results are shown in Figure 1, and demonstrate that the introduction of the enrichment in equation (3) offers approximately one order of magnitude reduction in error in comparison with the unenriched form of the dual BEM. Figure 2 shows the convergence of results for an inclined centre crack in a sheet. The problem is complicated by the presence of two crack tips, allowing the enrichment of one or both local displacement fields, and by the mixed mode character of the problem. The graph shows the normalised mode I stress intensity factor to converge very rapidly to the reference solution from Murakami [9], with the greatest levels of accuracy obtained when both crack tips are enriched.

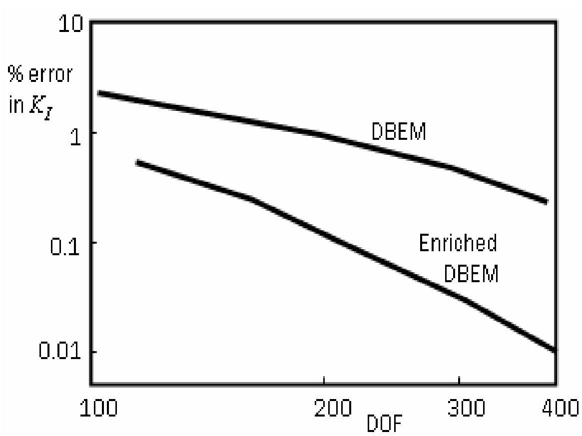

Figure 1 - Error comparison in K_I calculation for Mode I edge crack in plate

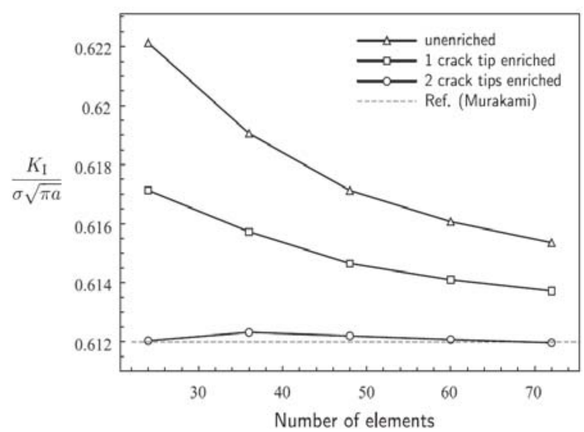

Figure 2 - Convergence of results for inclined centre crack in plate

2.3.5 Conclusions

2.3.5.1 A new formulation is presented in which enrichment of the Dual Boundary Element Method is achieved by including in the element formulation the known asymptotic behaviour around crack tips. The accuracy benefits of including the enrichment are marked, and may be achieved by the addition of only a few extra equations into the system. The use of accurate stress intensity factors is very important in fatigue assessments because they are raised to positive powers in crack growth laws.

2.3.6 References

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2.4 BEASY National Review Report 2011

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2.4.1 Introduction

2.4.1.1 Ongoing active development of the BEASY Crack Assessment and Crack Growth Simulation software tools has continued with new product releases this year. Along with continued expansion in the capabilities of the software increased robustness of the crack growth simulation process has been achieved. Overviews of the major developments are described in this report.

2.4.1.2 An additional new capability described is the Simulation Based Corrosion Management of Aircraft Structures.

2.4.2 Crack assessment and crack growth simulation

2.4.2.1 Integration with NASGRO 5

2.4.2.1.1 The BEASY fatigue growth tools have now been linked with the data supplied with the NASGRO 5 analysis suite. This enables users with NASGRO 5 to use the material libraries supplied with that package, in a BEASY crack growth or fatigue calculation analysis.

2.4.2.2 Rainflow counting tool

2.4.2.2.1 In the latest release of the BEASY software, a Rainflow counting tool has been incorporated. This tool converts a load-history data set into a BEASY load spectrum file using Rainflow Counting and removes the requirement to use additional 3rd party software for this operation. The process used in this tool is based on ASTM E1049-85.

2.4.2.3 FE integration tools

2.4.2.3.1 In the latest phase of developments, new features have been included allowing users to create BEASY models from structures created in a range of standard FE packages (ABAQUS, NASTRAN, ANSYS). The FE model can be directly converted into a BEASY model and loading applied.

2.4.2.3.2 This improved integration also extends into post processing the fracture simulation results within the FE environment.

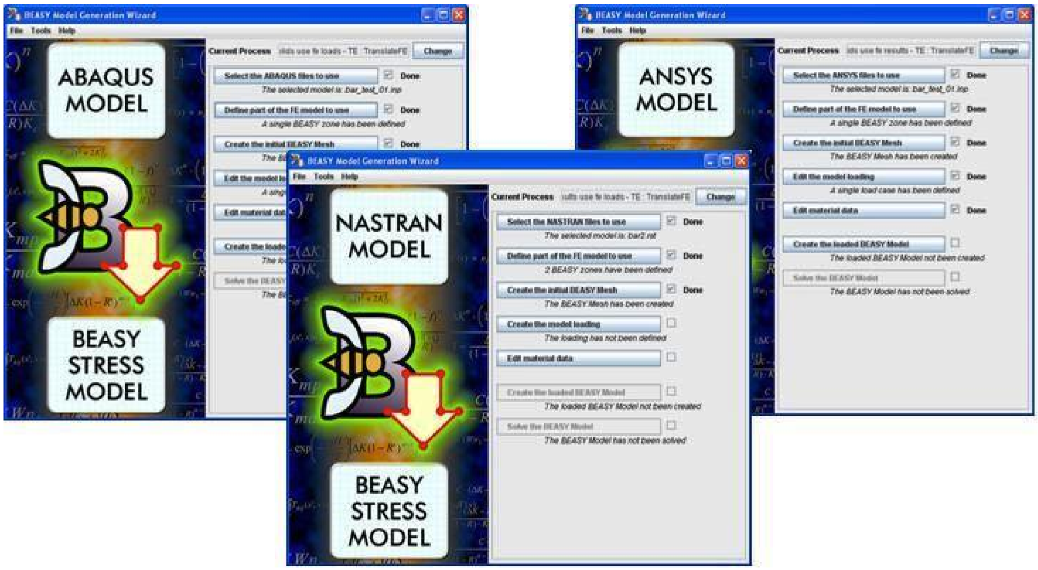

Figure 1 - FE integration tools which enable FEM model to be converted to BEASY crack simulation models

2.4.2.4 Crack growth using time dependent thermal stress results

2.4.2.4.1 One research project that has been carried out is an investigation into methodologies for growing cracks in a transient thermal stress environment. This research work has explored methods of expanding the use of the BEASY fracture analysis into non-standard BEM methodologies. This investigation has developed a procedure for growing cracks in any non-linear stress field by use of loading applied directly to the crack faces.

2.4.2.5 Short crack growth laws (UNIGROW SBIR)

2.4.2.5.1 One of the development projects was a US-led SBIR project into methods for fatigue analysis of ‘short’ cracks. This identified the need to incorporate new fatigue growth formulations where the crack tip exhibits an elastic growth regime, rather than conventional elasto-plastic growth.

2.4.2.5.2 “Trial” fatigue crack growth laws have been developed by a number of researchers - primarily based on a Vasudevan crack growth model. Various ways of computing the terms in the growth law had been proposed. Elements of these were implemented into the BEASY fatigue analysis methods, allowing for further subsequent study of the growth behaviour.

2.4.3 Defect assessment: Defect scanner

2.4.3.1 Another major addition to the BEASY fracture analysis capability has been the BEASY Defect Scanner. This is a tool that can be used with either a BEASY model, or a FE stress model (ABAQUS, ANSYS or NASTRAN), in order to identify ‘critical’ locations.

2.4.3.2 The tool creates a “map” of critical crack sizes on a model using computed stress values. The critical crack size at any point is the crack size at that point where the SIF value reaches a defined SIF value. This value can be the threshold stress intensity factor, in order to establish the minimum size at which cracks may start growing; or the critical SIF value in order to determine the size of crack that will cause part of the structure to fracture.

2.4.3.3 The smallest critical crack sizes shown on the map enable users to clearly identify the areas of greatest concern for that component.

2.4.3.4 In addition, different ‘regions’ of the model can be defined in order to identify the how the critical crack sizes differ between defined parts of the structure. This process could then be integrated with inspection and approval processes (e.g. for incoming parts, or reports from maintenance inspections) in order to refine and optimize the decision making process for material rejection/scrappage.

2.4.3.5 The locations of critical crack sizes identified with this tool can then be used, if required, as an input to a more detailed crack analysis using the BEASY Fracture products.

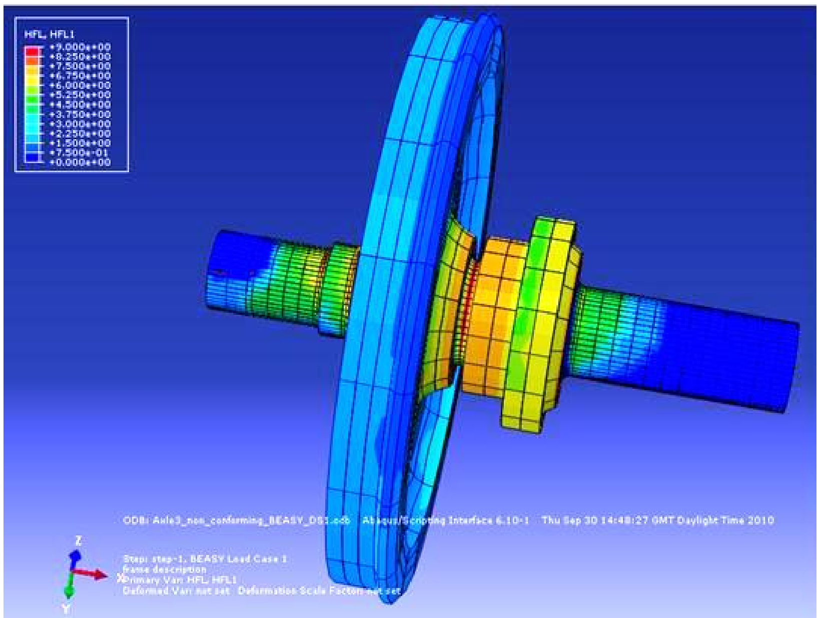

Figure 2 – ‘Map’ of critical crack sizes

2.4.4 Simulation based corrosion management of aircraft structures

2.4.4.1 BEASY is a major contributor to an international research project SICOM which aims to develop computer models capable of simulating corrosion and surface protection measures in aircraft structures

2.4.4.2 Corrosion modelling tools for prediction of corrosion occurrence and corrosion propagation will be a driver for new technical advances in the fields of corrosion maintenance, development of new materials, structural designs and surface protection systems. SICOM will provide models that can become an essential part of future predictive maintenance concepts to avoid unanticipated and unscheduled maintenance with high costs. Data from monitoring systems and non-destructive inspection can be used as model input. Model outputs will be utilised for the repair decision process or can supply structural integrity concepts and thereby fill the gap between monitoring or inspection and calculation of the structural impact of corrosion. Aircraft development costs will be reduced through saving on testing time and quantity.

2.4.4.3 A major development is the Galvanic Corrosion Decision Support system which can be used to model and optimise surface protection systems used in aerospace structure.

