REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN THE UNITED KINGDOM DURING THE PERIOD MAY 2007 TO APRIL 2009

Compiled by J E Moon

2.1 INTRODUCTION

This review summarises aeronautical fatigue investigations carried out in the United Kingdom during the period May 2007 to April 2009. 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, full scale fatigue testing, developments in fatigue monitoring, fatigue in composite materials and structures, and damage tolerance. A list of references related to the various items is given at the end of the paper.

The authors gratefully acknowledge the contributions generously provided by colleagues in the aircraft and associated industries, universities and at QinetiQ. The names of the principal contributors, and their affiliations, are shown in brackets after the title of each item. In addition, contact details are provided in the list at the end of the report.

2.2 DEVELOPMENTS IN FATIGUE DESIGN TOOLS

2.2.1 ESDU Design Data (A C Quilter, ESDU International plc, London)

Crack resistance curves computer program

Work on an ESDU Data Item and an accompanying computer program is in progress. The Data Item presents a program based on the method described in ESDU 85031, “Crack resistance curves”. The program determines either the fatigue crack length that will cause fast fracture of a component under a given applied stress or *vice versa*. The program gives results in the form of both numerical and graphical data. All of the resistance curve data presented in ESDU 85031 are available within the program and the facility for users to add their own data is also provided.

Cyclic stress-strain and strain-life data for aerospace materials

Local strain-based fatigue analysis has been in use since the 1970s; its applications being initially rooted in the military aircraft and automotive industries of the US where much of the developmental work was based. The technique tracks conditions of local stress and strain at a notch root and in order to estimate life two sets of data are required for each material - cyclic stress-strain data and strain-life data. Most of the large number of data initially produced are held privately by industry, and relatively few data entered the public domain. The technique is now widely accepted throughout the aerospace industry, yet the extent of published data (whilst increasing) remains limited and much of the testing continues to be done on a private basis. In many cases this can involve duplicating tests carried out by another company on the same material.

ESDU began work in 2006, reported in the last National Review, on the collection and collation of the raw cyclic stress-strain and strain-life data points for 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 then benefit. Considerable support and enthusiasm were expressed for this project and generous donations of data were received from a number of companies. The ESDU Data Item containing the data is nearing completion and will be issued shortly.

Fatigue of Titanium Alloys

Work is currently in progress on extending existing high-cycle fatigue data on titanium alloys.

Crack propagation life prediction

Work will begin shortly on a Data Item on the fundamental principles of, and the various approaches that have been developed to, crack propagation life prediction.

2.2.2 Developments in BEASY software and associated research (R A Adey, C M BEASY Ltd, Southampton)

Workers from BEASY are presenting a paper at this year’s ICAF Symposium [1] focussing on the 3D simulation of crack growth in airframe metal structures exposed to complex multi-axial loading. This review describes the other major developments in the latest release of the BEASY software, released in November 2008, along with information on some of the research projects undertaken.

Simulating Crack Closure and Sliding

Software development work has been completed that provides a new capability to model crack closure and sliding. Predicting the behaviour of cracks under compressive loading provides an important analytical component and is helpful in understanding the fretting fatigue behaviour of fracture critical components. Leveraging existing experience using boundary element based solutions for contact mechanics, significant code development has been completed so that contact boundary conditions can now be applied directly on crack surfaces in 3D models using the BEASY Fatigue and Crack Growth software. The contact condition applied to the crack surface is currently based on a Coulomb friction criterion, as an approximation, to simulate the shear resistance on a crack surface. Crack surface friction is obviously much more complicated but this approach provides an initial capability that can be modified as more research becomes available in the area of crack surface frictional resistance. The crack contact solution methodology has been developed using both node to node and node to surface algorithms. These algorithms continue to be tested to determine which may be preferred for modelling fretting fatigue cracks. In addition, testing continues in order to determine the most efficient grid design for the crack mesh and its associated impact on SIF solution. A 3D contact model of a punch and plate with a compressive remote bulk stress and inclined edge crack was analysed to assess the accuracy of the K_{II} values calculated, as shown in the figure below.

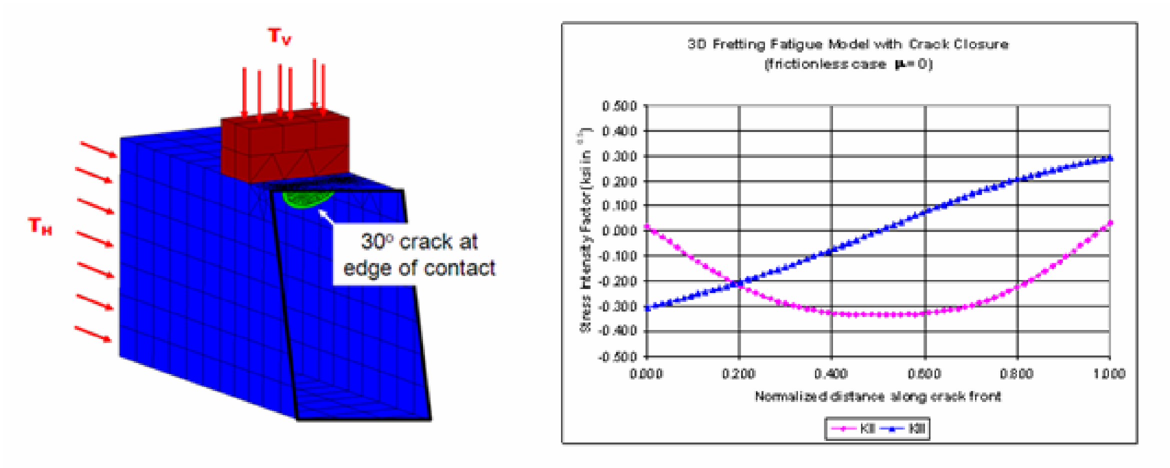


Figure 1 New capability to model crack closure and sliding. Predicting the behaviour of cracks under compressive loading is helpful in understanding the fretting fatigue behaviour of fracture critical components

Predicting crack initiation near the edge of contact

The two-dimensional contact algorithm has been enhanced to enable the use of non-conforming contact, which provides a more accurate prediction of the stresses and displacements on the surfaces between components in contact. In particular it provides information on the highly stressed area at the edge of the contact, which is required for crack initiation and crack growth studies. The following 2 figures present some typical results.

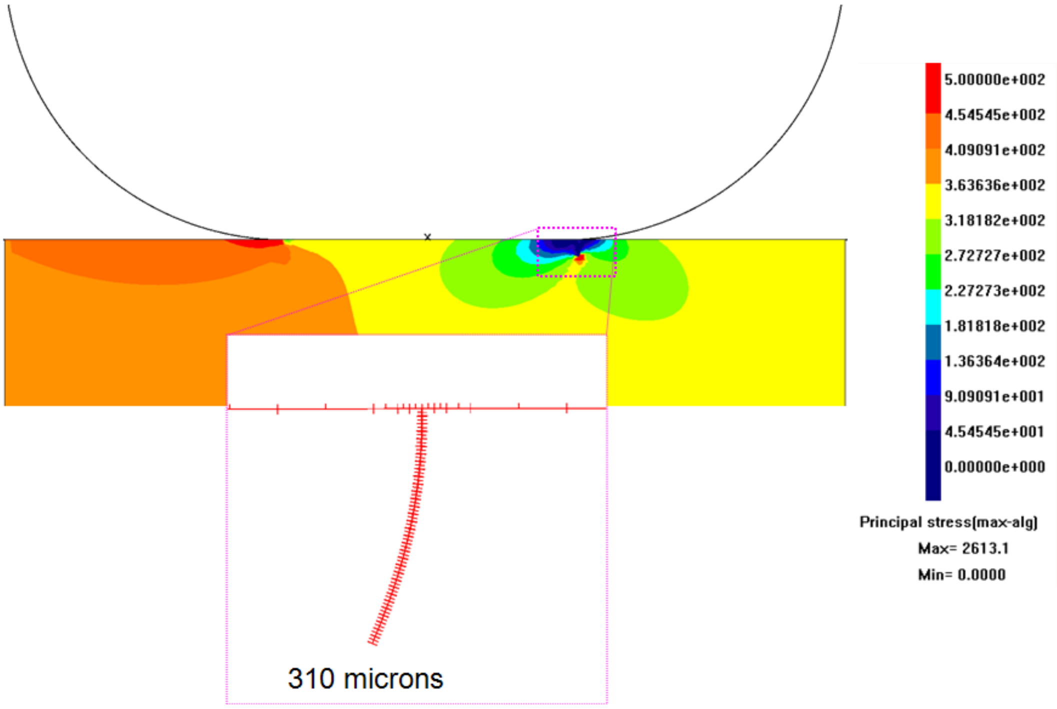


Figure 2 Principal stress and shear stress near the edge of contact for rounded punch on plate. Fretting fatigue cracks typically initiate at these locations

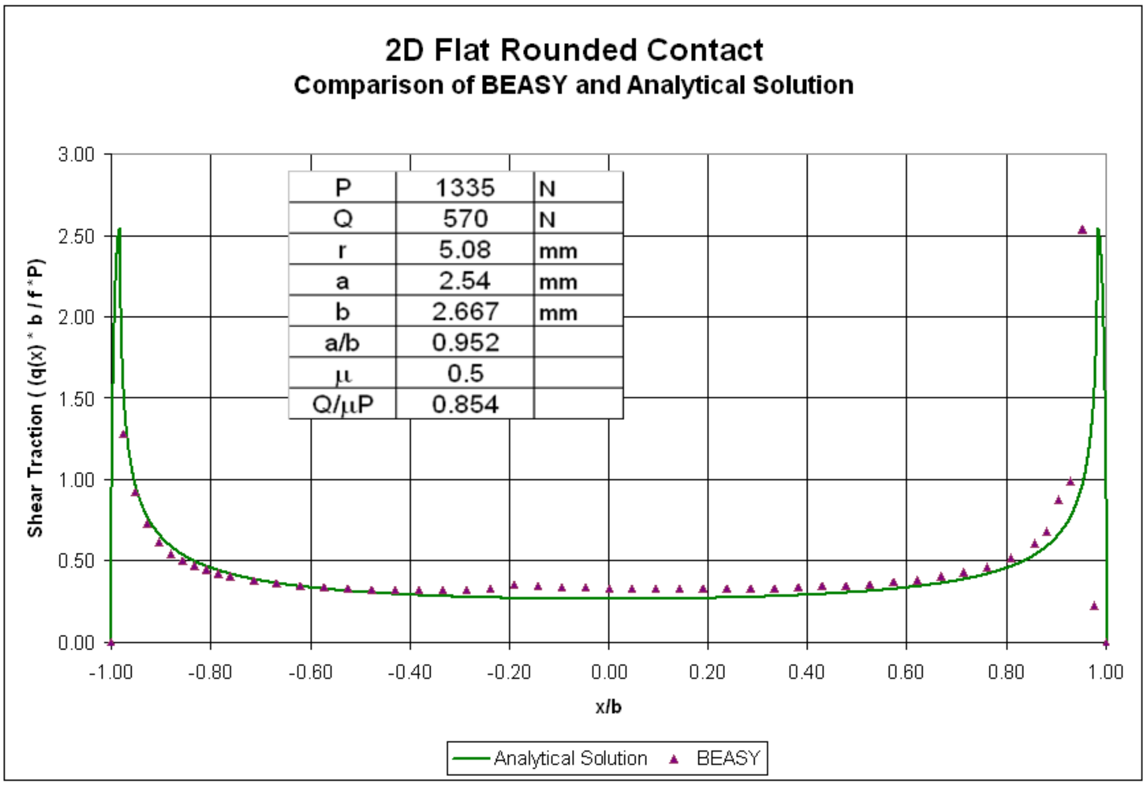


Figure 3 Shear Traction distributions for flat rounded punch on a plate

Integration with Finite Element Models

Enhanced techniques have been developed to improve the mapping of stress fields from large-scale FEM models. This provides the capability to create detailed sub models of regions of a component or structure to predict how cracks will grow while at the same time automatically capturing the correct loading and residual stress fields. FEM systems supported include ABAQUS, ANSYS, NASTRAN and models imported into PATRAN.

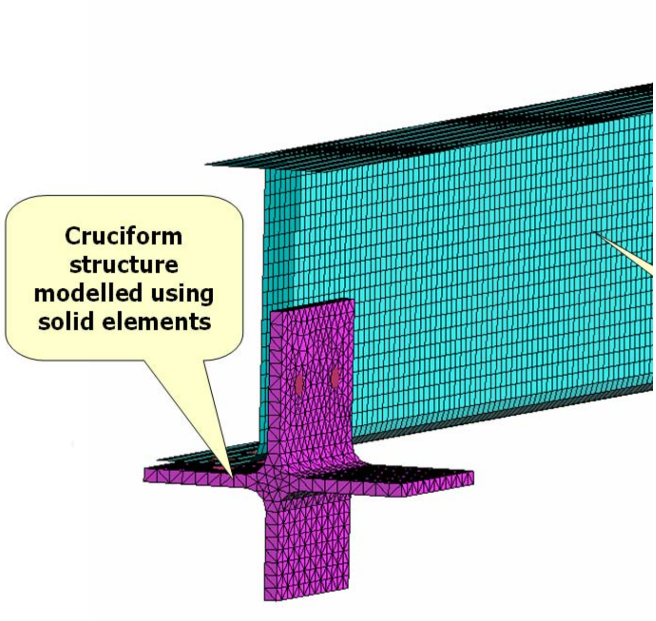


Figure 4 Crack growth in sub model performed using NASTRAN result files and BEASY Model Generation Tool

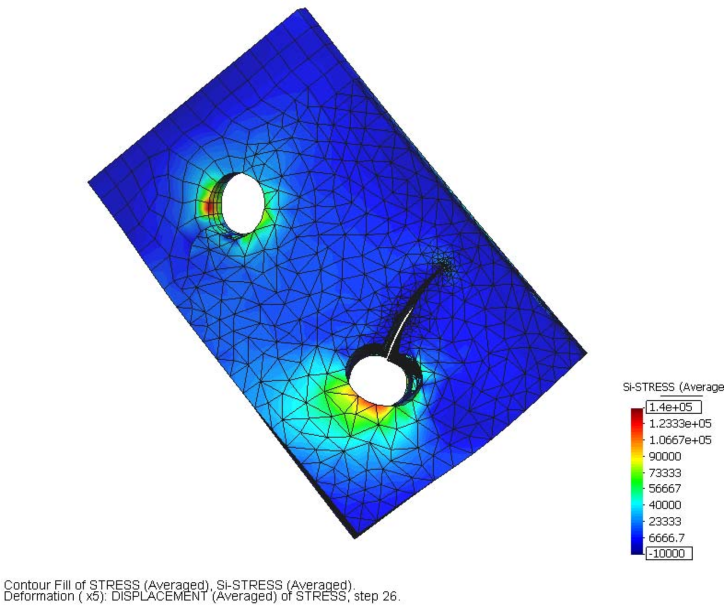


Figure 5 Predicted crack growth. The loads and stress field have been automatically mapped from the large FEM model

Probability of Failure

As part of its work for the NATURALHY Project, a software tool has been developed to assess the failure probability (POF) of a structure due to the existence of crack-like and metal loss defects such as corrosion. During the simulation, various parameters such as defect sizes, material properties, loading, and the performance of inspection procedures are modelled as uncertainties.

The failure may occur when a crack propagates or metal loss corrosion grows to the point where the failure criteria are exceeded. Based on Monte-Carlo simulation the software not only provides information about the probability of failure but also the predicted number of repairs required over the structure life, thus providing data suitable for economic and integrity management models.

The tool simulates the cumulative probability of failure and hazard functions if an inspection and repair programme is – or is not – introduced.

The user can interactively add various parameters to perform the simulation and calculate the probability of failure.
The major applications of the tool are to:

PREDICT FAILURE: The failure probabilities for each defect and the whole structure can be predicted by the tool.

OPTIMISE MAINTENANCE STRATEGY: Different inspection and repair criteria can be investigated to achieve an optimal maintenance strategy.

ECONOMIC MANAGEMENT: The tool provides not only data on the probability of failure but also the predicted number of repairs required over the structure life.

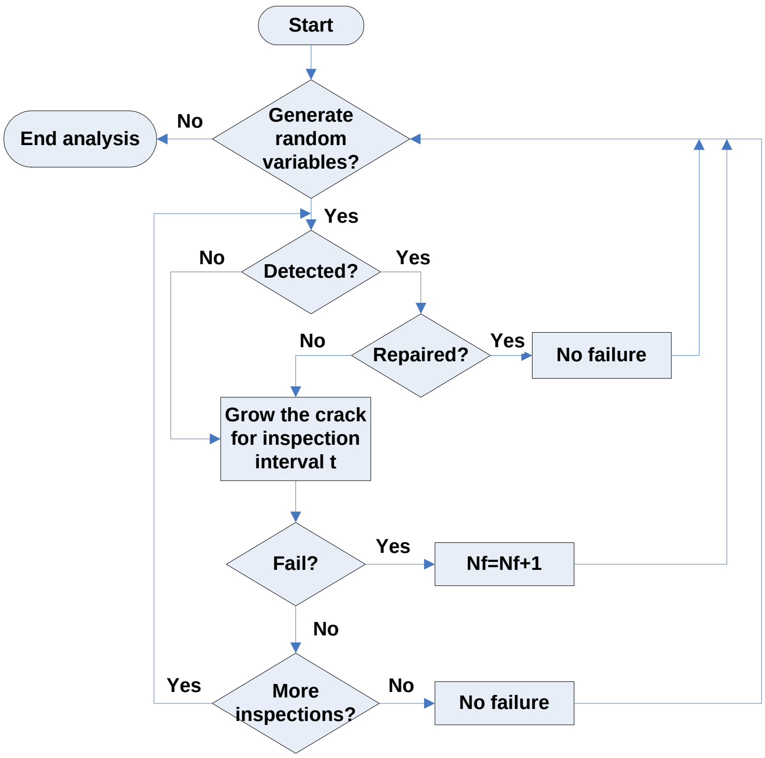


Figure 6 Flow chart for probability of failure analysis

Corrosion in Aircraft Structures

As part of the work on the SICOM project, the corrosion modelling software tools are being extended to enable typical corrosion scenarios to be modelled and predictions made.

SICOM will develop models that will become an essential part of future predictive maintenance concepts. They will deliver the information about onset and evolution of corrosion and hereby fill the gap between corrosion detection or monitoring and the calculation of the structural impact of corrosion. Data from environmental condition or corrosion monitoring systems and non-destructive inspection can be used as input data. Models output will be utilized for the repair decision process or can supply structural integrity calculation programs.

SICOM will develop a numerical micro scale model to simulate localized corrosion of Al-Alloys with regard to microstructure and the micro-electrochemical condition. It will provide corrosion rates of Al-Alloys in the mesoscale of occluded cells by means of numerical calculation as a function of physical and geometrical factors for given macro-environments. A numerical model for prediction of galvanic corrosion behaviour will be developed and up-scaled for application to structural elements of aircraft. The influence of surface treatment on modelling results will be included with regard to inhibitor release from protection systems, role of clad layer influence and oxide degrading effects. A decision support tool will be established for exploitation and implementation of the project results in scientific and technical applications.

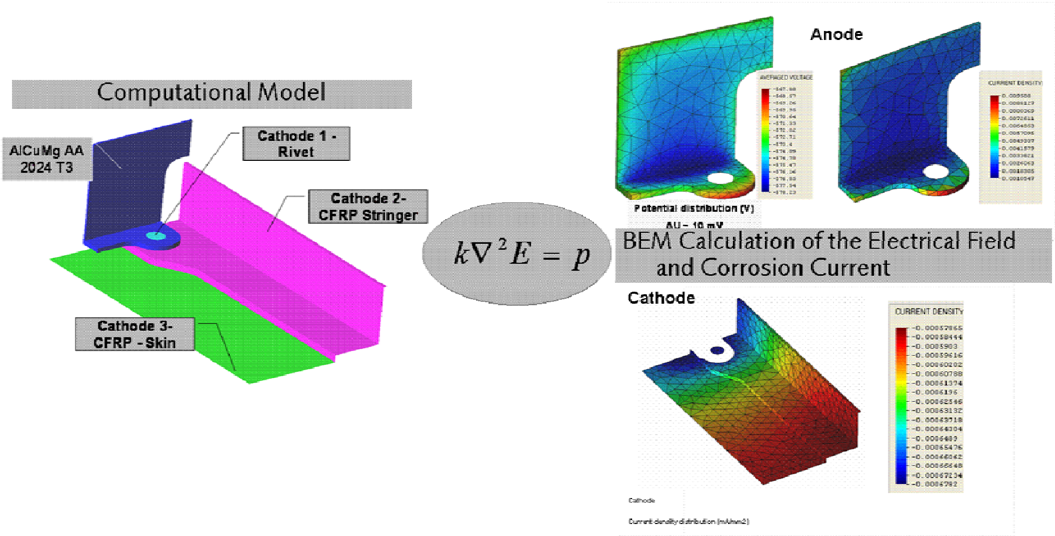


Figure 7 BEASY model used to determine corrosion related electric fields in aircraft structure

Experimental Validation of Predicted Crack Growth Rates

A recent study has demonstrated that CMI's modelling technology is capable of accurately predicting 3D crack growth behaviour. The objective of the study was to predict the crack growth velocity and direction and compare results to experimental testing.

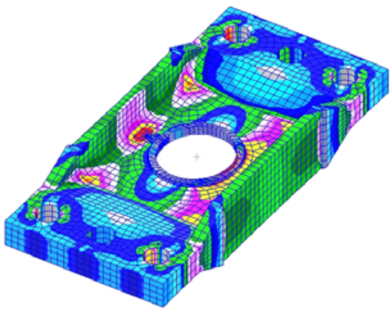


Figure 8 Fracture Model of the Test Specimen

The model results were compared to experimental test data and published in a paper presented at the 8th Aging Aircraft Conference [6]. The fracture model of the test specimen is shown in Figure 9.

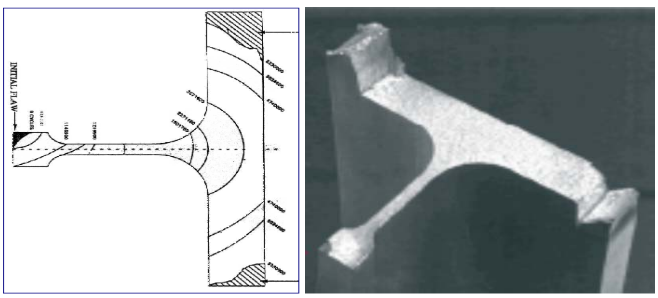


Figure 9 Crack growth path and cross section of the failed test specimen

The BEASY™ K-solutions were used in the FASTRAN crack growth model to predict the number of flight hours versus crack length. Good correlation was achieved with the test data using this approach and is shown in the figure below.

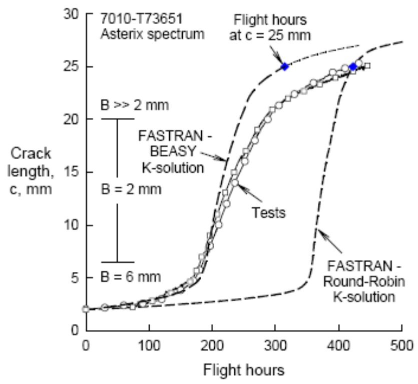


Figure 10 Measured and predicted crack length vs. flights for the test structure

2.2.3 Developments in nCode fatigue analysis tools (A Halfpenny and R Plaskitt, HBM-nCode)

In this last couple of years, nCode's older fatigue analysis software products, nSoft and FE-Fatigue, have been rewritten and replaced by GlyphWorks and DesignLife. The older nSoft and FE-Fatigue products are still in use in many aerospace companies as they are locked into analysis procedures for particular aircraft programmes.

GlyphWorks has replaced nSoft for crack growth analysis, stress-life and strain-life fatigue analysis (uniaxial and multiaxial), from stress and strain sequences.

DesignLife has replaced FE-Fatigue for stress-life and strain-life fatigue analysis from finite element analysis results.

Both GlyphWorks and DesignLife have many new fatigue analysis features; the most important of these are;

- Crack Growth: to allow users to import their own crack growth solver algorithms and material property parameters

- Stress-Life: to allow users to import their own stress-life solver algorithms and material property parameters

- Strain-Life: to allow full control over the strain-life material curves used in the analysis, through a nest of strain-life curves, each at constant R-ratio, and interpolation of these for mean stress correction

The purpose of these is to allow the proprietary fatigue analysis algorithms and material properties found within aerospace companies to be used within commercial software whilst retaining their intellectual property within the algorithms. This also enables researchers to add new algorithms and quickly compare their results against accepted methods.

From an applied research perspective, the most significant new fatigue analysis capability is for vibration fatigue analysis. This is based on the "Fatigue Damage Spectrum" (FDS) proposed by Lalanne [2]. (In this context "Spectrum" refers to a frequency domain spectrum, like a "Power Spectral Density" (PSD), rather than a flight loading spectrum.)

Following initial work by Bendat [3] and Rice [4] to determine the fatigue damage directly from a PSD of stress, Lalanne was able to utilise this technology to create a closed form calculation for the FDS directly from the acceleration PSD. The explanation of the fatigue and vibration theory of this is beyond the scope of this review. For more details see reference [5], which also presents a case study to help the explanation. In addition, reference [6] offers further useful background to the subject and presents a useful review of the most popular methods for cycle counting using a PSD representation of the loading and compares the results with traditional Rainflow extraction.

This method enables quantifiable fatigue assessment of the endurance vibration qualification requirements contained in the following military standards "DEF-STAN-0035" (UK), "MIL-STD-810" (USA), "GAM-EG 13" (France) and "AECTP 200" (NATO).

In practice this enables;

- The ability to monitor the cumulative fatigue damage spectrum, calculated from measured data during flight testing, to ensure that the flight test programme remains within allowable fatigue damage spectrum limits from available test evidence

- The ability to quantify the fatigue damage for an actual or proposed vibration (shaker) test, and if appropriate to accelerate this test, using objective, justifiable and quantitative methods

- The ability to qualify a component in a new vibration environment using read-across evidence from a qualification in an existing vibration environment.