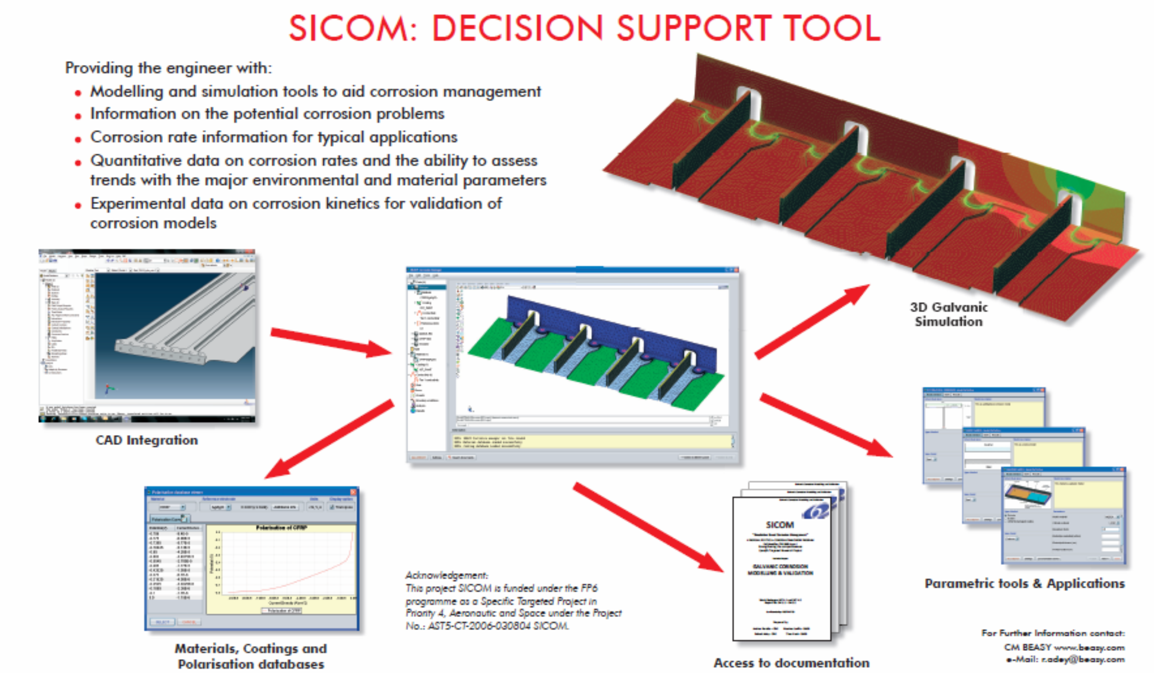

Figure 3 – Decision support tool to assess surface protection in aircraft structures

3 Fatigue of metallic structural features

3.1 Residual stresses in bonded crack retarders

Contributors: M. E. Fitzpatrick, C. D. M. Liljedahl
Affiliation: Materials Engineering, The Open University, Milton Keynes MK7 6AA

3.1.1 The use of integral structures can potentially reduce the weight and the cost of aerospace assemblies. An inherent inconvenience with integral structures is, however, that there are no natural crack stoppers as there are in riveted structures. Research has been under way to investigate the role of adhesively bonded reinforcements in improving the damage tolerance characteristics of integral structures.

3.1.2 At The Open University we have been investigating the effects of the chosen reinforcement on the residual stresses in the assembly, and the evolution of the residual stresses with fatigue crack growth. The reinforcement, which is usually present in the form of an elongated plate or ‘strap’, should have a reasonably high strain to failure, high strength and good fatigue resistance. In order to achieve these properties at minimal additional weight, this implies that a different material than that of which the integral structure is made will be used for the reinforcing strap. As the bonding adhesive used to affix the strap will be cured at an elevated temperature, when the structure subsequently cools residual stresses are induced due to the mismatch of coefficient of thermal expansion between the integral structure and the strap.

3.1.3 Our most recent work has focussed on the effect of temperature change on the residual stress below the strap. Residual stresses were evaluated using neutron diffraction, where a collimated beam of neutrons is used to map the residual strains within a sample. A cooling chamber with neutron “windows” was used to perform the measurements. The sample studied was an aluminium alloy compact tension specimen with a bonded GLARE strap.

3.1.4 Figure 1 shows the residual stresses measured at different locations below the strap at (a) room temperature and (b) –50˚C. It can be seen that the peak residual stresses have approximately doubled as a consequence of the reduction in temperature, which has implications for the damage tolerance of the assembly.

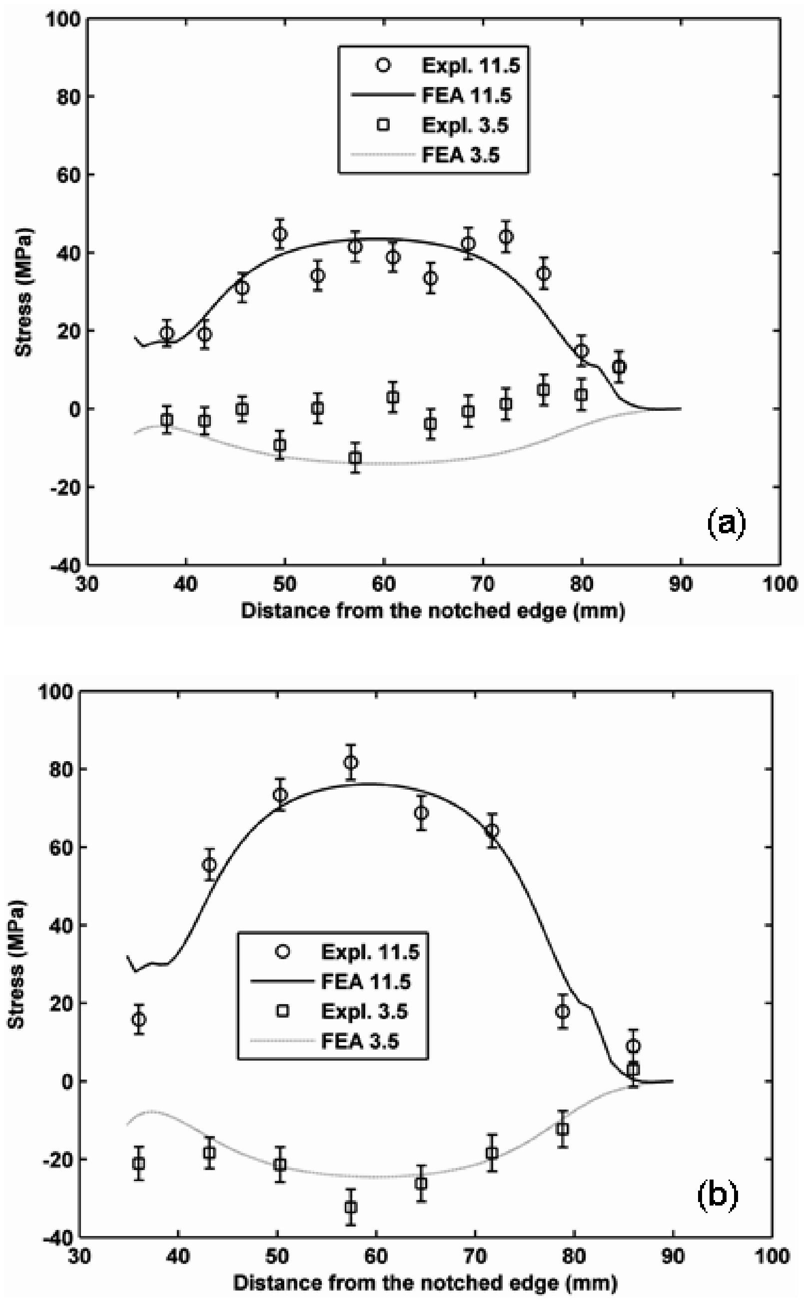

Figure 1 - Residual stresses, measured using neutron diffraction

Note to Figure 1: Residual stresses, measured using neutron diffraction, below a GLARE strap in a C(T) specimen at (a) room temperature and (b) –50˚C. The symbols are measured data, the lines are corresponding predictions from FE modelling. Measurements were obtained at two positions through the thickness of the sample, 3.5 and 11.5 mm from the un-bonded surface [1].

3.2 Laser peening of aerospace alloys

Contributors: M. E. Fitzpatrick, M. B. Toparli
Affiliation: Materials Engineering, The Open University, Milton Keynes MK7 6AA

3.2.1 The Open University is working on the characterization of residual stresses induced by laser shock peening of Al 2024-T351, in both thick and thin sections. Laser peening is attractive for introducing deep (>1 mm) compressive residual stresses into fatigue-critical locations. Extensive data has been acquired on the residual stress profile using various laser peening parameters. The data are being used in the development of predictive models for the peen stress, and in a partner project with Cranfield University for the evaluation of fatigue crack initiation and growth. Measurements have been made using combinations of X-ray and neutron diffraction, incremental hole drilling, and the novel contour method.

3.2.2 The contour method involves cutting into two a part containing a residual stress. The relaxation of the stress on the cut surface causes measurable deformations. These deformations can be determined using a contour measuring machine (CMM), and then applied in an FE model to back-calculate the residual stress profile. The method has the advantage that it gives the stress profile on an entire plane, and is insensitive to microstructural and compositional variations.

3.2.3 Figure 2 shows results from a laser peened sample showing high compressive stress (>200 MPa) on the peened surface.

3.2.4 The Open University is also investigating laser peening of thin sections (2 mm) where the peen stresses are complex owing to the interaction of the shock wave with the back face of the sample.

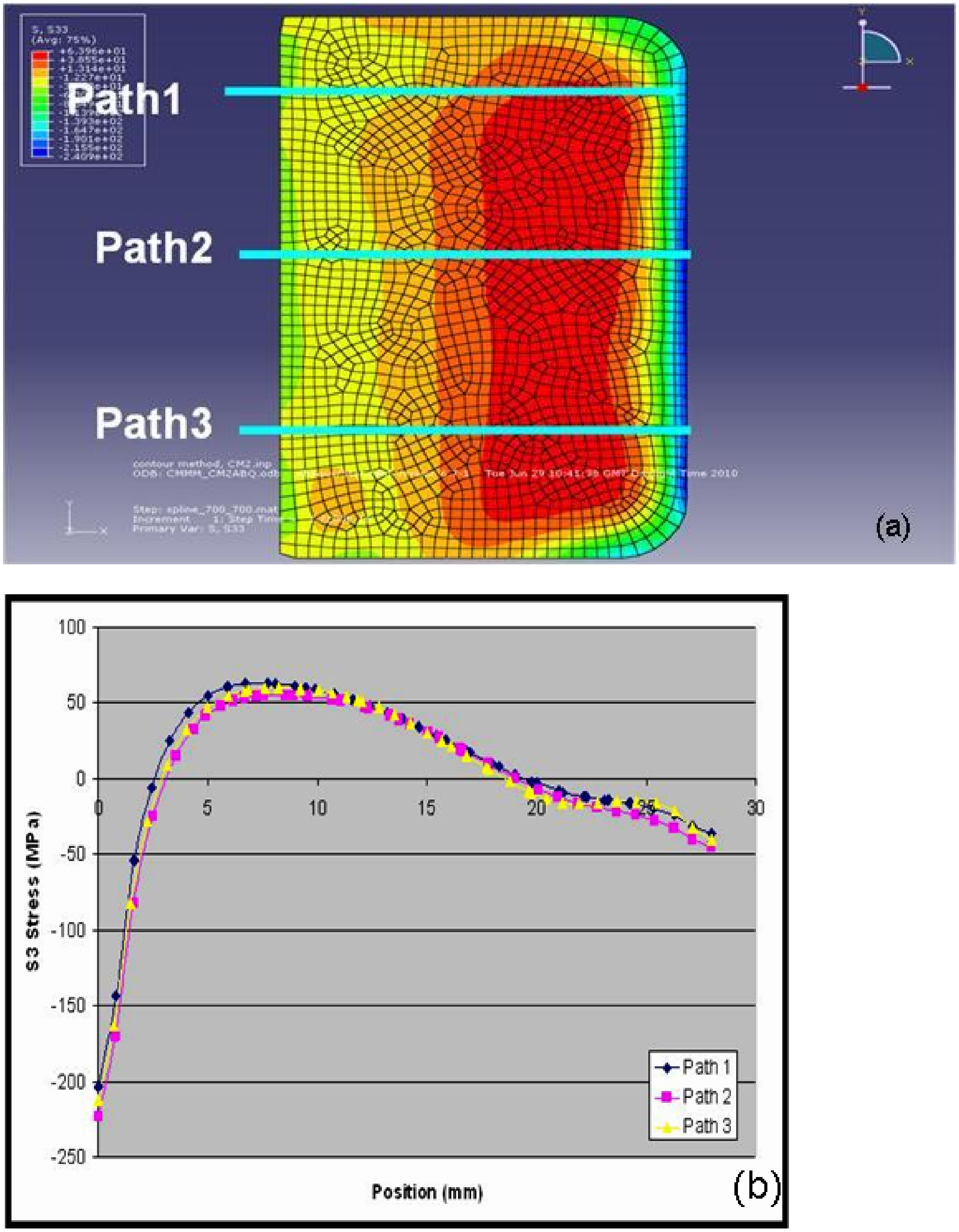

Figure 2 - Residual stress profile on the cross-section of a laser peened aluminium bar.

Note to Figure 2. (a): Residual stress profile on the cross-section of a laser peened aluminium bar. The right side of the sample was peened. Figure 2(b): Line profiles of residual stress along the paths shown in 2(a), with distance from the peened surface. The peak surface stresses of over –200 MPa are balanced by tension of around 50 MPa in the centre of the bar.