- The ability to predict whether components will meet vibration environment qualification tests from CAE models

In addition to software products, HBM-nCode also operates a material testing laboratory, which has expanded and moved to a new and much larger site. It specialises in stress-life and strain-life fatigue testing of specimens, coupons and small components, the majority of which is for the UK aerospace industry.

Note that in August 2008 nCode were bought by HBM-nCode, who supply sensors, data acquisition instrumentation, software and services used by many aerospace companies within their structural fatigue test laboratories, hence the change in contact details.

2.3 FULL SCALE FATIGUE TESTING

2.3.1 Major Fatigue Testing at Marshall Aerospace (A Chilton, Marshall Aerospace Test Services)

A significant part of the testing currently underway at the 21,500sq.ft. purpose built facility at Cambridge, concerns the Hercules C-130 aircraft. The C-130K fuselage test rig was built about 5 years ago and is currently running following a major service/inspection, whilst the C-130J wing test has recently been commissioned and is undergoing its first strain survey.

Both tests are following the basic UK requirements of testing a production standard airframe using loading derived from Operational Loads Measurement (OLM) programmes. The current programme, which has been running for 3 years, comprises, 2 UK RAF OLM aircraft and one in service with the Royal Australian Air Force (RAAF).

31 actuators load the C-130K fuselage test, shown in Figure 11 below, with reaction points around the undercarriage. As is usual, a full flight-by-flight spectrum is simulated, including gusts and manoeuvres, cabin pressure cycling and landing.

Figure 11 C-130K Fuselage Test (the mesh and perspex pen acts as a safety guard)

The C-130J wing test, shown in figure 12 below, is being conducted for the RAF and RAAF, is suspended in a rig originally built for a similar test on a C-130K wing and employs 42 actuators. The test specimen is a complete tip-to-tip wing, and loading includes simulation of fuselage pressure loading of the centre section.

Figure 12 C-130J Wing Fatigue Test

Other current major activities include the Airbus A340 500/600 nose landing gear extended fatigue testing for Messier Dowty and the fuel tank for the long range variant Boeing 777. This tank, which was designed and manufactured by Marshall Aerospace, fits in the cargo hold and allowed the B777 to set the world non-stop distance record at 11,664 nautical miles. The test rig, which can be seen in the figure above, on the right side of the fuselage test, has now undergone 2 lifetimes testing (30,000 flights) and is about to enter the next phase of a further 30.000 flights with simulated damage and standard repair schemes.

At the time of preparing this review, the company had just been contracted by Bombardier Aerospace, Montreal, to perform the certification structural testing of the RTM composite outboard flap for their CRJ1000 *NextGen* airliner. This will include damage tolerance testing from induced impact damage and in-service repairs.

2.3.2 Major fatigue testing activities at Bombardier Aerospace, Belfast (B McCoubrey, Bombardier Aerospace, Belfast)

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.

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.

At present the test has completed 16 spectrum blocks representing 16000 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.

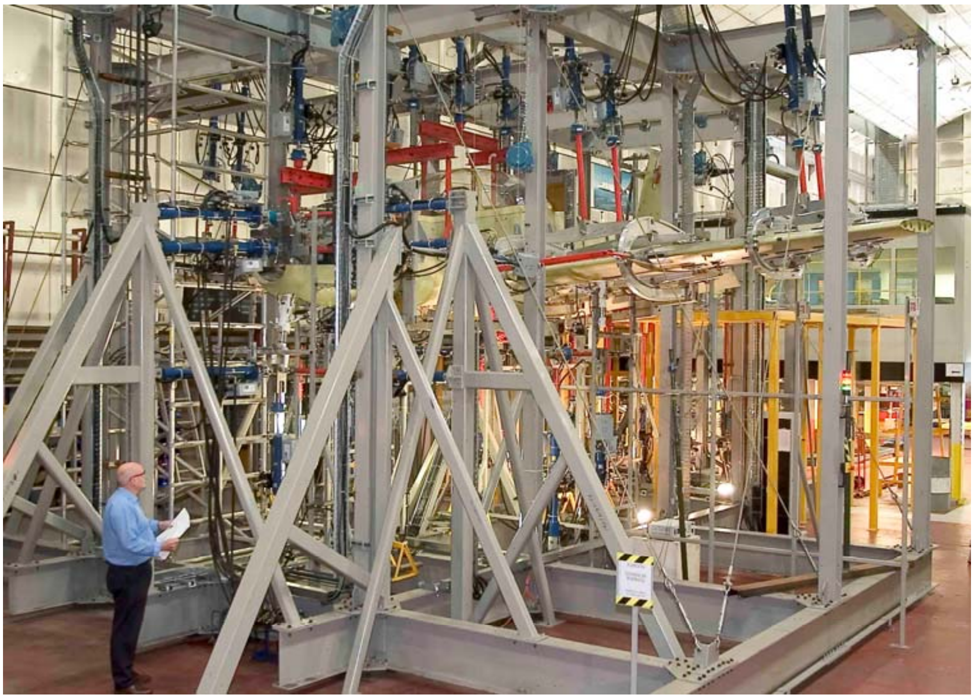


Figure 13 Tucano Full Scale Fatigue Test Specimen

The Stress Department in Belfast has also provided technical support to five major test rigs at the Bombardier site in Montreal. Belfast has responsibility for fuselage structure on CRJ 700/900 Regional Jets and the Challenger 300 business jet.

The CRJ 700 forward and aft fuselage tests, designated A/C 0004 and A/C 0006 respectively, have completed 160,000 cycles of fatigue testing (2 lifetimes) and have successfully completed Residual Strength Testing. The Centre Fuselage Test, designated A/C 0005, has completed 150,452 cycles (160000 cycles to complete fatigue testing requirements). The Residual Strength Test programme for CRJ 700 is planned to start at the end of 2009.

The CRJ 900 Centre Fuselage Test, designated A/C 15995, has completed 141,000 cycles of fatigue testing.

The Challenger 300 has completed 37500 cycles of fatigue testing (2.5 lifetimes) and has successfully completed the Residual Strength Test programme phase.

2.4 DEVELOPMENTS IN FATIGUE MONITORING

2.4.1 Structural usage monitoring of an ageing fleet using service history analysis and teardown evidence (Kate Lucas and M Duffield, QinetiQ, Farnborough)

This is the subject of a paper to be presented at this year's Symposium [7]. The VC10 has been in continuous service with the Royal Air Force (RAF) for over 40 years. It is required to remain in service for several years to come until the planned replacement by a new fleet of modern tanker/transport aircraft. This requirement dictates that structural usage monitoring of the fleet is essential, which itself relies on a proper understanding of the service histories of the individual aircraft since entry into service. Therefore, the basis for structural usage monitoring is a comprehensive record of flying data for each aircraft. These records may be used to generate estimates of fatigue loads spectra, which can then be analysed in terms of fatigue and damage tolerance criteria.

There are currently three versions of the VC10 in service with the RAF and each version has a distinctly different typical history. The CMk1K aircraft were built as multi-role transport aircraft for the RAF and were upgraded to an additional tanker capability during the mid-1990s; the KMk3 aircraft served with a commercial operator during the 1970s before being converted to 3-point tankers for the RAF and entering military service during the early 1980s; the KMk4 aircraft served with another commercial operator for many years and were eventually converted to 3-point tankers for the RAF, albeit to a different overall configuration to the KMk3, during the mid-1990s. Whilst the service records from 1991 onwards of all aircraft are complete and available in an easily interrogated database, the earlier service histories are limited to basic and, usually, incomplete information. This means that it is not possible to easily or directly determine the total value of the service histories of the aircraft in terms of structural usage.

As reported in the UK National Review at the 2007 ICAF Conference [8] a structural monitor using the NzW method (where Nz = normal acceleration or 'g' and W = nominal aircraft mass) was developed for the CMk1K. This methodology can also be applied to the KMk3 and KMk4 aircraft. However, in order to quantify the historic usage of the aircraft, additional work was needed to generate a baseline for the monitoring programme. This involved a comprehensive analysis of the available information for the different variants, including the KMk2 aircraft, which had been retired from service during the late 1990s.

The KMk2 aircraft were of particular interest because they had been used to provide a large number of samples taken from the wing structure for the purposes of teardown inspection – as described in the UK National Reviews at the 2001 and 2003 ICAF conferences [9, 10]. The results from those inspections were combined with the analysis of the service histories of the donor airframes in order to validate the fatigue calculations for the other variants of the aircraft remaining in service.

Various elements of the theoretical and practical assessments of the aircraft in terms of historic and current flight profiles, analysis of 'g' spectra, teardown findings and fatigue and damage tolerance calculations have been combined to provide a credible basis for structural usage monitoring of a varied fleet of large, ageing aircraft. The results have been used to demonstrate that the structural integrity of the critical joint features on the VC10 wing can be assured until the planned retirement from service at an average age of over 40 years.

2.4.2 Introduction to Service of an Artificial Neural Network based Fatigue Monitoring System (S Reed, Dstl (MOD), B McCoubrey, Bombardier Aerospace Belfast, A Mountfort, QinetiQ Farnborough)

Individual aircraft fatigue and usage monitoring is an essential element of structural integrity assurance. This is particularly significant in the military environment where the scatter in usage between individual aircraft within a fleet and the difference between design-assumed usage and in-Service usage can both be highly significant. In the UK military, substantiation of the individual aircraft fatigue monitoring or tracking system is undertaken using an Operational Loads Measurement (OLM) programme. Within these programmes, a proportion of the fleet is fitted with a range of strain gauge sensors and associated parametric sensors. One of the key outputs of such programmes is an assessment of the performance of the individual aircraft fatigue monitoring system.

Many legacy military aircraft have relatively simple individual aircraft fatigue monitoring systems based upon, for example, exceedence counts from a normal accelerometer (Nz). These data are coupled with additional information, such as aircraft mass and store configuration and some assumptions of usage, such as point-in-the-sky dynamic pressures. This information is combined within fatigue meter formulae to give an indication of fatigue consumption, for Nz-driven critical features, usually on a sortie-by-sortie basis. Substantiation of these systems using OLM data is usually based upon average performance of the fatigue meter formulae in comparison with the OLM strain-based data. It is usual for corrections to be applied to these formulae as a result of this process; often these corrections can be very significant.

Sufficiently accurate monitoring of in-Service fatigue life is essential from both a safety and cost of ownership perspective and methods of improving the accuracy of apportioning fatigue life consumption on an individual aircraft basis have significant implications for fatigue management. However, obtaining funding for improvements to equipment in individual aircraft fatigue monitoring systems for legacy aircraft is unlikely to be successful due to higher-priority funding requirements.

The reference (X), which will be presented at this ICAF Symposium**,** describes an alternative, cost-effective approach to obtaining a significant increase in individual aircraft fatigue monitoring accuracy, using legacy equipment and ride-along data from an existing OLM programme. In this process, artificial neural networks are used to determine the relationships between input parameters from the legacy equipment, such as Nz counts and the flight-by-flight fatigue damage calculated from strain data captured during the OLM programme. Neural networks are able to determine generalised, non-linear relationships between data in a controlled environment and present an attractive solution for multi-dimensional regression-type problems. Within this paper, the development, verification and validation of the Structural Health and Usage Neural Network (SHAUNN) based fatigue meter formulae for 2 critical wing features for the Tucano TMk1 military trainer is described. The training, testing and independent validation environment used in the SHAUNN framework, using nearly 900 sorties of OLM data from 3 aircraft, is explained. Emphasis is placed upon understanding the response of SHAUNN to data outside of its learning experience and establishing processes to cater for such eventualities. Additionally, processes for the ongoing monitoring of the continued performance of the SHAUNN monitor in Service are illustrated.

2.5 FATIGUE IN COMPOSITE MATERIALS AND STRUCTURES

2.5.1 New numerical methods for the prediction of damage initiation and propagation in composites (S Hallett, University of Bristol)

Recent research in the Advanced Composites Centre for Innovation and Science (ACCIS) at the University of Bristol on fatigue of composites has focussed on the development of new numerical models for the prediction of damage initiation and propagation [12,13,14]. Since fatigue damage occurs at load levels substantially below ultimate failure it is matrix dominated failure modes such as matrix cracking and delamination that predominate. Cohesive interface elements are becoming more widely used within finite element analysis for prediction of quasi-static delamination failure.

The work at Bristol has concentrated on implementing fatigue damage accumulation laws within the cohesive element formulation to predict both the initiation propagation of fatigue failure. For the propagation case this takes the form of extracting the strain energy release rate from the crack tip interface elements and relating this to a Paris type growth law. This in turn allows a direct relationship to be established between the damage accumulation rate and crack propagation rate as shown in Figure 14.