3.2.5 References

[1]. 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: 2010. doi: 10.1111/j.1475-1305.2010.00768.x

3.3 Fatigue crack growth in aluminium friction stir welds

Contributors: Prof P E Irving and Dr X Zhang
Affiliation: Cranfield University

3.3.1 Background

3.3.1.1 Cranfield University participated the COINS (COst effective INtegral metallic Structure) project which is a collaborative project funded under the sixth EU Framework Programme for research and technological development (FP6). The top level objective of the project is to extend the application of integral metallic structures utilising Friction Stir Welding (FSW) by 'advancing the state of the art of FSW technology, developing new geometries for FSW, and through innovations in structural design'.

3.3.1.2 Fatigue tests were performed on M(T) specimen made of 1.6 and 3.2 mm thick 2198 ally (for fuselage cover application) and 8 mm thick 2195 alloy C(T) and ESE(T) geometries (for wing skin application) at R = 0.1, 0.3, 0.6.

3.3.1.3 In order to study the effect of welding-induced residual stress field on crack growth rates, for the M(T), crack started from either a single longitudinal weld or between double welds, and for the ESE(T) crack started from outside the weld in the compressive residual stress field. Crack growth rates have been measured and compared.

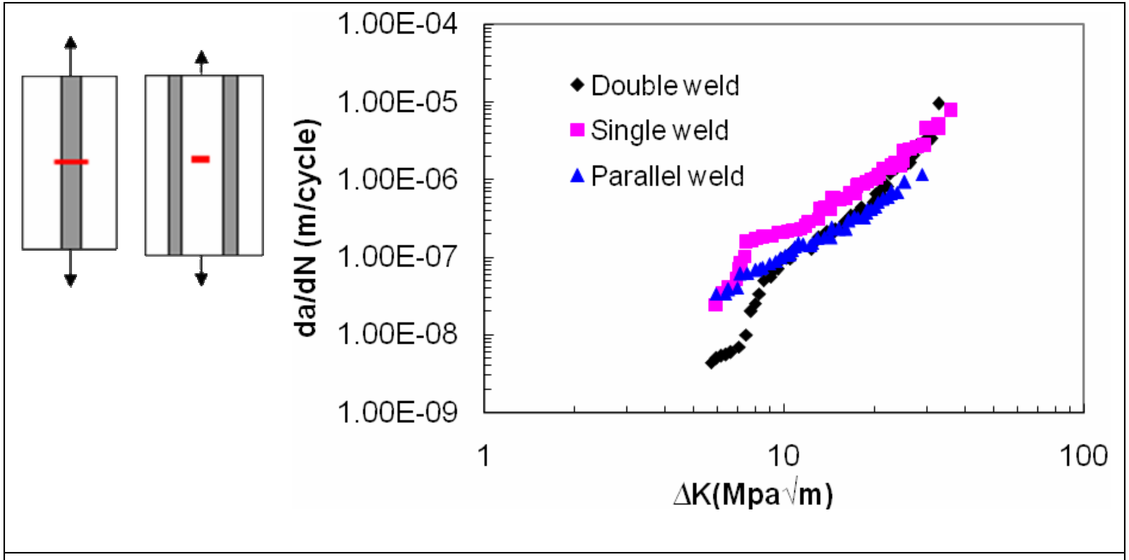

Figure 1 - Crack growth rates in specimens 200 mm wide with 3 weld configurations

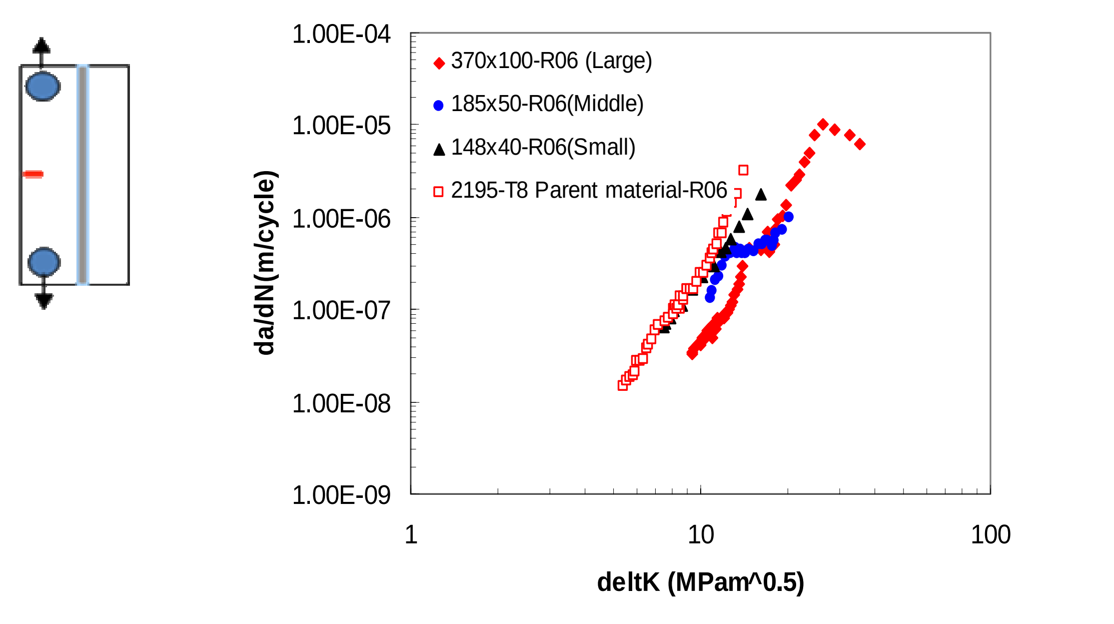

Figure 2 - Crack growth rate vs. ΔK for 2195 alloy at *R*=0.6. Three different sizes at 40 mm, 50 mm & 100 mm wide ESE(T). Cracks perpendicular to the weld. Comparison with parent plate *R* = 0.6.

3.3.2 Summary:

3.3.2.1 Thin 2198 alloy:

(1) Crack growth rates in cracks running parallel to the weld on the weld centreline are always slower than parent plate at all values of ΔK
(2) Crack growth rates of cracks perpendicular to single weld samples are very similar to the parent plate
(3) Crack growth rates for cracks propagating between double welds are slower than parent plate when they are between the welds, and become similar at long crack lengths once they have propagated through the weld.

3.3.2.2 Thick 2195 alloy:

Due to the compressive residual stresses, it was found that at R = 0.1 it was not possible to grow cracks from the ESE(T) sample notches in 50 and 100 mm wide samples. This is believed to be because of intense compressive residual stress fields. Tests for these samples were performed at R=0.6 only and are shown in Fig. 2 together with the 40 mm sample data at R = 0.1 and the parent plate growth rates. It can be seen that parent plate has the fastest growth rates, followed by the 40 mm, 50 mm and 100 mm with the 100 mm being the slowest.

3.3.3 Reference

[1] Y. Ma, PE Irving, et al. Part I experimental Part II modelling, Submitted to Int J of Fatigue October 2010.

3.4 Development of cracks from scribes

Contributors: Prof P E Irving and Dr X Zhang
Affiliation: Cranfield University

3.4.1 This project explored the influence of mechanical damage in the form of scratches or scribes on the fatigue life of 2 mm thick 2024 T351 sheet in the clad and unclad conditions and in tension and in bending. The occurrence of damage such as scratches poses two questions in fatigue design & maintenance

- What is largest size of scratch that can be left in service?
- What is the remaining life of scratches which exceed the maximum size for zero crack growth?

3.4.2 Scratches are unusual in that the have a long dimension parallel to the sheet surface but in the depth direction their depth is less than 200 microns and they must be considered as short cracks.

3.4.3 Fatigue samples were of dogbone shape with a minimum width of 80 mm. Reproducible and accurately specified scratches were cut in the 2024 sheet using a diamond tipped tool with a root radii of 5, 25 and 50 µm. Scribes depths were of 25, 50, 100 and 150 µm deep and were cut perpendicular to the applied stress axis across the minimum sample width. Fatigue testing was performed at and R = 0.1 with σmax =200 MPa. Fatigue crack growth rates were measured using striation counting from crack lengths of 50 µm from the notch root up to final failure crack lengths approaching 750 µm. Finite element calculations were made of notch root stress fields and of plastic zone sizes which were formed at the notch root.

3.4.4 Examples of the scribe profiles are shown in Figure 1 and the relation between scratch depth and fatigue life in figure 2. Fatigue crack growth rates measured from striations spacing is shown in comparison with long crack data in Figure 3. The fatigue tests show that scribes can reduce fatigue life by up to 97% for the deepest and sharpest scribes. In contrast, 25 µm deep scribes 25 µm deep had a negligible effect. Fatigue crack growth rates showed marked departures from macroscopic LEFM behaviour (Figure 3). Using the crack growth data is was possible to calculate the fatigue cycles to grow the crack from 50 µm to final failure, and by subtraction from the total life to calculate cycles to achieve a 50 µm crack. For 25 µm scribes over 90% of total life was spent creating the 50 µm crack. This reduced to 65-85% for 185 µm deep scribes.

3.4.5 The calculation of Kt and notch root stress fields using FE analysis allowed the fatigue results to be plotted against Kt instead of notch depth and demonstrate that for the same Kt, samples with blunter notches such as the 50µm have smaller fatigue lives than ones with sharper 5 µm radii. This behaviour can be associated with the 50 µm notches having greater stresses and larger plastic zones at the notch root than 5 µm notches; these enhanced stresses leading in turn to earlier crack initiation. This behaviour would be predicted b critical distance theory but this approach does not provide a quantitative mechanistically based explanation for the lives obtained. Many of these results can be found in the paper published at Fatigue 2010 [1].

3.4.6 Reference:

[1]. A Cini, P E Irving "Transformation of defects into fatigue cracks; the role of Kt and defect scale on fatigue life of non pristine components"; Procedia Engineering 2 (2010) 667-677.

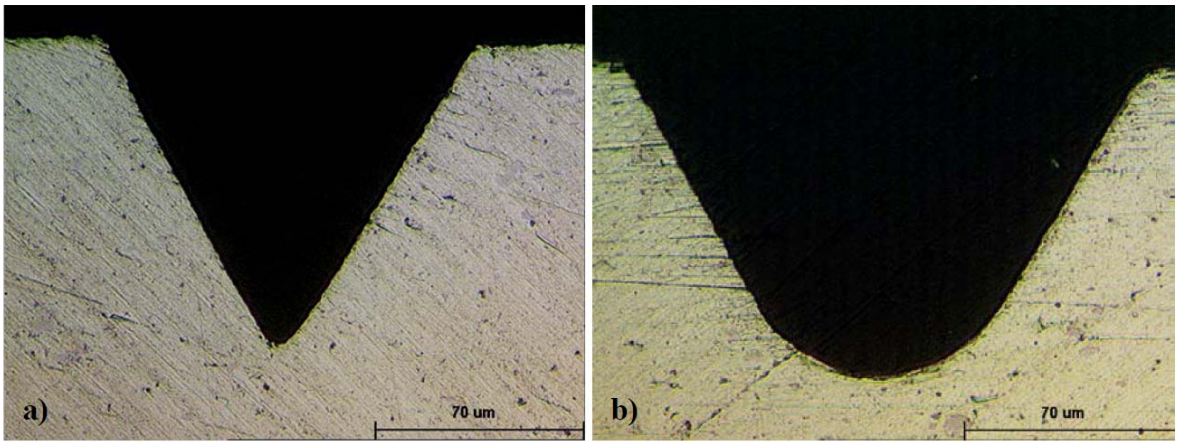

Figure 1 - Cross section shape of diamond tool machined notches: (a) 100 µm deep 5 µm root radius notch; (b) 100 µm deep 50 µm root radius notch

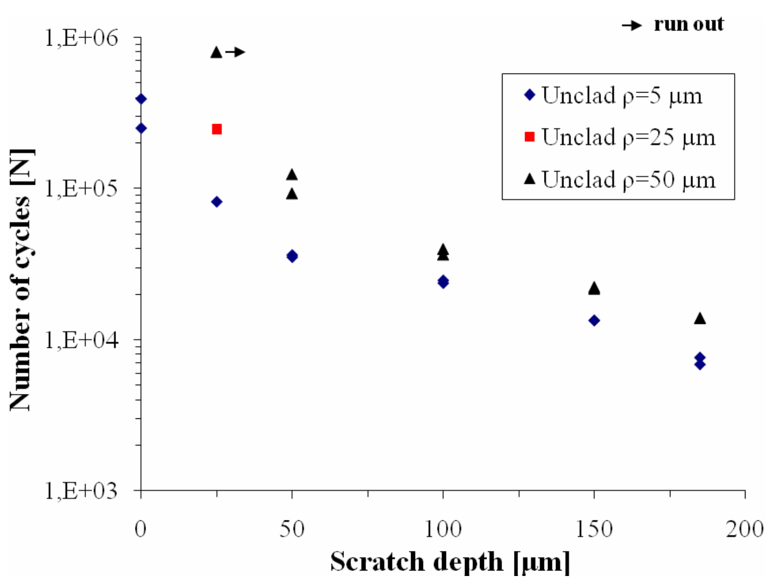

Figure 2 - Fatigue life as function of notch depth and root radius (a) for unclad samples