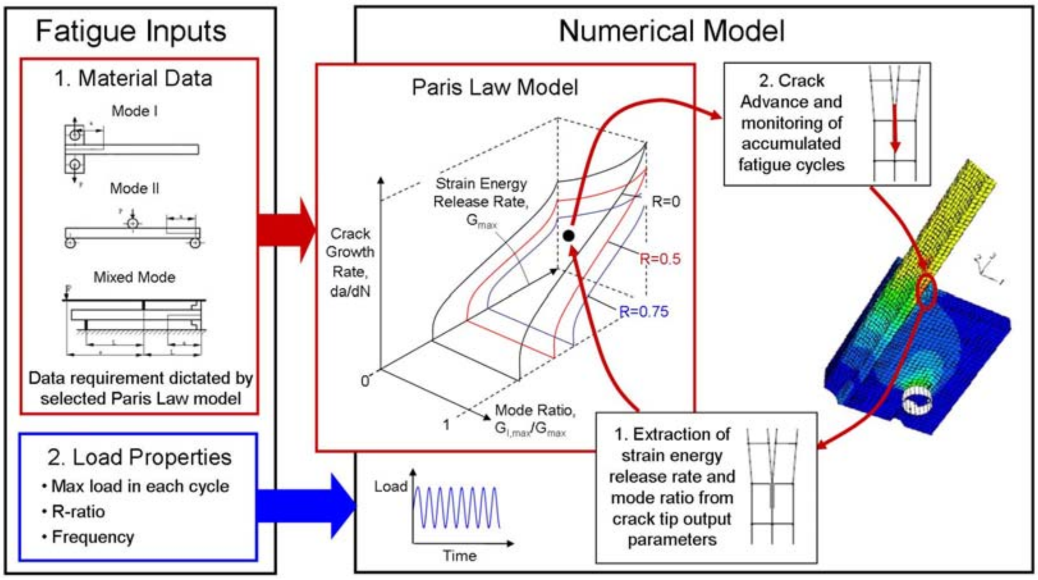


Figure 14 Linking the Numerical Model to a Paris Law Model

This technique has been implemented in the explicit finite element code LS-Dyna. The model avoids explicitly simulating each fatigue cycle by employing a cycle jump approach, which captures the envelope of loading and requires the R-ratio and frequency as additional input parameters (Figure 15). This has been successfully applied to and validated against simple single and mixed mode tests such as double cantilever beam (DCB), end notched flexure (ENF) and mixed mode bending (MMB) (Figure 16).

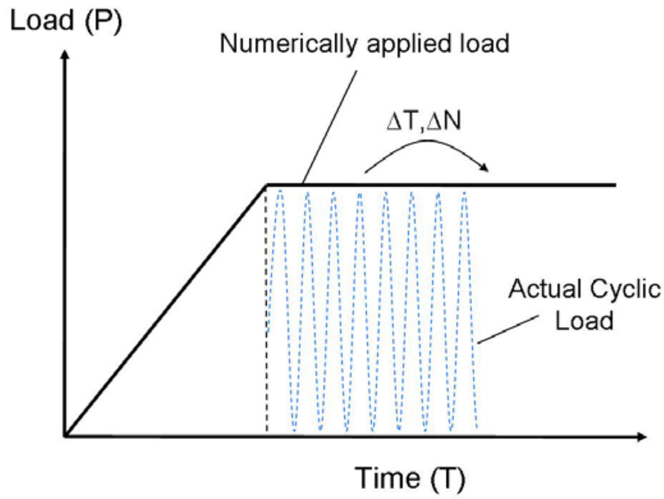


Figure 15 Cycle-Jump approach to numerical fatigue modelling

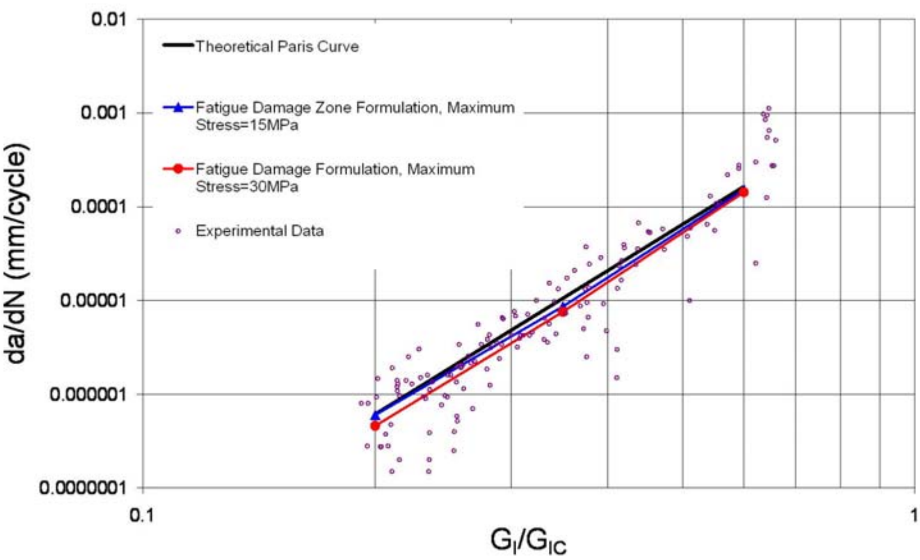


Figure 16 Mode I DCB Paris Law Results

This approach works well when the models contain a sufficient stress concentration to have already initiated the damage e.g. a pre-crack. However there are cases where the initiation phase of the damage accumulation accounts for a significant proportion of the fatigue life. To ignore this can result in substantially over conservative designs. The cohesive interface technique is attractive in this respect because for quasi-static loading it is capable of capturing both stress based damage initiation and fracture based damage propagation. This advantage has also been exploited for fatigue modelling, using S-N curves to accumulate damage in the cohesive elements as a function of number of cycles during the initiation phase. This has been successfully able to predict inter- and intra- laminar failures in a range of specimens such as short beam shear, double notch shear and three point bending tests (Figure 17). It is thus able to seamlessly move from the initiation phase of damage accumulation into the propagation phase making a complete fatigue life assessment in a single numerical model possible. It can also be used to predict residual strength of fatigued samples. This has potential for integration into the design process and application to modelling more complex components, which is the subject of ongoing research.

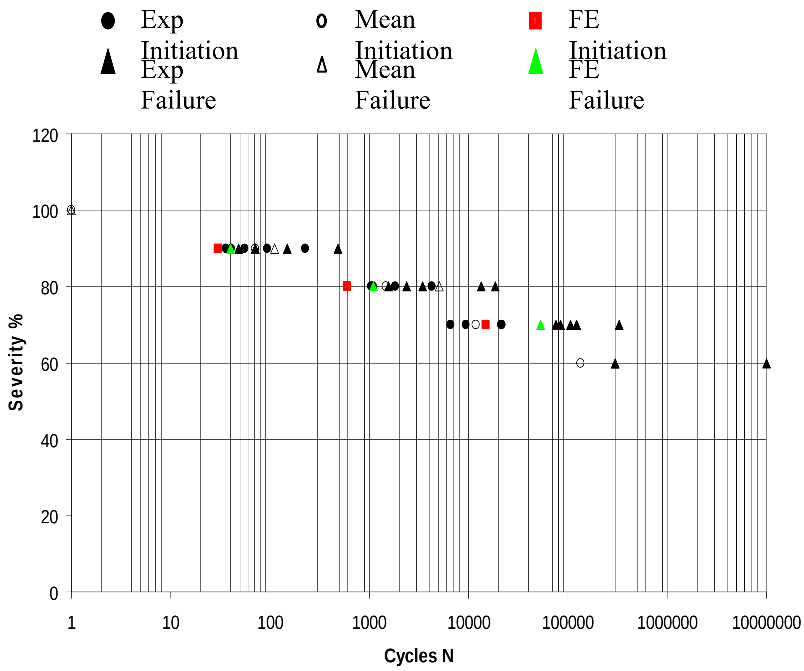


Figure 17 Comparison of predicted short beam shear SN curve with experiment

2.5.2 Post-buckled propagation model for compressive fatigue of impact-damaged laminates (R Butler, University of Bath)

One of the major restraints on exploiting further the potential weight savings offered by composite materials is delamination damage caused by impact loads. Such damage causes a reduction in compressive strength and can propagate under fatigue loading, leading to further reductions in strength. At present, this propagation is suppressed in design by applying empirically derived strain limits at design ultimate loads. The opportunity to save structural weight by increasing the damage tolerance limit requires accurate prediction of the behaviour of delaminated composite materials under compressive strain. Such strain can promote buckling of sub-laminates in the damaged region, which causes opening of the delamination. Workers at the University of Bath have been developing mechanical models to predict the threshold strain for a general laminate. The latest model [15] builds on earlier work [16] and represents the complex damage morphology as a single circular delamination at a critical level within the laminate and calculates the strain at which thin film buckling of the delaminated region occurs. The threshold strain is defined as the strain at which the strain energy release rate (G_I) for the fracture of post-buckled delaminated plies along the delamination is equal to the critical Mode 1 value (G_{Ic}) for the resin. An example prediction is presented in Figure 18 below, in which G_I is plotted against strain for each level and the threshold strain can be determined from the intercept of these curves with the G_{Ic} value, the first to intercept the being the strain and level at which propagation occurs; 5 plies in this case.

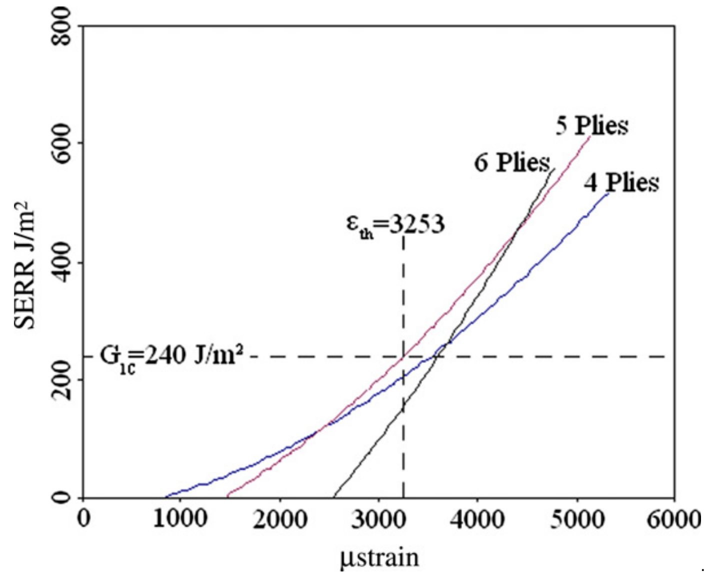


Figure 18 Strain energy release rate (SERR) for propagation at 4, 5 and 6 ply depths in HTA/6376 ZD laminate

The model predicts the critical through-thickness level for delamination, the stability of delamination growth and also the experimental error in geometric measurements of the damage area. Results obtained using the new model show an agreement of fatigue strain within 4% of experimental values for 4 sets of data reported in the literature. The precision of the current model is highlighted in Figure 19 (plate model), the experimental results being taken from several sources with a range of laminates with varying materials and lay-ups. Also presented in this figure is a comparison of the new "Plate" model with the previous "Beam" model.

The model also has the potential to provide a tool to design laminates with enhanced damage tolerance.

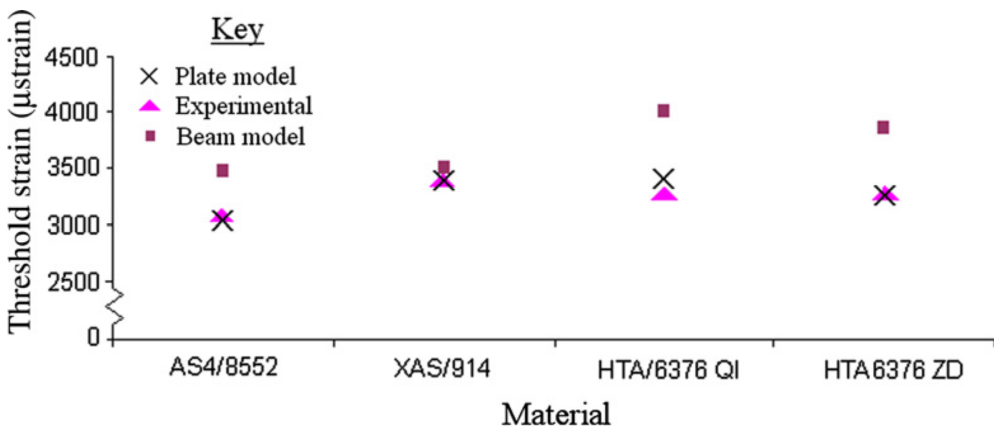


Figure 19 Comparison of threshold strains

2.6 FRACTURE MECHANICS AND DAMAGE TOLERANCE

2.6.1 Effect of plasticity-induced closure on fatigue crack growth rates (M Pavier, University of Bristol)

Accurate and non-conservative predictions of fatigue crack growth rates are essential when designing aircraft structures subject to cyclic loading. One cause of conservatism in fatigue growth rate prediction has been the neglect of the phenomenon of closure; for when closure occurs the stress intensity factor range is less than would be expected.

In work undertaken in the Department of Mechanical Engineering at the University of Bristol [Refs 17-21] the effect of plasticity induced crack closure on fatigue crack growth rate has been investigated for a 2024 aluminium alloy plate. The work was supported by EPSRC and Airbus and was a joint programme with the University of Oxford.

The aluminium alloy plate had a central hole representing a fastener hole and was subjected to cyclic loading. Measurements were made of the growth rate of fatigue cracks emanating from the central hole and the level of crack closure.

A three-dimensional finite element model was developed of the cracked plate. The load on the model was cycled and the crack extended by releasing nodes so as to predict the development of a plastic wake behind the advancing crack. The opening load was predicted from the finite element displacement versus load results. These opening load predictions agreed favourably with the experimental measurements, as shown in Figure 20.

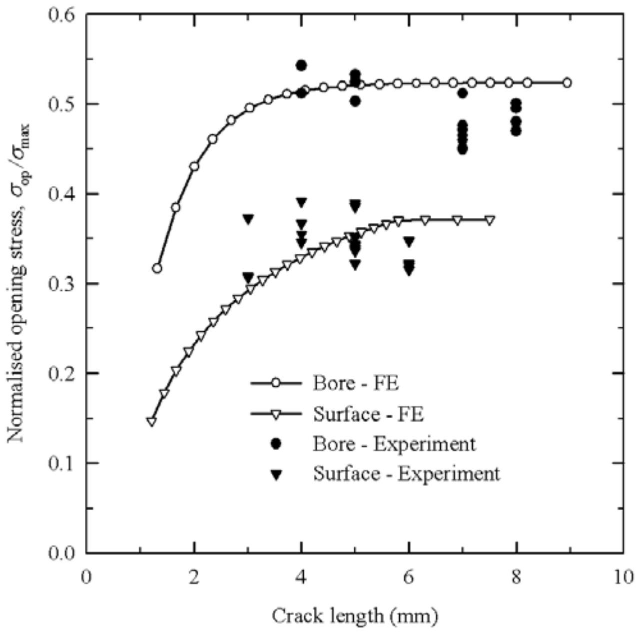


Figure 20 Comparison of FE closure with experimental results

The finite element model was also used to predict the fatigue crack growth rate. This was achieved by first evaluating the effective stress intensity factor range from the stress distribution ahead of the crack tip. A Paris law fit to high R-ratio test data was then made to allow the corresponding growth rate to be calculated. Encouraging comparisons of the finite element predictions of fatigue crack growth rate with experimental measurement were obtained, Figure 21.

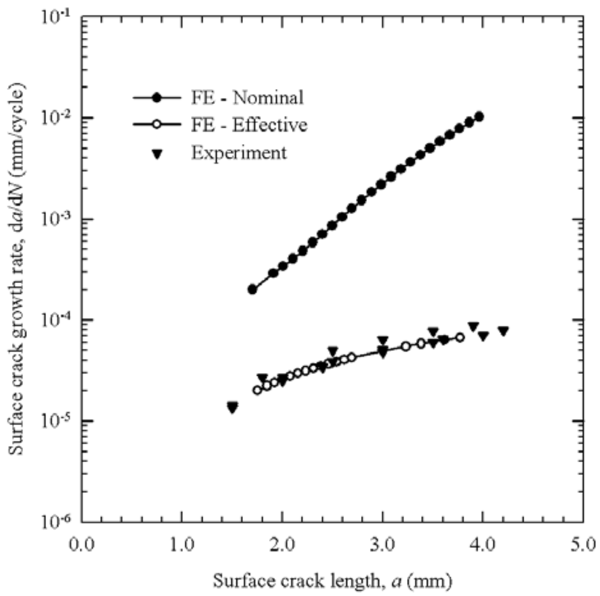


Figure 21 Comparison of FE da/dN with experimental results

2.6.2 Residual stresses in bonded crack retarders (M E Fitzpatrick and C D M Liljedahl, The Open University)

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.

The Open University has 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 [22-26]. 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 (CTE) between the integral structure and the strap.

Residual stresses were evaluated using neutron diffraction (figure 22), where a collimated beam of neutrons is used to map the residual strains within a sample.

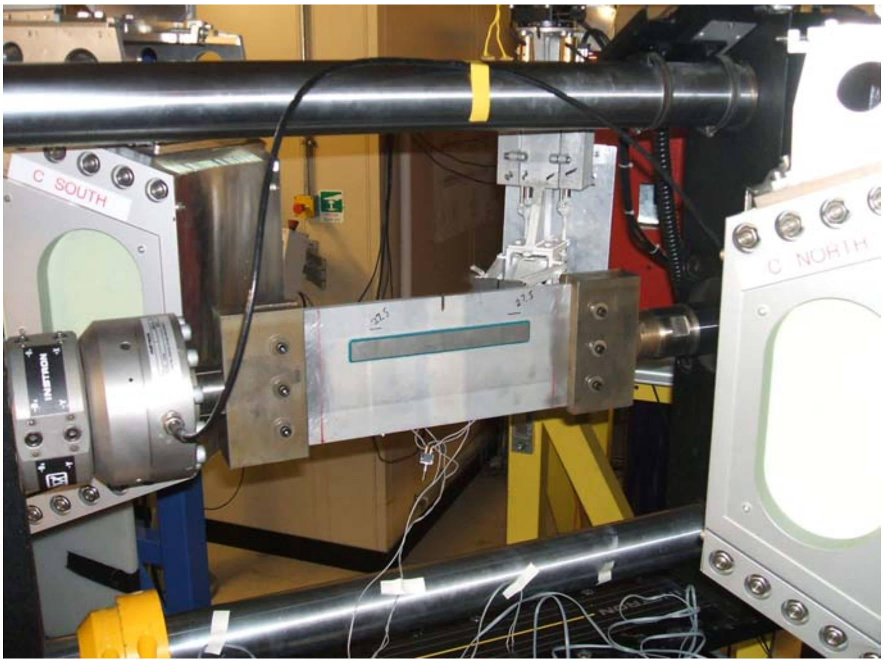


Figure 22 Aluminium plate with a single reinforcing strap being measured at the ENGIN-X neutron diffractometer at the UK ISIS neutron source

The residual stresses beneath the strap are found to be a function of the CTE mismatch between the aluminium plate and the strap material. As an example, figure 23 shows the stresses transverse to the strap length for a titanium strap. The solid lines are FE model predictions of the stress, that agree extremely well with the measured data points.

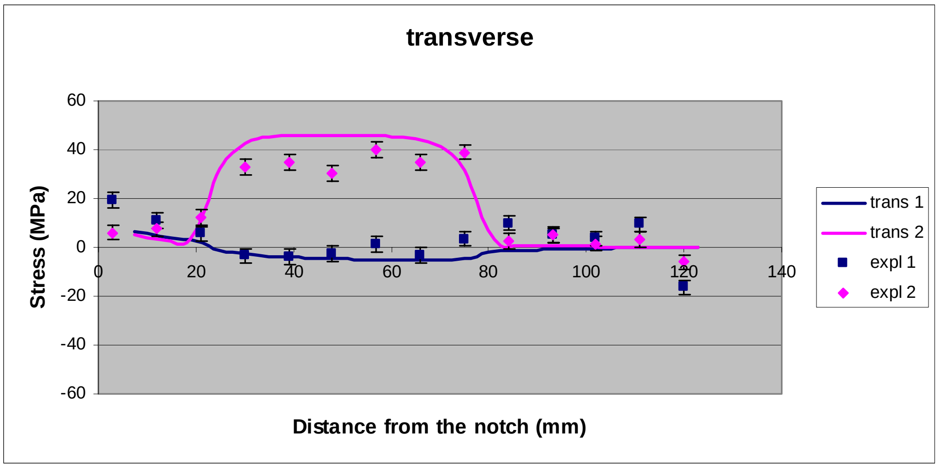


Figure 23 Residual stress beneath a titanium strap of 4 mm thickness and 60 mm width

Smaller stresses were found beneath straps made of GLARE and GFRP.

The evolution of the residual stresses when a crack grows past the strap was modelled using FE, and again extremely good correlation was seen with measured data. Figure 24 shows the predicted and measured stresses, at two positions through the thickness of a 10-mm-thick Al plate with a CRFP strap.

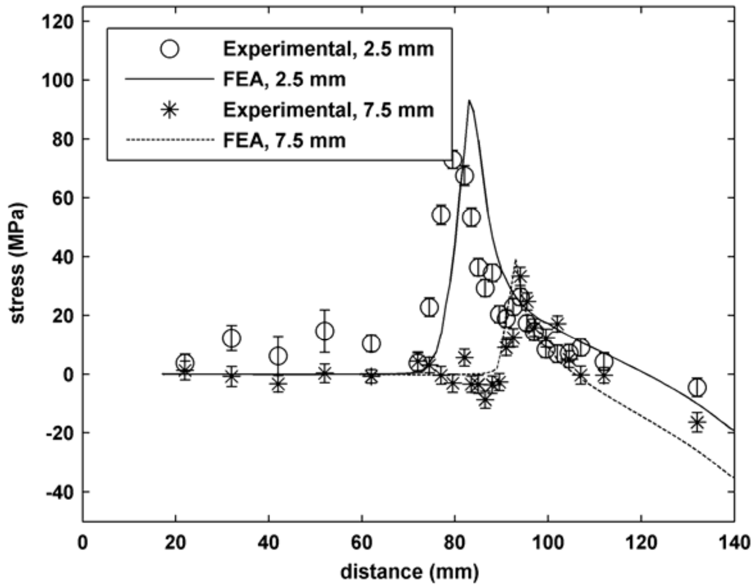


Figure 24 Predicted and measured stresses as a crack grows past a reinforcing strap

Measurements were also obtained at cryogenic temperature, to investigate the effect of in-service temperatures on the residual stresses.

2.6.3 The prediction of fatigue life of structures containing defects (P Irving, Cranfield University)

Work on this subject at Cranfield University has been directed in the following two areas:

The effect of scratches and scribes on fatigue life of aluminium fuselage structures

The influence of corrosion pits and crevice corrosion on development of fatigue cracks in precipitation-hardened stainless steel.

These projects are both devoted to the general problem of how defects transform into fatigue cracks, and prediction of fatigue life of samples and structures containing defects. If a crack initiation approach is employed, ignoring the presence of a 50-100 μm defect, then a life predicted using pristine sample data will be non- conservative. If a fracture mechanics approach is used, the predicted life will be conservative, but generally unrealistically so.

Both for corrosion pits and for scratches or scribes the issues are:

(1) What is the size of defect that can be safely left in the structure without degrading the fatigue performance?
(2) How can the fatigue life of structures with defects that exceed (1) be predicted?

The issues become particularly acute for high strength undercarriage materials where the fatigue initiation performance of pristine samples is related to the great materials strength – yield in excess of 1,000 MPa, but the fatigue crack growth performance under the influence of the high service stresses is very poor as cracks grow fast under the large values of ΔK. The transition between these two very different states takes place as a 50 μm pit transforms to a fatigue crack of similar size and grows.

A paper on the influence of scribes in aluminium alloys was presented at the conference on "Fatigue damage in structural materials" at Hyannis in September 08 [27], which is summarised below.

Experimental studies were performed on clad and unclad 2024-T351 samples into which micro mechanical damage had been introduced. A diamond tipped cutting tool was used to introduce V notches of root radii between 5 and 50 μm and depths up to 185 μm across the entire sample width. The influences of notch geometry, load condition and the presence of the clad layer on constant amplitude fatigue life were determined under conditions of tension and bending stresses and on clad and unclad aluminium. The scribes caused substantial reduction of fatigue life, even with notches of only 50μm depth. It was found that fatigue life reductions produced for a specified value of elastic stress concentration Kt, depended on the root radius of the scribe. Examples of data are shown in the figure 25 and 26 below.

Elastic- plastic finite element models are being developed to investigate stress field and plastic zone at the notch root and to explore the conditions for crack nucleation.

As the entire crack growth process through the thickness of the sheet (2 mm) is in the short crack regime, life prediction cannot be made using LEFM. Striation spacing measurements have been used to derive crack growth rates. Accelerated growth rates relative to the long crack data for this alloy are shown in Figure 27.