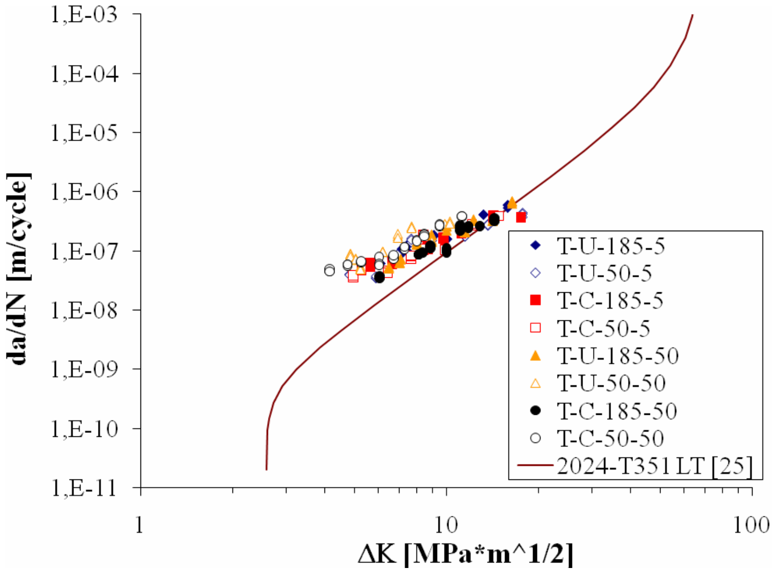

Figure 3 - Crack growth rate: from striation spacing Plotted against stress intensity factor range ΔK

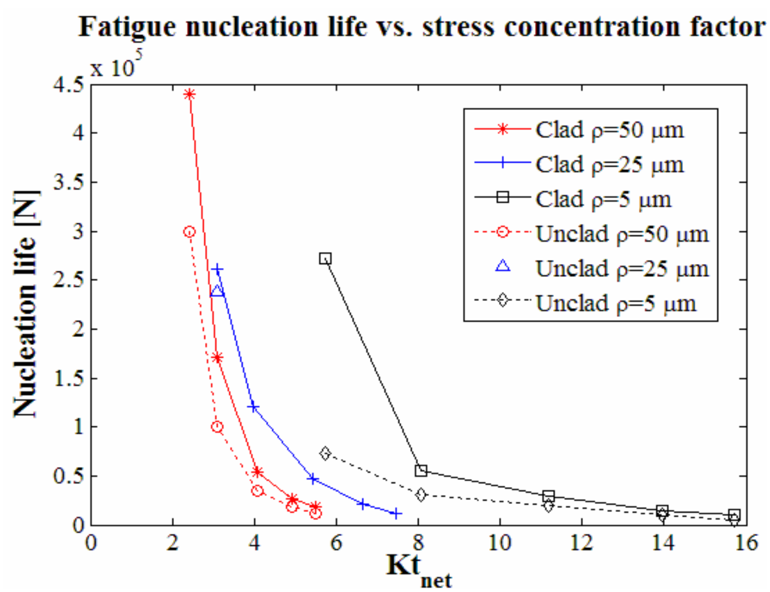

Figure 4 - Fatigue nucleation life to produce a 50 µm deep crack plotted against Kt for clad and unclad samples with different notch root radii.

3.5 Development and early growth of fatigue cracks from corrosion damage in high strength stainless steel for under carriage applications

Contributors: Prof P E Irving and Dr X Zhang
Affiliation: Cranfield University

3.5.1 The geometry of corrosion damage is far less reproducible than is a geometric scratch; hence in this work corrosion damage was generated by subjecting dogbone samples to crevice corrosion, followed by fatigue testing. Fatigue crack growth was monitored using replica techniques. As a consequence of using real defects the stress concentration was not well known. The gross shape of the defects could be well defined and the Kt calculated using FE analysis. However, the local Kt values associated with local irregularities within the defect were not well specified. Calculated Kt values were between 1.2 -1.7; however the Kt inferred for the ratio of corroded to pristine samples was of the order of 3.0- significantly greater. The crack initiation and early growth phase (to 200 µm) and crack growth phases 200 µm to failure were measured. It was found that the early crack growth behaviour was erratic with great variability in life to 200 µm; whereas growth beyond 200 µm was consistent and predictable using fracture mechanics models. Some of the work is reported in [1].

3.5.2 Reference:

[1] E Rezig, P E Irving, M Robinson "Development and early growth of fatigue cracks from corrosion damage in high strength stainless steel" Procedia Engineering 2 (2010) pp 387-396.

3.6 Use of laser peening to regain fatigue strength in mechanically damaged aluminium sheet

Contributors: Prof P E Irving and Dr X Zhang
Affiliation: Cranfield University

3.6.1 This research explores the use of laser peening to reverse the degradation in fatigue life of thin sheet brought about by the action of scribes. Both experimental fatigue testing and modelling of the influence of the Laser peened process are being performed. Laser peening consists of subjecting the surface of samples and components to an array of high power laser pulses forming a raster pattern over the surface of the sample. The shock wave produced by the laser pulse causes intense local plastic deformation and compressive residual stresses are formed which increase the resistance of the component to the initiation of fatigue cracks. Laser peening has been applied many times to demonstrate substantial improvements in fatigue strength in large high strength components of thicknesses of 20-30 mm. Its use to treat 2 mm sheet has not been reported previously.

3.6.2 In this work dogbone samples of 2024 T351 have been scribed to produce scratches of 5 µm root radii and depths of 50 and 150 µm. The fatigue strength of samples with scribes is between 5% and 15% of the original life of pristine samples- see the work under the scribes project above. The samples were subjected to different laser peening treatments surrounding the scribed region. Some treatments were more successful than others; In the best the life of the samples with 50 µm scribes was returned to 50% of the original, but samples with the more severe 150 µm scribes could only be returned to 10-15% of the life of the original. (See Figure 1 below).

3.6.3 The research is proceeding in collaboration with the Open University who is conducting detailed measurements of the residual stress field produced by the laser peen process, and of changes in residual stresses produced by modifications to the laser treatment conditions. One of the difficulties of application of laser peening to 2 mm sheet is that deflections associated with changes in residual stress fields cause deflection of the sample. Constraint of the sample to maintain a plane sample suitable for mechanical testing further modifies the residual stress field and will change the fatigue life (see Figure 2).

3.6.4 The modelling work objectives are to quantitatively predict the influence of the laser peening residual stresses on the fatigue life of the sheet. Modelling of the crack growth stage has been accomplished using the Kres approach but much of the life changes are associated with changes to initiation and microscopic crack growth stages.

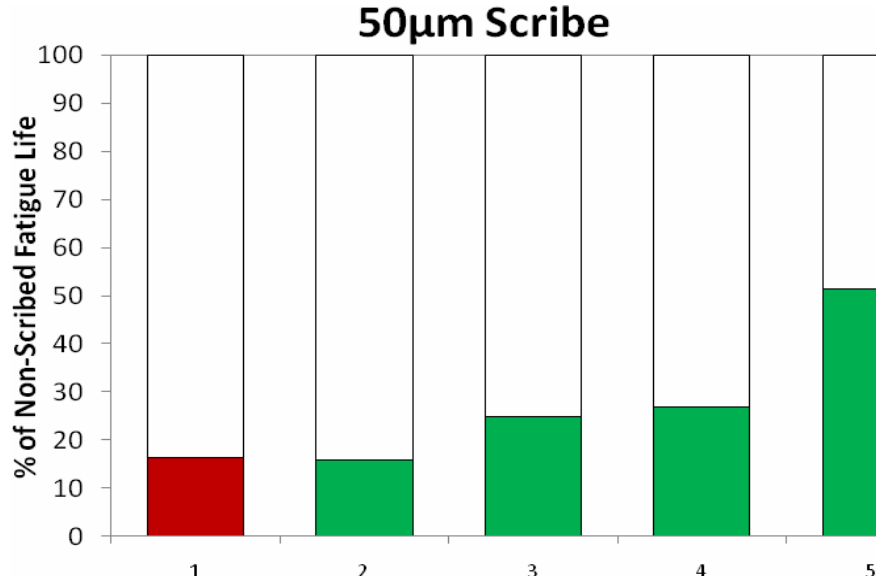

Figure 1 - Fatigue testing of 2 mm 2024 samples with 50 µm deep scribes in unpeened state (1) and with various laser peening treatments (2-5) showing return to 50% life.

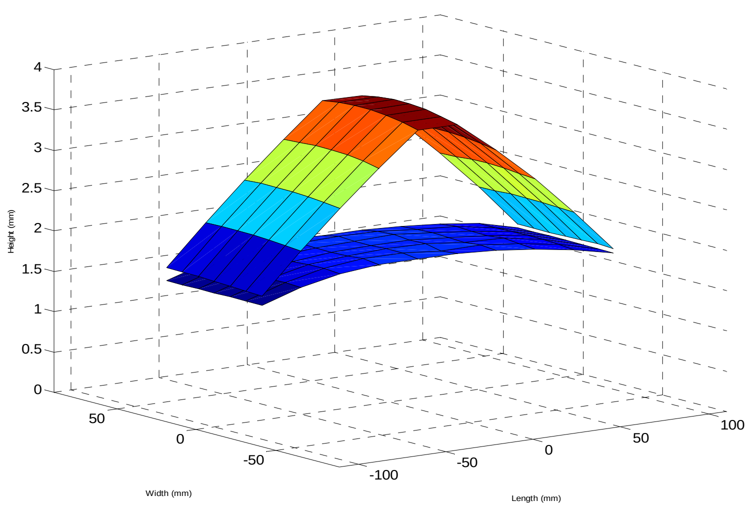

Figure 2 - Distortion of 2 mm sheet of 2024 before and after laser peening

3.7 Fretting fatigue, friction and laser shock peening

Contributors: Prof David Nowell and Prof David Hills
Affiliation: University of Oxford

3.7.1 Introduction

3.7.1.1 Research in structural integrity for aerospace applications continues at the University of Oxford. Much of the work is closely associated with the University Technology Centre for Solid Mechanics, established in 1990 in association with Rolls-Royce plc. Professors David Nowell and David Hills are associated with a number of projects, including the following:

3.7.2 Fretting Fatigue

3.7.2.1 Oxford has a long tradition of work in this area. A particular focus for recent work has been high temperature fretting. We have recently recommissioned a dedicated high temperature rig, which is capable of achieving temperatures of up to 680^{o}C. This will be used to test a range of aerospace alloys for fretting behaviour at elevated temperature. This regime is more challenging than room temperature, since oxidation plays a significant role in controlling the surface conditions and oxidation is, itself, in competition with surface wear. Hence a wide-range of multi-physics problems need to be understood. In parallel with the experimental programme, development of appropriate life prediction methods is taking place. The experimental results will be used to validate the methods proposed.

3.7.2.2 Separately from the high temperature work, research continues on the more theoretical aspects of the problem, including the behaviour of 'complete' (i.e. sharp-edged) contacts.

3.7.3 Frictional behaviour

3.7.3.1 A key variable in many fretting problems is the frictional behaviour at the interface. Fundamental work is being undertaken in collaboration with Imperial College London, aimed at understanding frictional behaviour and its evolution over time. Measurements of tangential contact stiffness have been made, and compare with simple models. These provide important input into the modelling of the vibration behaviour of multi-component systems. The work also encompasses measurement of friction coefficients and the development of asperity-level models of friction. Figure 1 shows a finite element model of asperity interaction, together with the variation of tangential force obtained. This force history can be combined with that for the normal force and used to obtain a local friction coefficient, which can be scaled up by use of a statistical approach.