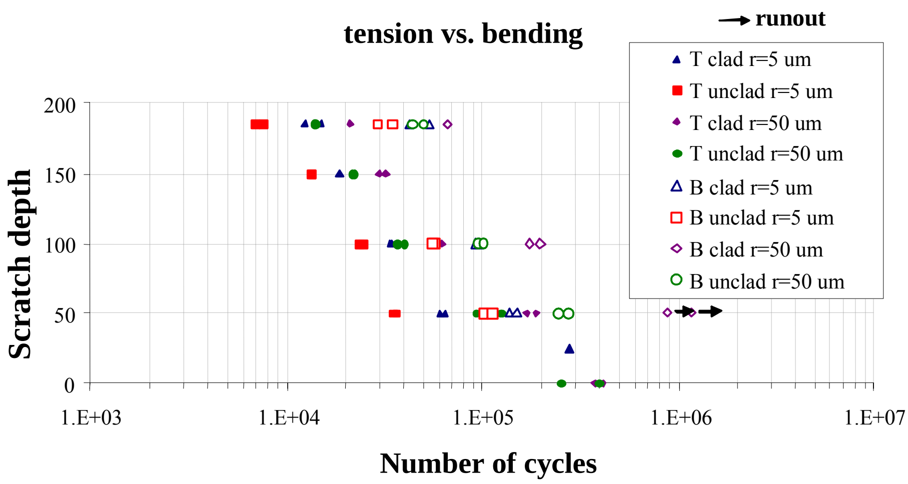


Figure 25 The influence of scratch depth on fatigue life for both tension and bending loading

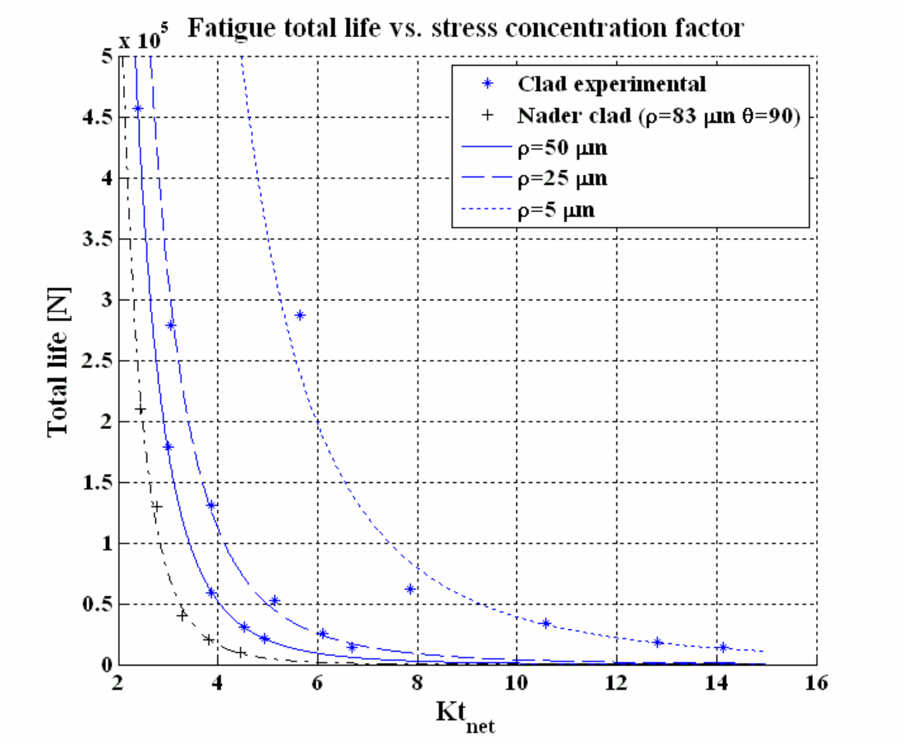
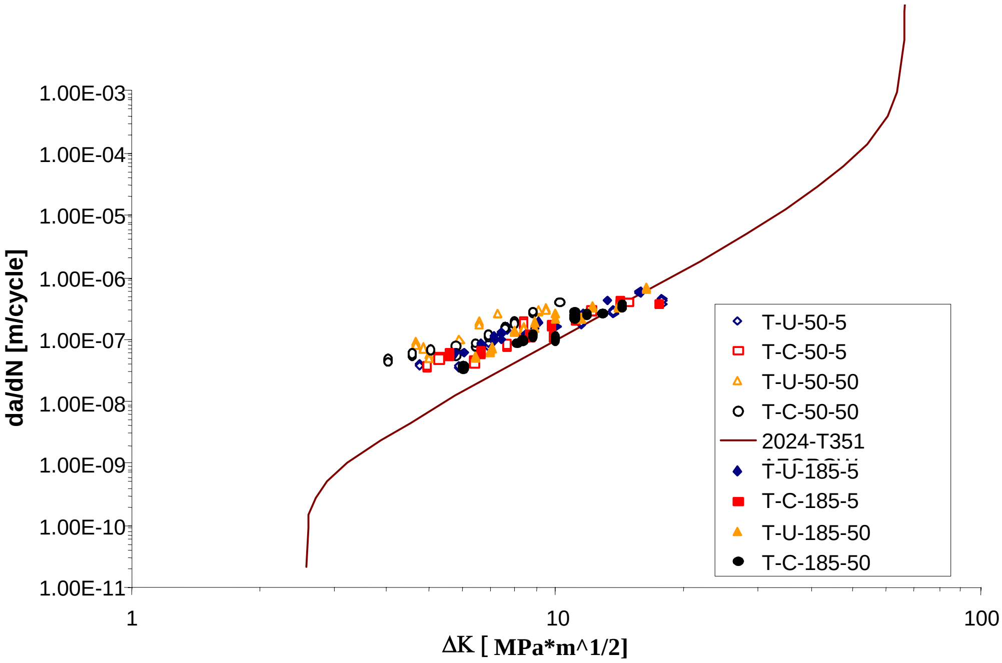


Figure 26 Fatigue total life vs. stress concentration factor



(calculation as through thickness crack and quarter elliptical crack including notch depth)

Figure 27 Crack growth rate of shorts cracks from scribe marks in tension

2.6.4 Control of crack growth rates and crack trajectories for enhanced fail safety and damage tolerance in welded aircraft structures (P Irving and Xiang Zhang Cranfield University)

The use of welds in aircraft structures creates significant local inhomogeneties in material microstructure, in strength and toughness, and in residual stress fields – all located in and around the line of the weld. Initiation and growth of fatigue cracks in the vicinity of the weld line is markedly affected by these inhomogeneties. Welding in addition creates large integral structures, which require additional design considerations and analysis techniques in order to improve and enhance the fail safety and damage tolerance capability of this kind of structures. Frequently weld residual stresses and microstructure changes can act to accelerate fatigue crack growth rates. However, weld stresses can be modified via cold work and by post weld machining operations, and could result in reduced tension or even compression stress fields which will reduce crack growth rates and enhance fatigue and damage tolerance behaviour. This attractive prospect is contingent on two key capabilities.

- The ability to control development of microstructure and residual stress during and after welding so that desirable distributions with reduced crack growth rates are achieved.
- The ability to predict crack fatigue growth rates and crack trajectories in response to material property distributions and to internal as well as externally imposed stresses.

Recent research has made significant progress in both control of residual stress and prediction of fatigue crack growth rates in the presence of local residual stress fields. This is to be presented at this ICAF Symposium [28] and describes work that has been undertaken in controlling residual stress in welded structures, together with recent work in predicting fatigue crack growth rates and crack trajectories under the influence of weld residual stress fields. The predictions have been validated against experimental data.

Experiments to explore the ability of cold work applied during and after welding to modify the residual stress fields associated with weld operations will be described. Residual stresses measured on weld samples with and without cold work demonstrate that the stresses can be successfully modified, and that this in turn has modified the fatigue crack growth rates through the welded samples.

To validate fatigue crack growth rate predictions, crack growth samples in CT, M(T) and ELSEN geometries of three different sizes were machined from friction stir welded 2198 and 2195 sheet and plate in a range of thicknesses and weld orientations. Residual stress distributions in the samples were measured using the neutron diffraction and synchrotron X-ray techniques. The different sample size and crack orientations resulted in a wide range of residual stress distributions. Fatigue crack growth rates were measured in the samples to provide an experimental reference data set for the predictions. Further tests were conducted to establish the influence of residual stresses acting together with local stress concentrations on fatigue crack trajectories and the stability of the crack path within and outside the weld.

To predict crack growth rates in the welded samples, values of stress intensity factors associated with the residual stress field (K_{resid}) acting on the crack tip throughout the crack trajectory were calculated using residual stress field data. K_{resid} values were used to modify the values of K_{max} and K_{min} acting on the crack tip due to the applied loads. Fatigue crack growth rate changes arising from the changed mean stress were calculated from parent plate data using the Walker and NASGROW equations. Good agreement of model predictions with experiments for all levels of residual stresses and crack growth paths was obtained.

The implications of the results on capability to control and predict fatigue crack development in welded aircraft structures is discussed.

2.6.5 The detailed characterisation of corrosion pitting as a basis for EIFS analysis and standard damage tolerant lifing calculations (M R Bache, Swansea University)

Over the past two years, this work at Swansea University can be divided by two main applications; aluminium alloys for fuselage components and high strength steels for landing gear structures.

Following the previous collaboration between Swansea University in the UK, DSTO and CSIRO of Australia and BAE SYSTEMS in both countries (SICAS - Structural Integrity Assessment of Pitting Corrosion in Aircraft Structures) [29], a follow up assessment of airframe aluminium alloy 7010-T7651 has been completed but this time incorporating worst case corrosion pitting, deliberately formed in various orientations with respect to plate rolling direction [30].

In the first instance, flat plate specimens were subjected to pitting damage via a laboratory based corrosion protocol. Secondly, a centre hole plate specimen was employed, in this case incorporating end grain corrosion within the root of the hole. Detailed characterisation of the pits demonstrates the critical role of microstructure on pit geometry. Both forms of pre-corroded specimen were subjected to a comprehensive matrix of constant amplitude load controlled fatigue testing under controlled humidity and room temperature. Multiple repeat tests were performed at specific stress levels to produce data sets corresponding to fatigue lives of approximately 1x104, 7x104 and 3x105 cycles. The future implementation of this data for LEFM based predictions of fatigue life is discussed.

In addition to this work on airframe aluminium alloys, a number of postgraduate projects have evaluated the fatigue response of high strength and stainless steels for the landing gear division of Airbus UK. In particular, the role of in-situ aqueous salt spray environments on fatigue crack initiation and growth has been evaluated. A major focus of all these studies has included the detailed characterisation of corrosion pitting as a basis for equivalent initial flaw size (EIFS) analysis and standard damage tolerant lifing calculations.

2.6.6 Performance of strap reinforced integral skin-stringer panels under a compression-stress dominated load spectrum (X Zhang and PE Irving, Cranfield University)

This comprehensive research programme has been carried out by Cranfield and the Open Universities together with industrial sponsors and partners including Airbus UK, Alcoa Inc, and Cytec. Recent research has demonstrated significant improvement to the fail safety and damage tolerance of integral structures via the installation of bonded straps [31,32,33]. These studies have focused on application to transport aircraft lower wing structures using representative load spectra with predominantly tensile stresses.

The research reported in [31-33] was performed using SEN and M(T) coupon samples containing bonded retardation straps. The samples were subjected to constant amplitude loading and the retardation performance of a wide range of strap materials (GLARE, glass fibre reinforced epoxy, 7085 aluminium and Ti-6Al-4V titanium alloys) was investigated. Residual stress profiles beneath the straps, induced by the bonding of the strap materials, were measured using neutron diffraction. (For further details on the residual stress measurement and prediction, please refer to the contribution by the Open University elsewhere in this section). Predictive models were developed based on finite element analysis. The models calculated stress intensity factors of substrate cracks, taking into account the effects of curing residual stresses, secondary bending, adhesive disbonding, and non-uniform crack profiles due to one-sided bonding. The predicted crack growth rate the calculated stress intensity values was then calculated from crack growth rate data for the substrate alloy.

The prediction tool was used to perform parametric trade-off studies to find the best strap configurations at a given fatigue life (in terms of the strap material, dimension and position, strap durability and fatigue crack growth life) under the constraint of minimum added structural weight.

To scale the work up from coupons, studies will be performed using integral skin-stringer panels to represent the upper wing of civil transport aircraft. These are of 7085 aluminium alloy and are reinforced by bonded straps. The panels will be subjected to a variable amplitude load spectrum containing a significant portion of compressive stress cycles. Most existing load interaction models are aimed at the tensile overload retardation effect and thus may not be suitable for predicting crack growth rates under compression-load dominated spectra. Hence there are difficulties in prediction of crack growth rates under variable amplitude loading containing significant proportions of compression cycles. To this must be added the complexities of the bonded strap performance under the same spectrum. Coupon tests have been performed under the upper wing spectrum, and large scale panel testing under the same spectrum is in progress.

This work will provide a way forward for design of bonded crack retarders for integral skin-stringer panels.

2.6.7 Load Sequence Effect and Enhanced Fatigue Life Prediction under Spectrum Loading (Y Xu, University of Hertfordshire)

Damage tolerant design of airframe structures relies on the life prediction of fatigue cracks propagating from a detectable size to the critical size. Enormous research efforts have been made to understand the crack growth behaviour of airframe structures under spectrum loading. It is however recognized that accurate life prediction for airframe structures is challenging due to the complex load sequence effect.

This work is aimed at gaining a further scientific understanding of the complex influence of the loading history on fatigue crack growth, which leads to the development of an enhanced fatigue life prediction methodology for airframe structures. The spectrum loading is systematically broken down into a number of simple yet representative loading scenarios with overload/underload superimposed onto the baseline constant amplitude fatigue loading. Detailed finite element (FE) simulation of the plasticity-induced crack closure (PICC) has been carried out to catch the transient behaviour of PICC. Figure 28 serves as an example of these simulation results. It shows the effect of the dominating first overload with the overload ratio of 2 on the variation of the crack closure of the second smaller overload with an overload ratio of 1.5 under the baseline stress intensity factor range of $\Delta K_{(BL)}$=12.6 MPa $m^{0.5}$ and stress ratio R=0. The load interaction effect of the first overload on the PICC variation of the second overload is dependent on the overload ratios and the spacing between the two overloads. The magnitude of the PICC of the second overload has been increased dramatically compared with the single overload case of the overload ratio of 1.5. The reason for calling the first overload as the dominant overload lies in the fact that it controls the overload affected distance.

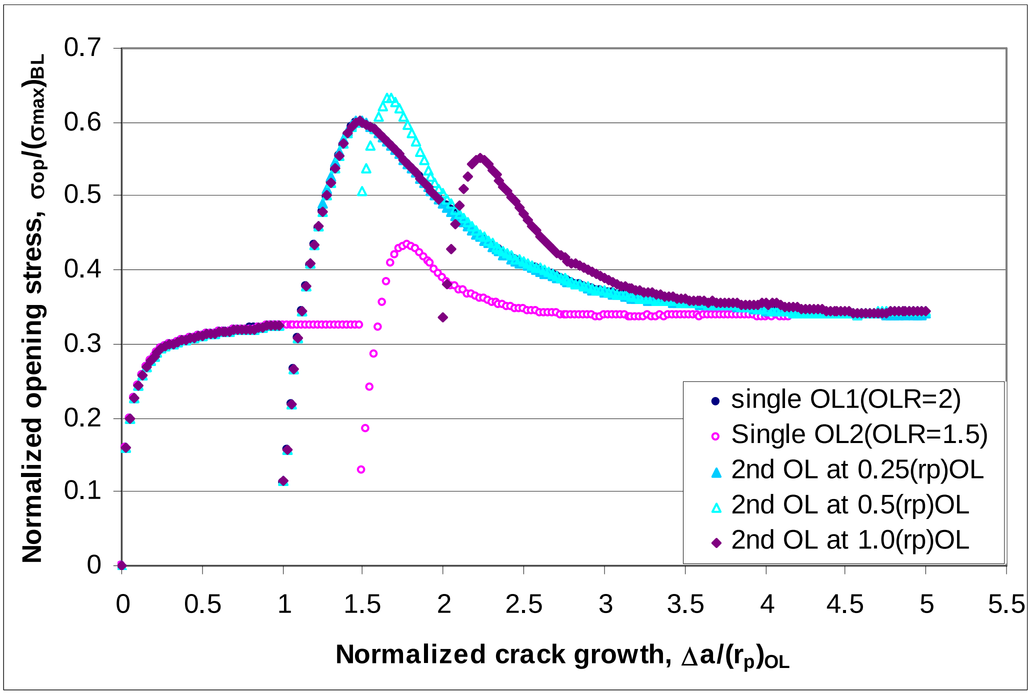
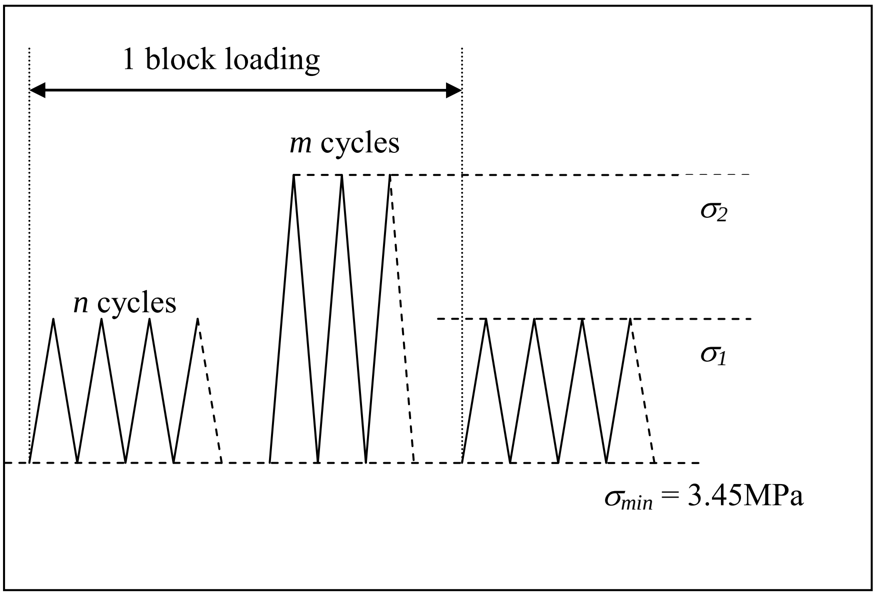
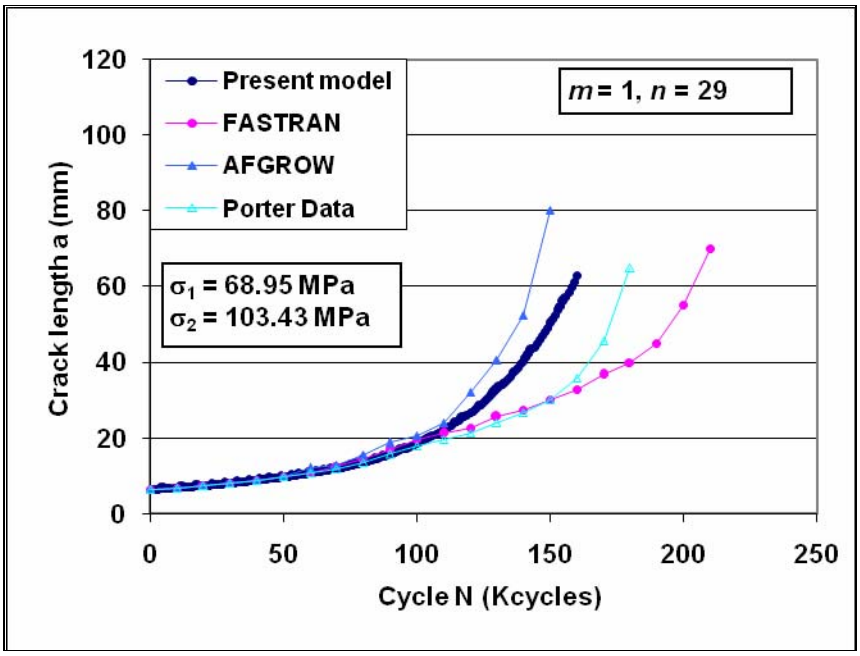


Figure 28 Effect of the dominating first overload on the variation of the crack closure of the second smaller overload (OLR$_1$=2, OLR$_2$=1.5, $\Delta K_{(BL)}$=12.6 MPa m$^{0.5}$, and R=0)

The simulation results of the PICC variations under various loading conditions have been quantified and implemented in the proposed life prediction model to rationalize the transient crack growth behaviour under the spectrum loading. A VB code has been developed to predict the crack propagation life under various loading conditions. As an example, Figure 29(a) below shows the profile of block loading with a block of *n* constant-amplitude cycles followed by a block of *m* cycles of a different constant-amplitude. Figure 29(b) shows the comparisons of the prediction of the present model with Porter's test data and the predictions of FASTRAN model and AFGROW model. The prediction of the current model is in-between the results of the FASTRAN and AFGROW models. It is conservative and agrees well with the test data.



(a)



(b)

Figure 29 (a) loading profile for model validation and (b) comparison of the present model with Al 7075-T6 test data and the results from the FASTRAN and AFGROW code

It has been concluded that while care should be taken in defining the crack closure, the concept provides a powerful tool in rationalizing the load sequence effect on fatigue crack growth behaviour. Good agreement is observed between the preliminary results from the proposed life prediction model and the results reported in the literature under typical spectrum loadings.

2.6.8 Analysis/Certification activities at Bombardier Aerospace, Belfast (B McCoubrey, Bombardier Aerospace, Belfast)

US Forestry Service C23A Fatigue Assessment

The C23A aircraft, developed in 1984, is a military variant of the Shorts SD3-30 Sherpa civilian aircraft. It was originally in service with the USAF as part of EDSA (European Distribution System Aircraft). Since 1990, four C23A aircraft have been in service with the United States Forestry Service (USFS) in a smoke jumping role.

The initial Service Life of the C23A airframe was 40,000 flights when operated to the EDSA mission profile. As the C23A aircraft are not being used in the original role for which they were procured, the USFS tasked Bombardier to carry out a fatigue evaluation of the structure under current usage. Limited data was available for the current usage; however the C23A aircraft are fitted with accumulating 'g' meters, which count normal acceleration exceedances at pre-defined "g" levels. Therefore the fatigue assessment undertaken was limited to structure where the loading is proportional to normal acceleration.

At Bombardier's request the USFS recorded flight-by-flight g exceedances on each aircraft for the 2008 flying season. This allowed a current usage spectrum to be developed and compared to the fatigue test spectrum applied to the SD3-30 test article structure, which established the 40000 flights life for the aircraft.

The damage assessment undertaken on the data from the 2008 flying season did not identify any major concerns over the current USFS usage, and no reduction in the 40,000 flights Service Life was considered necessary.

SD3 Series

A substantial amount of time was spent in 2008 understanding the FAA Part 26 regulations (continued airworthiness of and safety improvements for transport category airplanes) and their applicability to SD3-30 and SD3-60 aircraft. As of end of April 2009 the SD3-30 has been exempted from the regulations and the outcome of the petition for exemption for SD3-60 is still awaited.

Regional Jets

Bombardier Aerospace Belfast are currently finalising Damage Tolerance certification reports and Damage Tolerance Allowable Damage substantiation reports for CRJ 1000 fuselage, to support certification in the 3rd quarter of 2009.

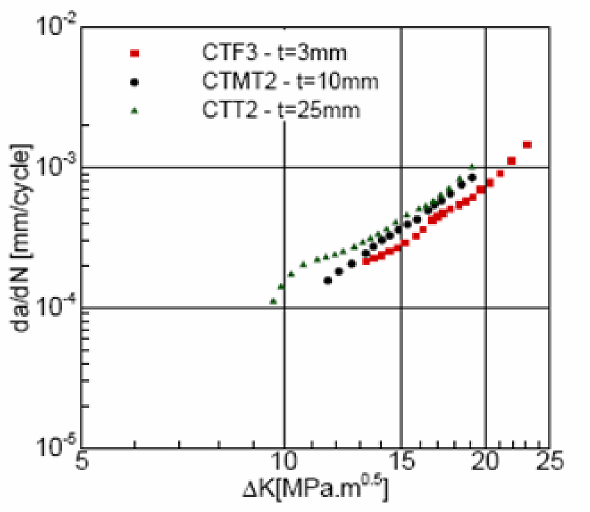
In addition the Damage Tolerance Allowable Damage substantiation reports for both CRJ 700 and CRJ 900 fuselages have also been completed.

2.6.9 Thickness effects in plasticity-induced fatigue crack closure (D. Nowell, University of Oxford)

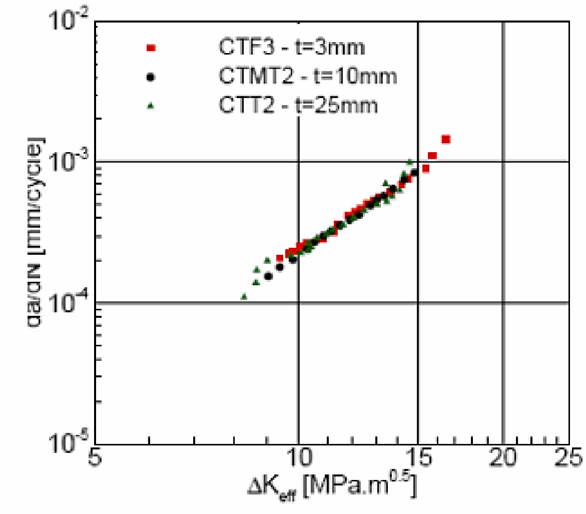
This project aimed to model plane stress and plane strain crack closure using boundary elements and finite elements. These models may be used to provide a calibrated method for incorporating three-dimensional effects into fatigue crack lifing models under non-uniform loading. Paulo de Matos completed his D.Phil. in April 2008 [34] and the project is now finished. He produced some detailed finite element models, which clearly illustrate the complex three-dimensional nature of the closure phenomenon.

Some experimental work was also undertaken which shows the potential for digital image correlation (DIC) techniques as a means of investigating crack closure in-situ. This work was presented at the recent FDSM VII conference in Hyannis [35] and a selection of the results are presented in the Figures below, which illustrate the effect of thickness. The experiments were conducted on aluminium alloy (6082 T6) Compact Tension (CT) specimens of thickness: 3, 10 and 25mm, under loading with an R ratio of 0.1. Crack closure was measured by the DIC method, a back face strain gauge and a crack mouth opening displacement gauge.

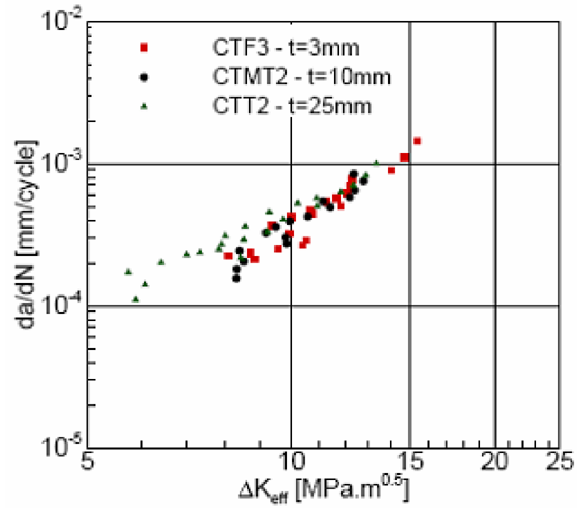
Experimentally measured crack growth rate is plotted against nominal ΔK in Figure 30a, demonstrating that cracks propagate faster in thick specimens than thinner specimens, in agreement with other workers results. Figures 30b and c plot growth rate against effective ΔK (ΔK_{eff}) taking experimentally determined crack closure into account. In the case of figure 30b, the back face gauge measurements are used, whereas DIC measurements are used in figure 30c. It can be seen that the back face gauge measurements provide a better correlation. This indicates that the growth rate is related to different levels of closure through the thickness. The DIC measurements effectively present closure at the surface where plane stress conditions apply, whereas the back face gauge compliance results present bulk measurements and thus more closely related to ΔK_{eff} for thicker specimens.



a) nominal ΔK



b) ΔK_{eff} from BF gauge



c) ΔK_{eff} from DIC

Figure 30 Comparison of use of nominal ΔK and effective ΔK

2.6.10 Crack propagation under fatigue and creep conditions (A Korsunsky, University of Oxford)

Non-local damage-plasticity models have been developed in order to predict crack growth rates and trajectories under creep and fatigue conditions. In this project, crack paths in nickel superalloy plates are investigated experimentally and predicted numerically with a view to providing aero engine designers with improved rules and predictive capabilities.