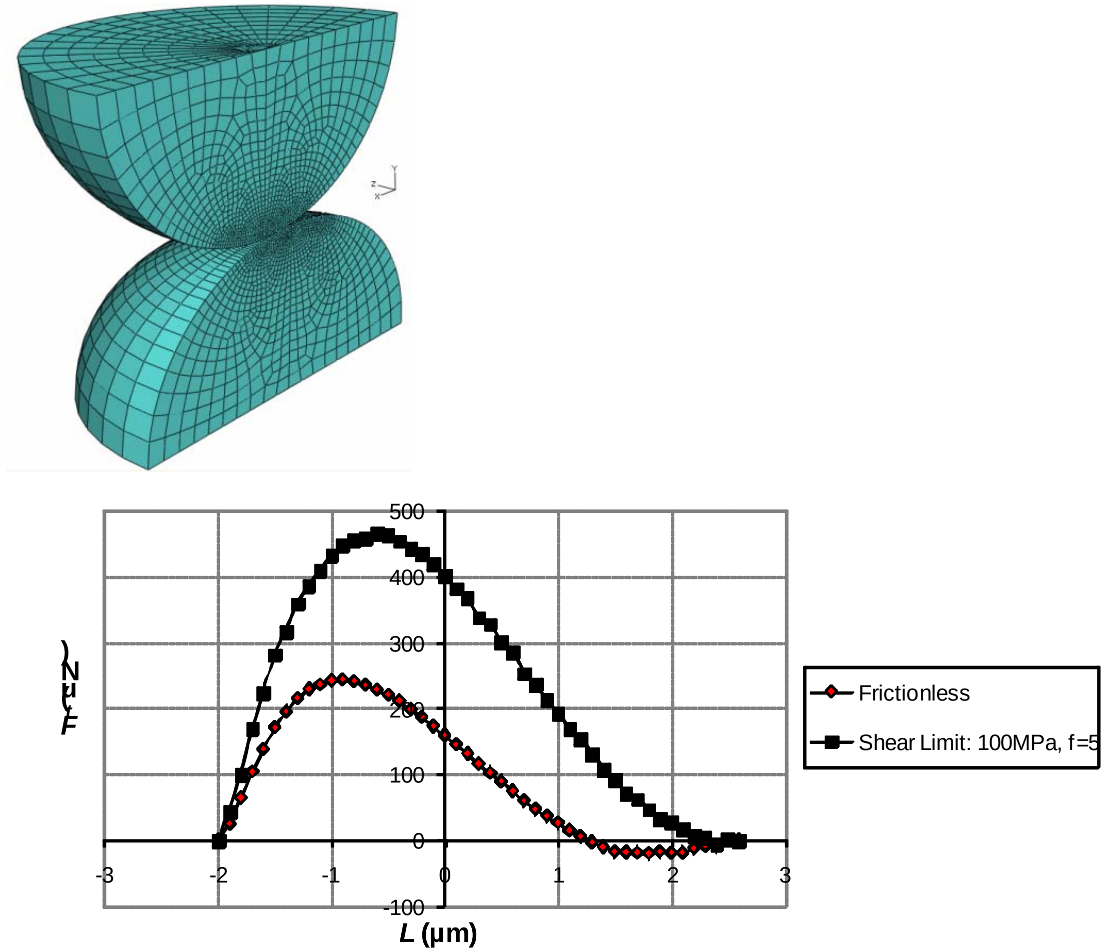

Figure 1 - Finite element model of asperity interaction and variation of tangential force with relative asperity position.

3.7.4 Laser shock peening.

3.7.4.1 Laser shock peening is becoming an important process for improving the fatigue behaviour of aerospace components. However, fundamental models of the process and its effect on fatigue life are relatively simplistic. Work is being undertaken in collaboration with Manchester and Swansea Universities (and with Rolls-Royce plc, Airbus, and Metal Improvements Co.) to better characterise the residual stresses present and their effect on fatigue behaviour. Oxford's role has been to develop improved process models, based on modelling the plastic strain introduced by a representative eigenstrain distribution.

4 Damage tolerance

4.1 The influence of bonded crack retarders on fatigue crack growth rates in aluminium alloys

Contributors: Prof P E Irving and Dr X Zhang
Affiliation: Cranfield University

4.1.1 Cranfield has performed research under two successive projects (BCR 2006-09 and Airstream 2010-13) funded by UK Research Councils, Airbus and Alcoa. These projects aim at exploring the viability of the bonded crack retarder concept as a device for life extension of damage tolerant aircraft structures. Fatigue crack growth behaviour in metallic substrates with bonded straps has been determined. Test coupons and large scale skin-stringer panels were tested at constant and variable amplitude loads. The strap materials were glass fibre polymer composites, GLARE, AA7085 and Ti-6Al-4V. Comprehensive measurements were made of residual stress fields in coupons and panels by our collaborators.

4.1.2 A finite element model to predict retardation effects was developed. Compared to the test result, predicted crack growth life had an error range of -29% to 61%.

4.1.3 Mechanisms and failure modes in the bonded strap reinforced structures have been identified. The strap locally reduces substrate stresses and bridges the crack faces, inhibiting crack opening and reducing crack growth rates. In the absence of residual stress, global stiffness ratio accounts for effects of both strap modulus and strap cross section area. In elevated temperature cure adhesives, retardation performance was best in aluminium and GLARE strap materials, which have the closest thermal expansion coefficient to the substrate. Strap materials of high stiffness and dissimilar thermal expansion coefficient such as titanium had poor retardation characteristics.

4.1.4 As an example, Fig. 1 and 2 illustrate the panel testing and life extension by bonded crack retarders. The plot of half crack length vs. cycles for the panel tests shows that initial behaviour of the three tests was similar up to a half crack length of 20-30 mm. After this the unstrapped and strapped curves diverged with the unstrapped propagating at a much faster rate eventually failing at a skin crack length of 320 mm, as the skin crack approached the second set of stringers. The tests of the wide GLARE and aluminium strapped panels were terminated where the skin crack was between 150-200 mm, largely for reasons of test time.

4.1.5 Examination of the failed unstrapped panel after test showed that the crack had become very asymmetric on the skin and on the stringer where the separate growth of the two sides is recorded. At the first stringer, the crack deviated parallel to the loading direction and no further propagation across the stringer occurred. Crack turning behaviour in 7085 has been observed on a number of occasions before in the course of the coupon test reported in the earlier sections of this report, and its occurrence in the stringer webs under conditions of stringer in plane bending is consistent with the observations made on the coupon samples.

4.1.6 In all the strapped tests, the crack on the stringer side approached and then tunnelled under the first strap. In the case of the panel with the wide GLARE straps the straps remained intact and the crack tip subsequently emerged on the other side of the strap, before entering the first pair of stringers. In the case of the wide aluminium strap, the substrate fatigue crack caused initiation of a fatigue crack in the strap itself, which then propagated together with the panel crack for the rest of the test duration.

4.1.7 In summary, the panel testing has shown that the wide GLARE straps work well, increasing the crack growth life of the panel compared with the unstrapped one by in excess of a factor of 2. Unlike the other strapped panels the wide GLARE ones remained intact throughout the test. The aluminium strap although it initially reduced crack growth rates to a smaller value than the GLARE straps as it had no thermal residual stresses, initiated a fatigue crack very soon after the crack tip tunnelled under it, and rapidly lost retardation capability.

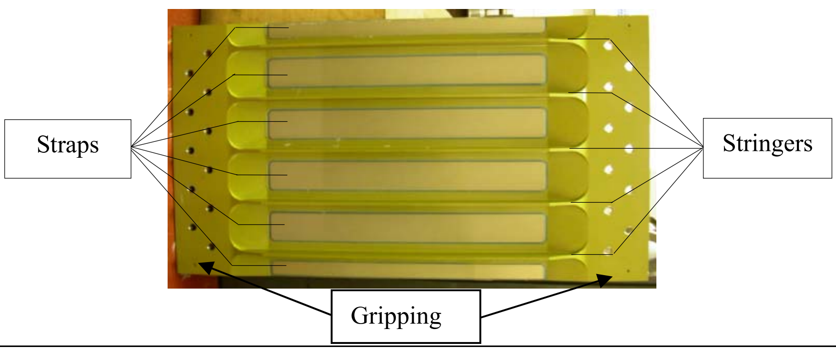

Figure 1 - Picture of panel with wide GLARE straps ready for testing

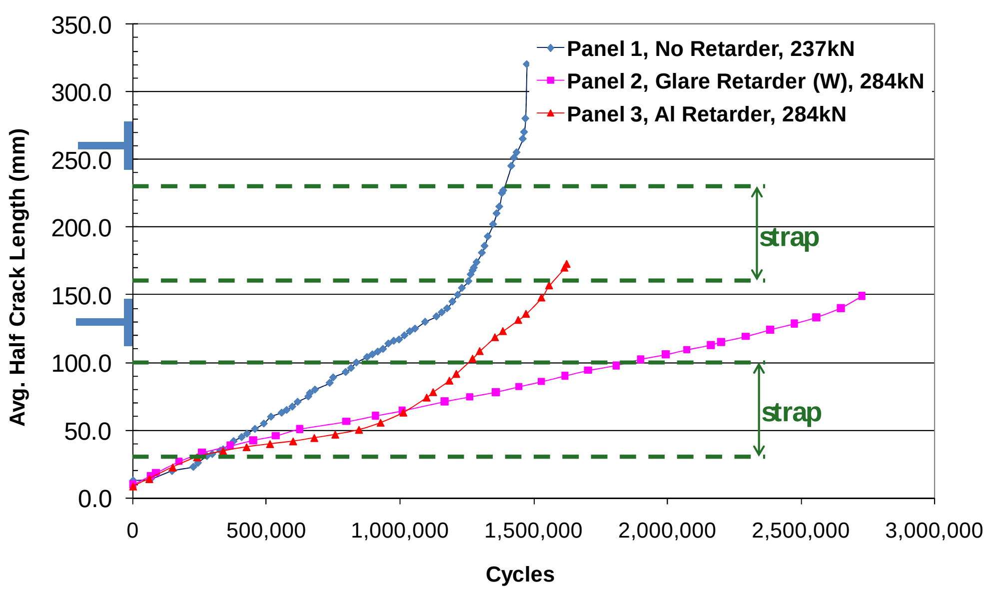

Figure 2 - Half crack length vs. cycles for panels tested under a flight spectrum.

4.1.8 Reference:

[1] PE Irving, X Zhang et al. to be presented at 26th Symposium of International Committee of Aeronautical Fatigue (ICAF 2011), Montreal, June 2011 To be presented at ICAF 2011]

4.2 Modelling the blast response of fibre metal composite laminates

Contributor: Prof C Soutis

Affiliation: Department of Mechanical Engineering (Aerospace), The University of Sheffield

4.2.1 Modelling the dynamic interaction of blast loading with primary aircraft structures is of great interest to both the military and civil sector as the threat of sabotage and terrorism increases. This work examines and models the dynamic behaviour of a fibre metal laminate known as GLARE to dynamic loading based on experimental data using theArbirtraty-Lagrangian-Eulerian multi-material formulation (ALE) in the explicit finite element solver LS-DYNA. To validate the predictive methodology, as well as to prove its ability to simulate complicated blast tests, two different scenarios were examined based on experimental observations and measurements. The first examined the blast response of GLARE flat panels subjected to an open air-blast and the second examined the blast propagation in a pressurised cylindrical barrel. The predicted numerical results agree very well with those of experiments. This computational approach is able to accurately predict the relevant aspects of the blast–structure interaction problem, including the blast wave propagation in the medium for both un-pressurised and pressurised loading cases and the response of the structure to blast loading that can lead to more damage resistant and tolerant designs.

4.2.2 References:

[1] Soutis C. “Recent advances in building with composites". Plastics, Rubber and Composites, 38(9/10), (2009), 359-366.

[2] Mohamed, G., Soutis, C. and Hodzic, A. “Modelling the dynamic behaviour of metallic and composite materials in aircraft structures”. Proceedings of ICCES’10: International Conference on Computational & Experimental Engineering and Sciences, 28 March-1 April, Las Vegas, USA. 2010.

[3] Mohamed, G., Soutis, C., Hodzic,A. “Modelling the damage tolerance of composites to blast loading in pressurised cylindrical structures”. Proceedings of ECCM14, 14th European Conference on Composite Materials, 7-10 June 2010, Budapest, Hungary. 2010.

[4] Mohamed, G., Soutis, C. and Hodzic, A. “Afluid-structure interaction model for pressurised composite structures subjected to blast loading”. Advanced Composites Letters, 19(3), (2010), 111-116.

5 Structural ageing aircraft programmes

5.1 UK MOD ageing aircraft audits

Contributor: Martin Hepworth
Affiliation: Aviation Support Consultants Ltd

5.1.1 Background

5.1.1.1 The requirement to carry out Ageing Aircraft Structural Audits on aircraft that are on the UK Military Register is laid down in Joint Services Publication (JSP) 553 Military Airworthiness Regulations. The Policy is that an AAA must be carried out 15 years after the declared In Service Date (ISD) for the type and thereafter at 10-yearly intervals. Joint Air Publication 100A-01, Military Aviation Engineering Policy and Regulation, provides further requirements and lays down the actions required of an Aircraft Project Team. The aim of an AAA is to 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. Moreover, an AAA is an activity intended to bring together the routine management activities, often carried out in isolation, in order to build a coherent picture of the state of the aircraft fleet, it should also seek to identify patterns or trends that point to future integrity problems. JAP100A-01 provides further separate Policy and guidance covering Aircraft Ageing Structural, System and Propulsion Audits.

5.1.2 Structural audits carried out by QinetiQ 2009/2010

5.1.2.1 During 2009/2010 QinetiQ have carried Ageing Aircraft Structural Audits on both the Tucano, and Dominie aircraft. Both types are operated in the Training role, the Shorts Tucano is a derivative of the Embraer EMB312 whilst the Dominie is a twin engined aircraft based on the original civil HS125. The approach to carrying out the Audit involved using a series of Work packages which addressed the various aspects of aircraft design, operations and in-service support.

5.1.2.2 The audits address two separate features of aircraft support, each concerned with validating, sustaining and, potentially, exploiting Structural Integrity:

- In-Service Project Team activities; e.g. intended and applied maintenance philosophy, adherence to limitations, defect reporting and analysis, management of Structural integrity (SI) recovery and enhancement.
- A review of Design Organisation (DO) based static and fatigue clearances compared with In-Service limitations and usage.

5.1.2.3 The requirement to address in-service activities was fulfilled by a combination of fact finding visits, technical reviews and analysis of ISSA and DO records relating to the airframe structure. Essentially the fact finding visits included discussions with maintenance staff on the problems encountered during inspection and repair. These proved particularly valuable in identifying potential aging problems.

5.1.2.4 The review of In-Service use compared the extant Statement of Operational Intent and Usage (SOIU) with the original intended to ensure the structural implications of any changes had been addressed. A review of the Release to Service (RTS) was carried out to ensure all DO limitations were captured; in addition, the Aircrew Manuals and Flight Reference Cards were audited to ensure they reflected any limitations.

5.1.2.5 The Audits sought not only to establish that current support functions were adequate but also to identify emerging and future aging problems. Throughout the audits a liaison was maintained with the UK Military Aviation Authority to ensure the policy was being met.

5.1.3 Emerging AAA policy

5.1.3.1 In addition to the requirement for Aging Aircraft Structural Audits there exist within the Policy the requirement for Aging Aircraft Systems and Propulsion Audits. There are clear synergies between all three auditing particularly in the auditing of in-services support functions. Much of the maintenance philosophy, documentation and recording span all three areas. The Tucano Project took advantage of this by following the Structural Audit with a Systems and Propulsion Audit using the same team of auditors thereby benefiting from the work carried out during the Structural Audit and reducing the overall cost. The MAA have recognised the advantage of combining the Audits and the next amendment to the Policy documents will reflect the requirement for an AAA encompassing Structures, Systems and Propulsion.

6 Fatigue testing

6.1 Major fatigue testing activities at Bombardier Aerospace, Belfast.

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Affiliation: Bombardier, Belfast

6.1.1 Tucano fatigue test

6.1.1.1 Most of the on-site activity in Belfast has centred on the second full-scale fatigue test on the RAF “Shorts” Tucano training aircraft. The Tucano T.Mk.1 2nd Full Scale Fatigue Test commenced fatigue testing in January 2005. The test article is the last RAF production airframe (designated T132) and includes the wings, fuselage, tail-plane and fin. The airframe also includes the fatigue modifications arising out of first full scale fatigue test.

6.1.1.2 The test spectrum has been developed primarily from Operational Load Measurement data recorded on three instrumented aircraft over a 17 month period. The spectrum is applied in a repeatable block that represents 1000 flying hours. This spectrum block is constructed from 75 flight types, and 755 balanced load conditions representing typical ground and flight loading events. The loads are applied to the test article through 42 active load channels using hydraulic actuators, and 7 grounded and monitored reaction points. The test article is fitted with an extensive strain gauge installation, which are being sampled at regular intervals throughout the test. These have proved useful in both monitoring the performance of the test and in highlighting fatigue cracks local to the gauges.

6.1.1.3 At present the test has completed 24 spectrum blocks representing 24000 flying hours. A number of damages have been recorded on the test resulting in the introduction of fleet inspections or the establishment of component replacement lives where appropriate. Most notably the detection of cracking on the wing centreline joint strap due to a change in strain gauge response has enabled a fixed life to be established for this critical wing component. The value of the Tucano fatigue test to the RAF has been further proved by the early detection of in-service cracking from the directed inspections, allowing remedial action to be undertaken.

Figure 1 - Tucano Full Scale Fatigue Test Specimen

6.1.2 Other Fatigue Test Activities

6.1.2.1 The Stress Department in Belfast has also provided technical support to two major rigs at the Bombardier site in Montreal. Belfast has responsibility for fuselage structure on CRJ700/900 Regional Jets.

6.1.2.2 The Centre Fuselage Test, designated A/C 0005, has completed 160,000 cycles (2 lifetimes). The Residual Strength Test programme for CRJ700 is almost complete. The 2 bay crack arrest is one of the outstanding tests.

6.1.2.3 The CRJ900 Centre Fuselage Test, designated A/C 15995, has completed 141,000 cycles of fatigue testing.

6.1.2.4 A major sub component test programme on flat pressure boundaries has been completed over the last couple of years in support of a design modification.

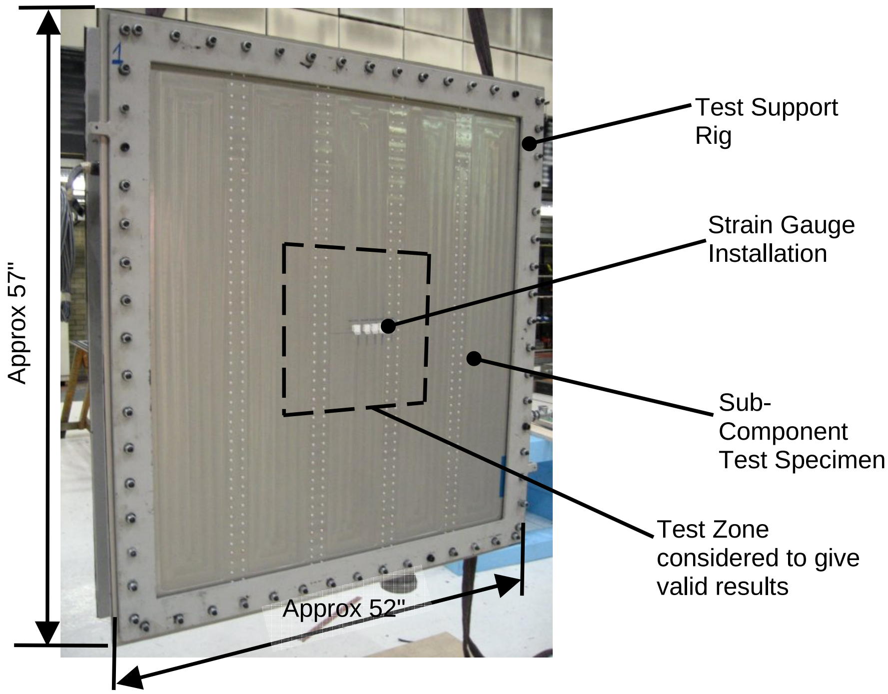

Figure 2 - Pressure Box Subcomponent Testing

7 Developments in fatigue monitoring

7.1 Advanced fatigue fracture and detection in landing gear structures using acoustic emission

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Affiliation: Cardiff School of Engineering

Contributors: Prof. K. Worden & Dr. J. J. Hensman
Affiliation: University of Sheffield

7.1.1 Messier-Dowty are world leaders in the design and manufacture of aircraft landing gear systems, structures and components. Each design requires certification for flight by the airworthiness authorities and this process relies on information obtained from structural fatigue testing (Figure 1). Traditionally, non-destructive testing (NDT) is used to confirm the integrity of the landing gear structure at key stages in the fatigue test regime. The NDT inspection requires the test to be stopped for a period of time to allow the structure to be dismantled and inspected and these periods of NDT can account for 25% of the total testing time. It was proposed that Acoustic Emission (AE) could be used to monitor the landing gear during the certification test in order to reduce the down time associated with conventional NDT inspections.

7.1.2 Acoustic Emission (AE) is a passive NDT technique that relies on the detection of the stress waves that are released during crack propagation. Piezoelectric sensors coupled to a structure detect the stress waves when they reach the surface. The sensors convert the surface displacements to a voltage that is sampled and based on user thresholds separated into individual discrete signals. Traditionally waveform parameters such as amplitude, energy and rise-time are extracted from the waveform and used for analysis.

7.1.3 Although AE techniques are currently employed in a number of industries, there is still some skepticism in aerospace engineering. A major aspect of implementing an AE solution for monitoring landing gears is that Messier-Dowty requires an automated system capable of identifying fractures at an early stage in what is a high-noise environment and in specimens that have complex geometry.

7.1.4 Initially during system development it was identified that source location was of paramount importance. Commercial techniques rely on the detection of a signal by an array of sensors and, based on a uniform propagating speed and measurement of arrival times at each sensor, a location is determined. Current source location techniques assume a straight path of propagation between sensor and source. These assumptions are very inappropriate for landing gear structures that have numerous geometric discontinuities and changes of thickness, which dramatically affect signal propagation and signal wave speed. A ‘touch and learn’ approach to signal source location was developed [1]. The technique relies on the user acoustically mapping the structure prior to the investigation and has demonstrated experimentally a large increase in accuracy over conventional techniques [2].

Figure 1 – Landing gear undergoing certification testing

7.1.5 Source characterisation in a high noise environment is very complex with the number of crack signals being extremely low when compared with the signals from noise (actuator noise and component rubbing and moving). However it was identified through laboratory testing that the signals recorded at a sensor due to a crack source showed little change in waveform parameters over time when compared with noise sources [3]. If the AE transfer function is considered (source, material, geometry, couplant, sensor, cable and acquisition system) in the example of a fracture, there is little change during the duration of a test. There is only a small alteration of the transfer function (geometry) due to small advancements in the crack and hence the change in detected signal will correspondingly be low. The use of signal variation of groups (or clusters) of located signals was employed successfully in a high-noise landing gear environment where an artificial source was detected and located [4]. Figure 2 shows the similarity of signals from location clusters (the higher the value, the higher the probability the source is from a fracture) from a research fatigue test on a landing gear component. During the initial stages when only noise sources are present similarity scores are low, indicating no fractures, however prior to the onset of fracture, as identified through visual observation, all channels adjacent to the fracture show a dramatic increase in signal cluster similarity.

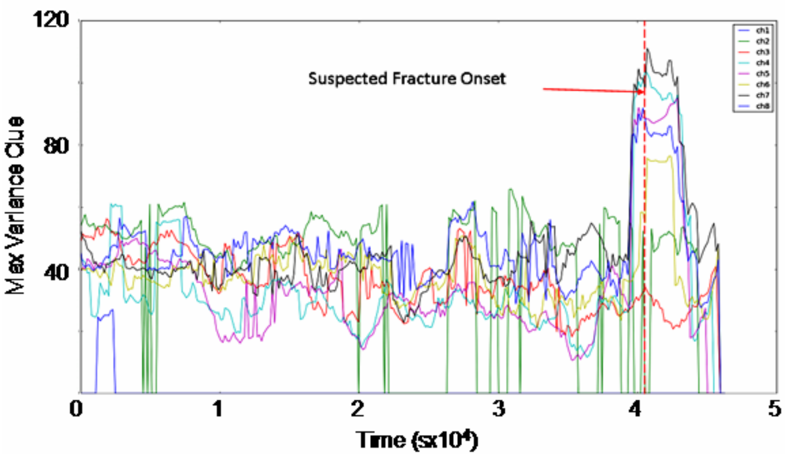

Figure 2 – Variance of clusters per channel through duration of test

7.1.6 A further advancement in AE signal processing was developed that utilised source location maps and novelty detection. It is assumed that the landing gear component initially is fatigue fracture-free and that during the initial stages no fractures develop. A ‘map’ or ‘finger print’ of the source locations from noise within the structure is recorded and using a novelty detection algorithm any new sources such as those from fatigue fractures are identified.

7.1.7 Further advances based on signal triggering and waveform parameters have also been developed and, in combination with the advanced source location techniques, a signal variance measurement and novelty location methodology for automatically identifying fatigue fractures in complex geometry and high noise environments has been created. These techniques have been validated though a series of fatigue tests where fractures were typically automatically identified approximately 2k cycles prior to failure. These fatigue tests will be the subject of future publications.

7.1.8 References

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7.2 Boeing E-3D Sentry data acquisition system

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7.2.1 Introduction

7.2.1.1 The Boeing E-3D Sentry is an Airborne Warning and Control System (AWACS) aircraft that provides all-weather surveillance, command, control and communications to local aircraft. A project was undertaken to install a Loads and Environmental Spectra Survey (L/ESS) recording system on a fleet of aircraft that would recorded airframe stress and other aircraft operational parameters on every flight. This data is eventually combined with that from other Sentry aircraft around the world to provide details on the airframes operational life and to aid maintenance.

7.2.1.2 The original equipment installed consisted of a Data Acquisition System (DAS) and a recorder. However, the company that provided the equipment changed their focus and the customer found themselves in a position where the installed DAS was no longer supported. Thus a replacement was sought. A standard KAM-500 DAS from ACRA CONTROL was selected.

7.2.1.3 The commercial off the shelf (COTS) solution was customised for the application by selecting the appropriate sized chassis and plug-in module cards – all of which was existing hardware requiring no bespoke design. The KAM-500 inherited several benefits from its heritage in the highly demanding field of flight test instrumentation over the original equipment. These included:

- Lower weight – 15Kg lighter
- Increased efficiency – 50% lower power
- More compact – used less than one quarter of the space
- Maintainability – standard product with no bespoke hardware
- Supportability – spares and new modules for expansion or upgrading readily available
- Future Proof – continuous development of technology and stable chassis design ensure long useful life
- Commonality – other aircraft use the same basic system building blocks

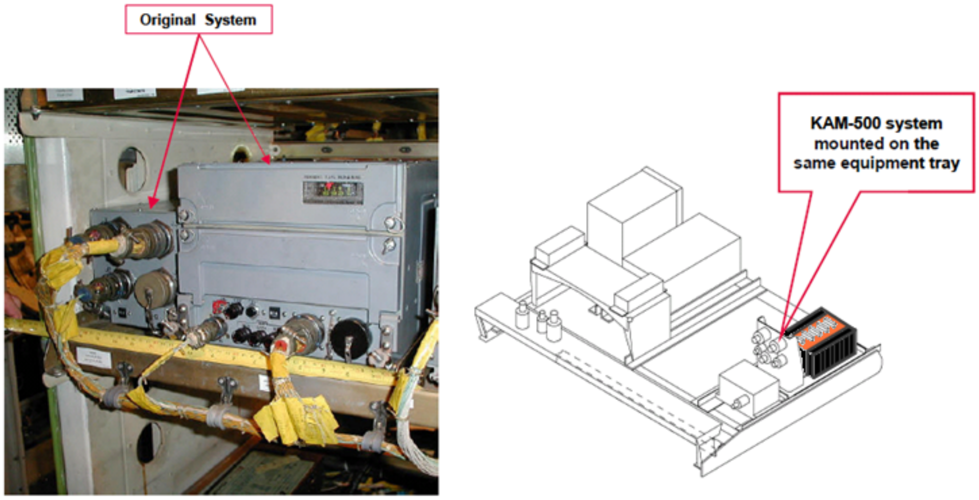

Figure 1 – Original systems and KAM-500 system

7.2.2 System Details

7.2.2.1 The system used a single chassis with various modules including PCM encoders, MIL-STD-1553 bus monitor, syncros and analog data acquisition modules with inbuilt sense lines. These sense lines enhance the accuracy of the data collected from the strain gage bridges by compensating for the effect of long cable runs. Given the aircraft's size, it can be seen from the diagram below that the additional cable resistance would otherwise introduce bias errors. The acquired and conditioned data was sent to a dedicated recorder.

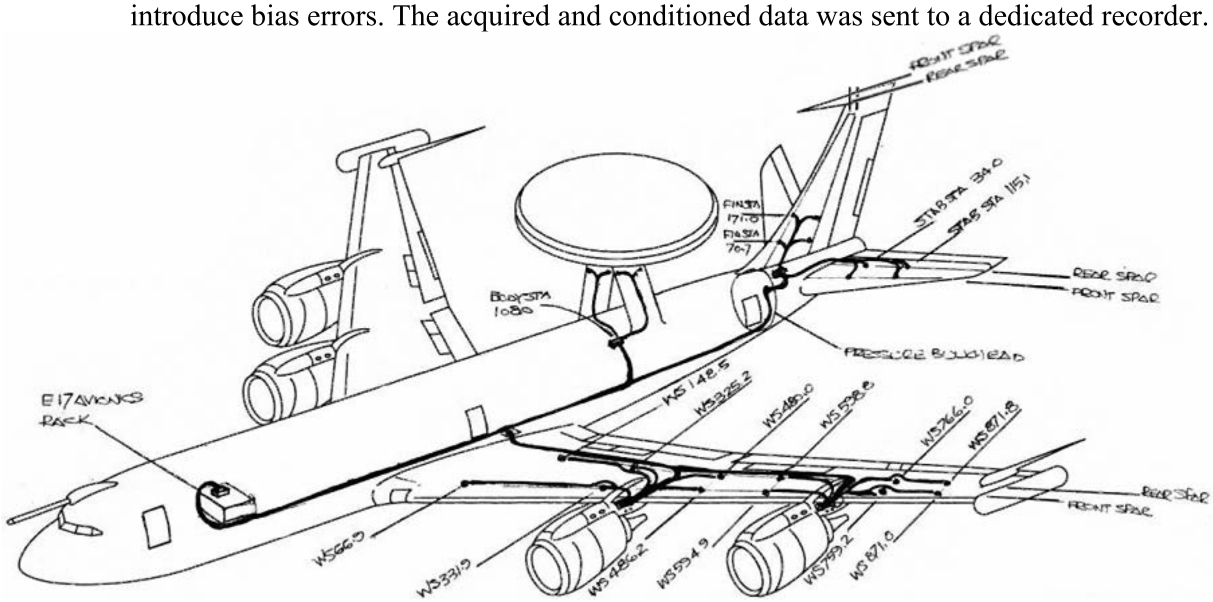

Figure 2 – Boeing E-3D Sentry

7.2.3 Data analysis

7.2.3.1 Data from all the aircraft is replayed into a ground processing system where it is scaled and formatted before being sent for analysis in the United States. The software originally used for this was upgraded to work in the latest Windows environment. Doing so had the benefit of allowing the quality of the raw data to be assessed using new software before reformatting. A simple piece of conversion software was produced to transfer the data stored in flash memory from the KAM-500 to a suitable format for further analysis.

Figure 3 – Data transfer illustration

7.2.3.2 The data, along with data from many other aircraft in use around the world, is collected, correlated and analysed to form a unique history of the all the aircraft's fatigue and usage parameters over the fleet's operational life. The analysis of such trend data helps to indicate if there are any potential fatigue or maintenance problems well before they become critical.

7.3 Projects in association with Cranfield University Centre for Integrated Vehicle Health Management (IVHM)

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7.3.1 Introduction

7.3.1.1 The Cranfield centre for IVHM was established in 2008 with the backing of a group of large Aerospace manufacturers including Boeing, Rolls Royce and BAE Systems. The centre provides a focus for necessary research for development of integrated end to end (from sensors to maintenance actions and business models) demonstrator level IVHM systems. It does not perform research into fatigue and durability of structures per se. However much of its work has implications for structural and aircraft system integrity & maintenance. Two examples of projects from the portfolio of research projects currently performed by the centre are given below.

7.3.2 Detection & location of fatigue cracks in aircraft using acoustic emission

7.3.2.1 The objectives of this work are to develop systems for location and monitoring of fatigue cracks in aircraft wing structures using the acoustic emission approach. Despite over 50 years of research into acoustic emission and the development of high data rate monitoring systems for detection of acoustic emissions, there is little quantitative information available to define capability of AE systems to locate and monitor developing fatigue cracks in structures. One of the key parameters required is the form of the Probability of Detection (POD) Vs defect size or location error for AE (or any selected health monitoring technique). The research is investigating factors controlling POD for detection and location in AE systems applied to simple laboratory samples and in complex wing structures, and will quantitative measure POD and benchmark performance for a range of geometries and scale of sample and structure.

7.3.2.2 A 4 channel COTS AE system is being used in a series of laboratory experiments to explore capability to detect and locate crack like defects in 2 mm thick 7075 aluminium alloy. POD curves have been defined for laboratory bench tests using simulated AE emissions; current testing is using real fatigue cracks in simple sample geometries.

7.3.2.3 Once the POD has been measured, this information can be used together with further Usage monitoring data and fracture mechanics models in development of a Structural Integrity Prognostic System (SIPS) for an aircraft wing structure. Integration of the various inputs and data processing to make the predictions will form part of a future stage of research.

7.3.3 Diagnostic & prognostics of fuel systems degradation

7.3.3.1 Many of the applications of system diagnostics and prognostics tools in IVHM systems are applied not to structures but to systems such as fuel systems. Elements in the fuel system such as the pump or the driving motors or valves can degrade due to fatigue, wear, or corrosion processes. The internals of the systems can be degraded due to contamination, filters can become blocked. The system can be monitored (pressure vibration, flow rates and so on). Monitoring of system state and prediction of future remaining life in the presence of damage would clearly have major benefits. The project seeks to develop a demonstrator diagnostic and prognostic system capable of detection and diagnosis of a range of faults and prediction of the future useful life. The diagnosis stage research is concerned with selection of suites of sensor systems and design software that diagnose faults with the minimum ambiguity and maximum sensitivity without influencing overall system reliability adversely.

7.3.3.2 In current work a laboratory bench fuel system of a scale comparable with that required for a UAV has been constructed and its performance under normal operating conditions characterised. Simulated faults have been introduced and their effect on a range of monitoring devices explored. Comparison of system behaviour with physically based simulation models has been made.

7.4 Low-cost operational loads measurement and usage monitoring of historic aircraft

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Contributor: Dr Steve Reed
Affiliation: Defence Science and Technology Laboratory, UK MOD

7.4.1 Introduction

7.4.1.1 The United Kingdom (UK) Ministry of Defence (MOD) is embarking upon a series of low-cost Operational Data Recording / Operational Loads Measurement (OLM) and usage monitoring programmes, for historic aircraft and small fleets of aircraft within the inventory. These programmes aim to meet UK Military Aviation Authority's (MAA) regulatory requirements.

7.4.1.2 However, the majority of these aircraft have very limited Design Organisation support and limited design and previous service usage data. Hence, there is a need for the MOD to undertake a more hands-on approach with the management of structural integrity (SI) for these platforms. Therefore the MAA, Dstl and MOD aircraft Project Teams are developing a process that will provide Regulators and Project Teams with a range of low-cost data capture solutions and a multi-flight data analysis tool.

7.4.2 Aircraft Data Analysis and Monitoring (ADAM) system development

7.4.2.1 In addition to the 'traditional' OLM/ODR programmes, which have generally used the ACRA KAM-500 data acquisition equipment, several of the historic aircraft have been fitted with the Formula-1-derived Cosworth Engineering (formerly Pi Research) Delta or Sigma acquisition units. The installation of the equipment has been undertaken by ARCo of Duxford, near Cambridge.

7.4.2.2 The Sea Hawk aircraft (Figure 1), operated by the Royal Navy Historic Flight (RNHF), has been the lead aircraft in this programme. Sea Hawk WV908 is the only flying example of this aircraft type worldwide.

7.4.2.3 In addition, Dstl has developed an Aircraft Data Analysis and Monitoring (ADAM) system to undertake the data-wide analysis, not easily undertaken on the Pi Toolbox, as currently configured.

Figure 1 – Sea Hawk WV908 in flight

7.4.2.4 First-line analysis is undertaken by the RNHF using the Pi Toolbox system, illustrated in Figure 2.

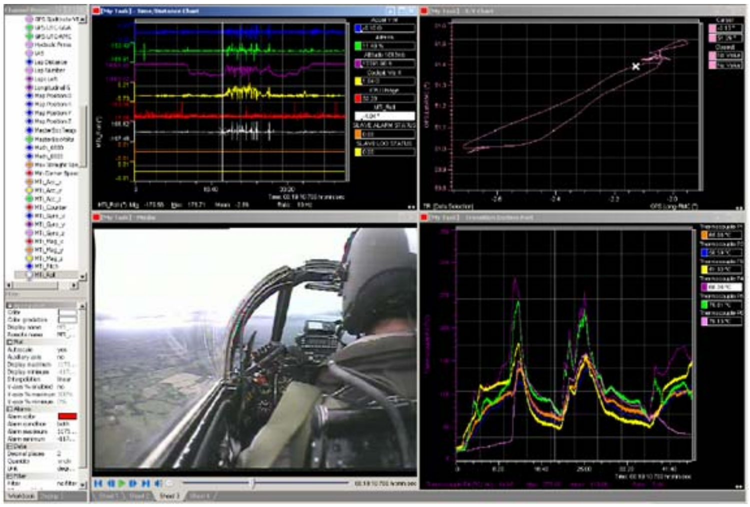

Figure 2 – Sea Hawk WV908 Pi Toolbox analysis screen

7.4.2.5 One of the principal difficulties in undertaking any of the aspects traditionally associated with an OLM programme on historic aircraft is likely to be the lack of design or qualification information to compare captured data with. For a more recent aircraft, the prime data used in the OLM programme are strains / stresses or loads at key structural locations and these are compared with either design assumed fatigue spectra or structural test spectra. Flight parameters are largely used to understand the strain outputs. However, for many of the historic aircraft these design and qualification data do not exist. Therefore, it is necessary to take a step back and look at what assumptions are made in the aircraft Safety Case in order to underwrite continued operations of the aircraft at an as low as reasonably practicable (ALARP) risk.

7.4.2.6 One would expect the safety argument to be along the lines that the aircraft is operated benignly, compared with its design envelope or its former in-service usage. Furthermore, the annual usage of the aircraft is likely to be low compared with original service usage. One would also expect that the three service historic flights (RAF, RN and Army) would argue, quite rightly, that their aircraft are maintained to the highest standards and subject to frequent maintenance compared with an 'operational' aircraft. From such a safety argument, substantiating whether the aircraft is in fact operated benignly should be a principal aim of an historic aircraft data capture programme.

7.4.2.7 It is also unlikely that a definition of what is meant by benign operations has been produced for each aircraft type. Aircraft may have reduced static limits; for example, an aircraft with a service release to 6g may be operated with a 4g limit but there is unlikely to be benign limit fatigue spectra defined. Also the normal acceleration (Nz) spectrum alone may not provide sufficient information to confirm benign operations. Depending upon the aircraft type and its usage in an historic flight, there may be other aspects of the usage that are more critical and these data should be included in the periodic review of Sea Hawk usage.

7.4.3 Therefore, the approach recommended and endorsed by stakeholders was to describe the usage of the Sea Hawk aircraft in terms of key flight parameters, such as normal acceleration and airspeed exceedences. These data would be compared with any design data or previous usage data available and with year-upon-year usage. This would allow stakeholders to identify any significant increases in usage severity and to confirm any assumptions of benign usage in the Safety Case.

7.4.3.1 The aim of the initial analysis was to superimpose the usage of WV908, in terms of normal acceleration (Nz) and indicated airspeed (IAS) (usually termed a V-g diagram), onto historic operational and design envelope data, obtained from a 1956 Royal Aircraft Establishment report [1]. The intent was to build up a picture of how the aircraft was operated in the RNHF, compared to its in-service usage in the 1950s and the design envelope. Thereafter, assuming the relevant authorities were content that the current usage falls within the understanding of benign usage, then this plot would be updated to track ongoing usage of the aircraft.

7.4.3.2 Royal Aircraft Establishment (RAE) Technical Note 187 reported on Sea Hawk V-g records captured between September 1954 and October 1955. In total, 308 V-g records, representing 312 flying hours, were obtained from Sea Hawk aircraft of No. 804 Squadron of the Fleet Air Arm. The records were then divided into Ground Attack (73 records, 67 flying hours) and General Duties (235 records, 245 flying hours) sortie types and each group were analysed separately. The RAE then estimated the V-g boundaries for each sortie type over a range of exceedences, once in 30 flying hours, once in 100 flying hours and once in 300 flying hours (for General Duties flying only as there were insufficient data to make this estimate for Ground Attack over 300 flying hours).

7.4.3.3 The data from three seasons, 2008 to 2010, containing 109 sorties accounted for 81 flying hours, were compared with the estimated one in 100 flying hour exceedence data produced by the RAE [1]. Although the WV908 data only represented 81 flying hours, it did represent 109 sorties and RNHF sorties are generally shorter than those flown operationally in the mid 1950s. It was therefore considered a reasonable comparison to make. Thereafter, the airspeed data were divided into 10 kts windows (e.g. between 300 kts and 310 kts) and the corresponding maximum and minimum NZ values were determined over the entire dataset. The results are plotted in Figure 3.

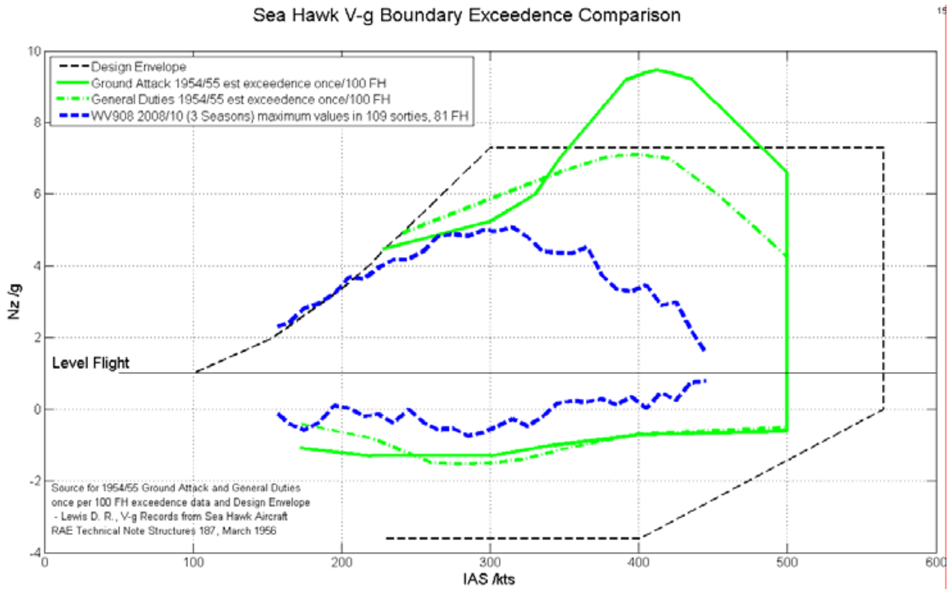

Figure 3 – Sea Hawk WV908 – V-g boundary exceedence comparison

7.4.3.4 It was concluded that the Sea Hawk parametric data could be used to provide a comparison of V-g usage between its current operation in the RNHF and its historical operational usage, design limits and RTS limits and that RNHF usage was considered to be benign. It is intended to monitor future usage using this method.

7.4.4 Development of usage monitoring capability using commercial MEMS-based equipment

7.4.4.1 There is a clear need to develop even more cost-effective solutions to validate design assumptions of aircraft structural usage. In recent years, a wide range of commercially-available low-cost sensor-related technologies have been developed that could have the potential to meet this requirement. The objective of this task was to investigate the feasibility of using these commercially-available sensors to meet the MOD's structural usage measurement requirements, at minimum cost. The prime focus of this work has been based upon the use of a Modular Signal Recorder (MSR) unit, using Micro-Electro-Mechanical Systems (MEMS) technology.

7.4.5 After a review of a number of potential MEMS-based accelerometer units, the Modular Signal Recorder (MSR)145/165 units, manufactured by MSR Electronics GmbH, Switzerland, were selected for further evaluation (Figure 4).

7.4.6 The battery-powered MSR data loggers incorporate a 3-axis accelerometer with a range of internal or external sensors to measure temperatures, pressures, relative humidity and light levels, as well as options to capture up to four analogue streams data from other external sensors. Data can be recorded at various sampling rates, using the MSR software, shipped with the units. The basic unit records up to two million measurements and, on the MSR165 unit, this can be expanded significantly with the use of a secure digital (SD) card memory facility (the units are shipped with a 4GB card).

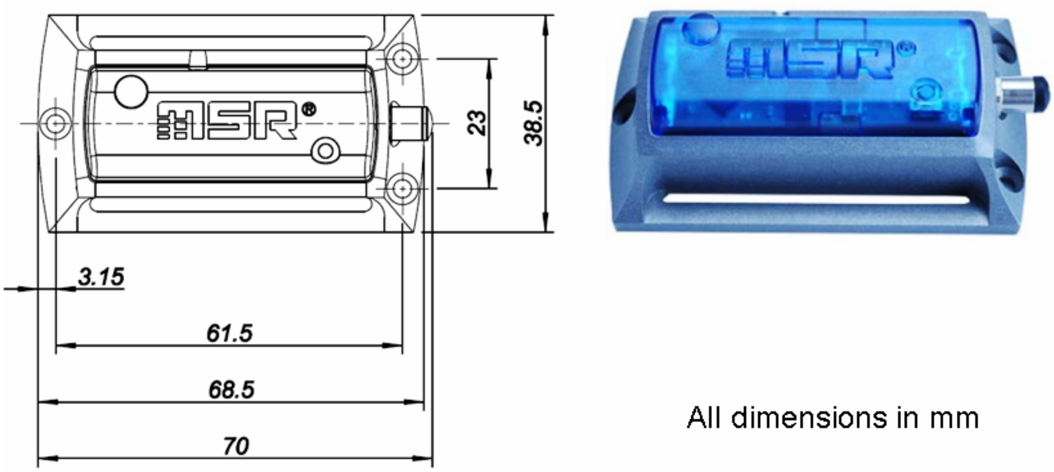

Figure 4 – MSR165 unit

7.4.6.1 Bench testing of the unit, compared with a Flight Test Instrumentation (FTI) standard accelerometer provided very comparable results under representative loading (Figure 5).

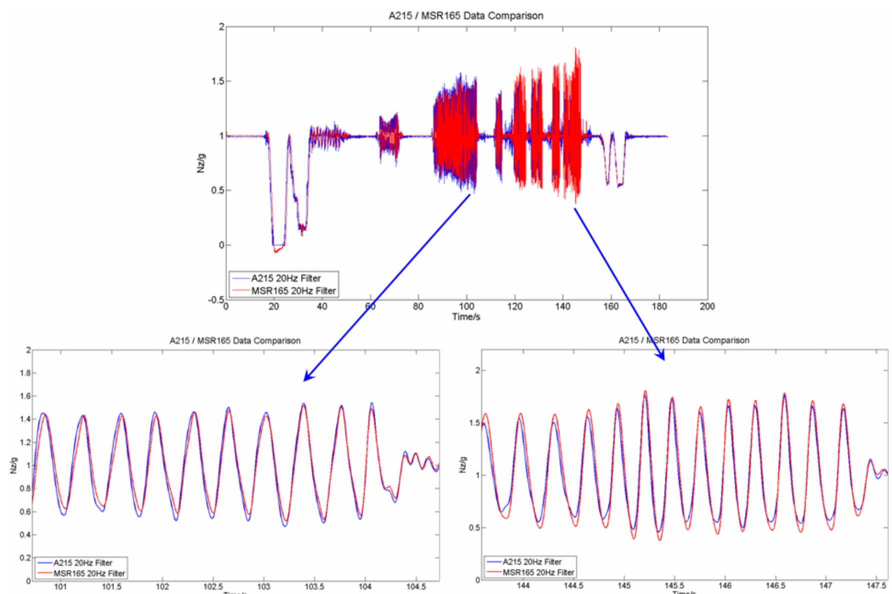

Figure 5 – MSR165 compared with 'FTI' accelerometer

7.4.6.2 Initial flight trials of the unit have been conducted on an Islander aircraft and further trials are planned this year for other aircraft types. It was concluded from this initial study that the MSR units have the capability to capture in-service usage data, within an affordable programme, and further pull-through of these advanced technologies has been recommended.

7.4.7 References

[1. Lewis D R, V-g Records from Sea Hawk Aircraft, Royal Aircraft Establishment Technical Note No: Structures 187, March 1956.

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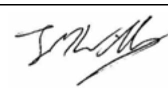
Reviewer	Mr Ian Wilcock		18 March 2011