2.6.11 The use of ultrasonic impact treatment to extend the fatigue life of integral aerospace structures (C A Rodopoulos, Sheffield Hallam University)

Besides attractive mechanical properties, especially in fatigue and strength, integral structures are claimed to offer cost and weight savings. Joining technologies like friction stir welding and laser beam welding have recently been identified by leading aircraft manufacturers as “key technologies” for fuselage and wing manufacturing. Although many industries are looking at the processes, problems associated with the damage tolerance performance of integral structures remain. In particular, research works dealing with the fatigue crack propagation in the welding direction or perpendicular to it, found more or less pronounced effects of the residual stresses especially in the case of near threshold loading. As a result damage tolerance methodologies based on material data can lead to unprecedented errors. In many works the problem was attributed to the presence of residual stresses. Tensile residual stresses have been found to be responsible for the premature initiation of fatigue cracks, the increase in the number of catastrophic cracks and hence the probability for crack coalescence, etc. The Ultrasonic Impact Treatment (UIT) is a technique that directly deforms the surface of materials using ultrasonic impacts. This technique fundamentally differs from contact methods of ultrasonic deformation treatment, the development of which dates back to 1950s. The UIT process is employing continuous ultrasonic vibrations at the ultrasonic transducer output end strengthened with hard materials (carbide-containing alloys, artificial diamonds etc.) and being in direct and generally continuous contact with the treated surface. The process is mainly controlled by the output of the ultrasonic transducer (frequency), the selected pressure, the feed rate and the number of passes (coverage). The process can induce on request different amounts of cold work and residual stress profiles. The depth of the latter can range from 0.8 to 4mm in aluminium alloys. The process is relatively cheap compared to controlled shot peening and can achieve process rates in excess of 300mm/min. The work that follows portrays experimental results conducted within the framework of the EC programme DATON [36,37]

Several test panels, shown in Figure 31 have been investigated. The panels were made of 6056-T651 and 2024-T3 aluminium alloys. Following joining of the stringers using laser beam welding, UIT treatment was performed according to the parameters shown in Table 1. Treatment followed a route designed to optimise the compressive residual stresses induced, Figure 32. Only the stringer pocket was treated. The residual stresses at different location to the vertical central panel were measured using X Ray Diffraction (XRD), Figure 33a and b. Crack growth tests were performed using a pre-notched 20mm central slit. The results shown in Figure 34a and b, indicate that UIT can significantly reduce the crack growth rate and enhance the damage tolerance of the panels.

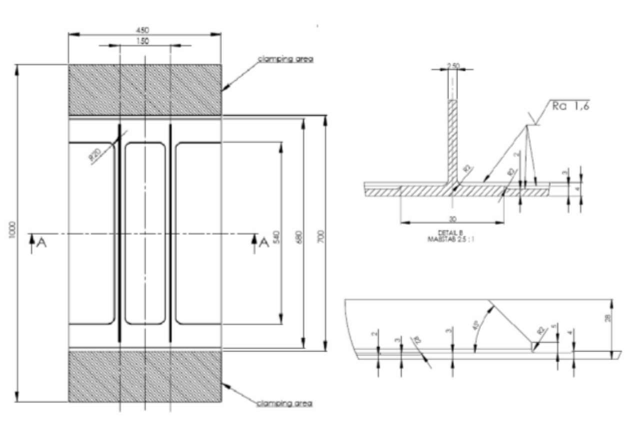


Figure 31 Schematic representation of the two-stringer testing panel

UIT process parameter	***Esonix***
Carrier frequency [KHz]	36
Pin dimension [mm]	∅ 6.3x 17, R25, Titanium
Normalized impact	64 impulses
Amplitude under load [µm]	12
Pressure [kg]	15
Impact frequency [Hz]	36
Tool Overlapping rate [%]	50
Coverage [%]	200
Feed rate [mm/min]	150

Table 1 UIT treatment parameters

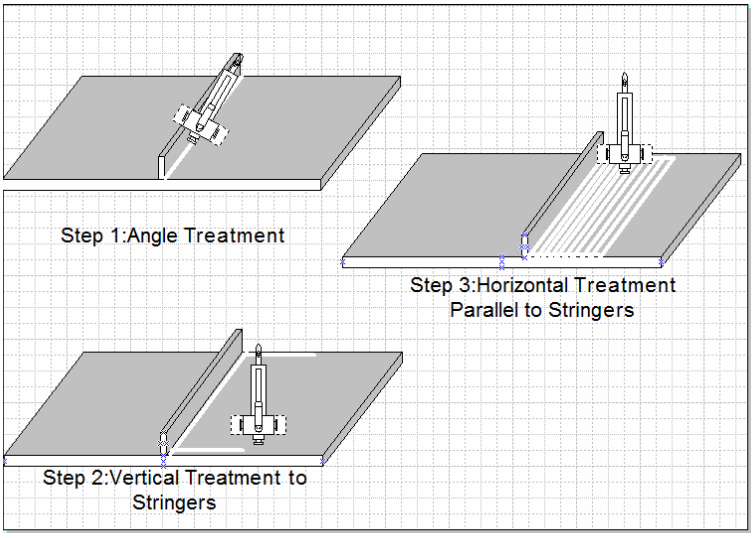


Figure.32 Treatment paths for 2-stringer LBW panels

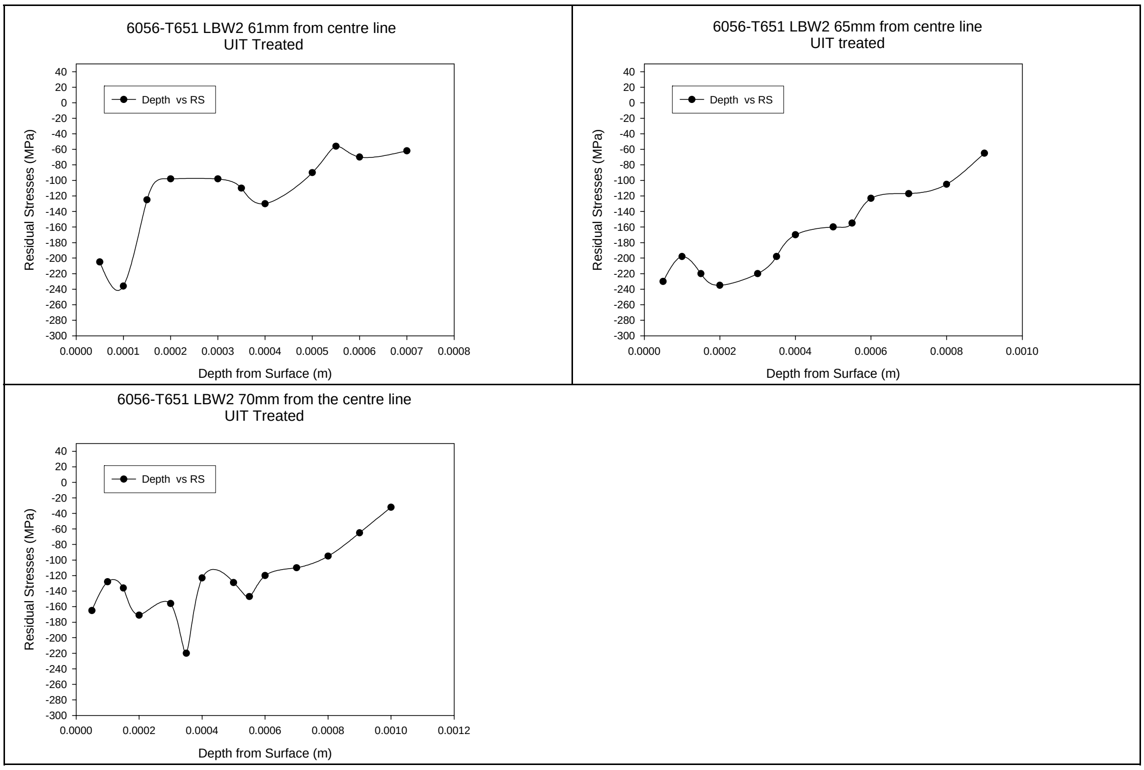


Figure 33a XRD measured residual stresses taken from different locations of the UIT treated zone for 6056-T651 panels

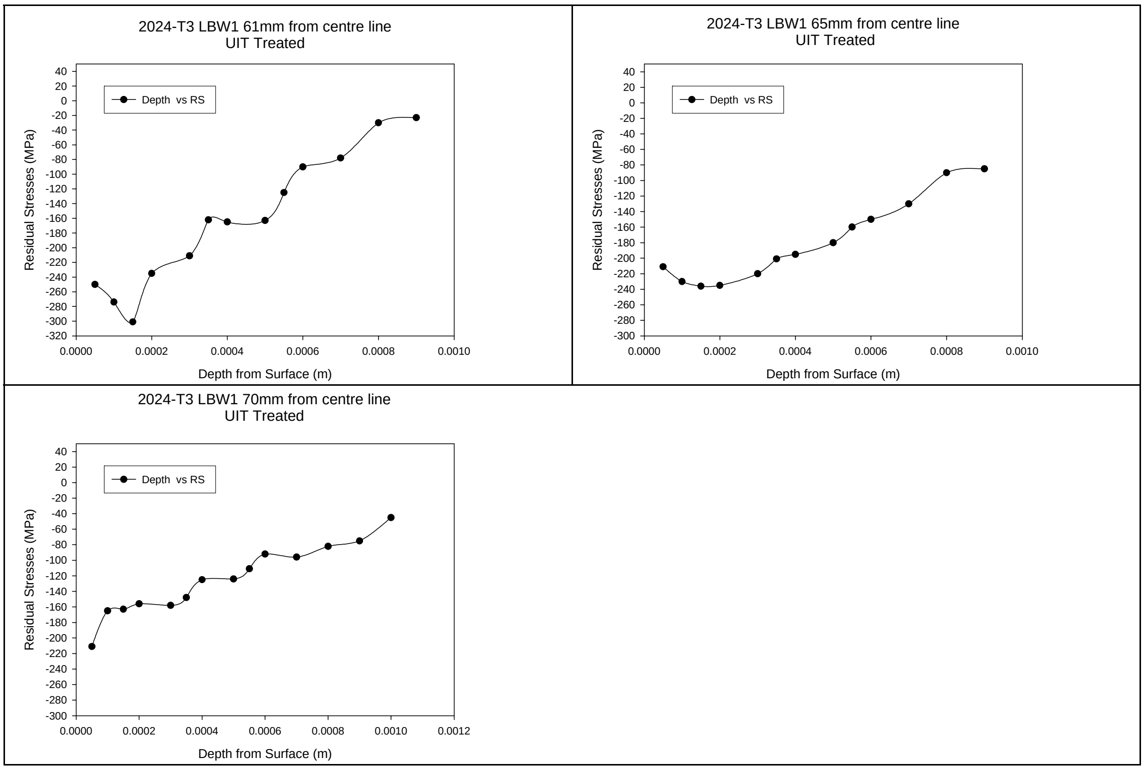


Figure 33b XRD measured residual stresses taken from different locations of the UIT treated zone for 2024-T3 panels.

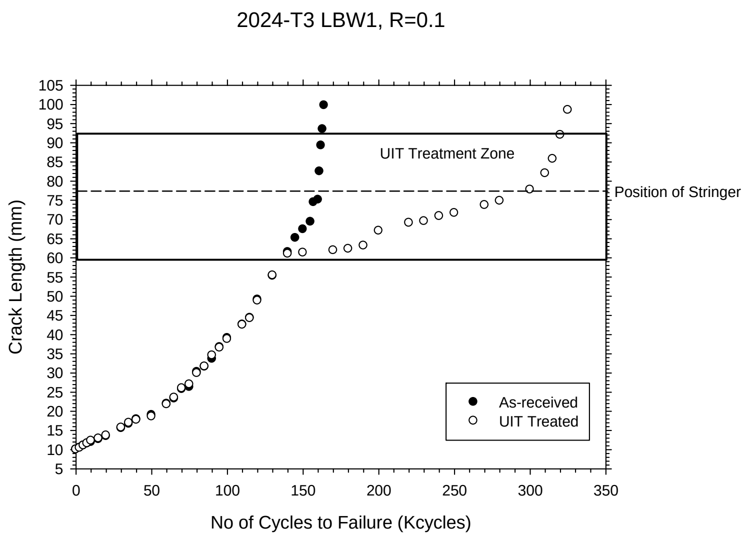


Figure 34a Comparison of crack growth between as-received and UIT treated panel of 2024-T3 LBW tested at a maximum stress of 90 MPa

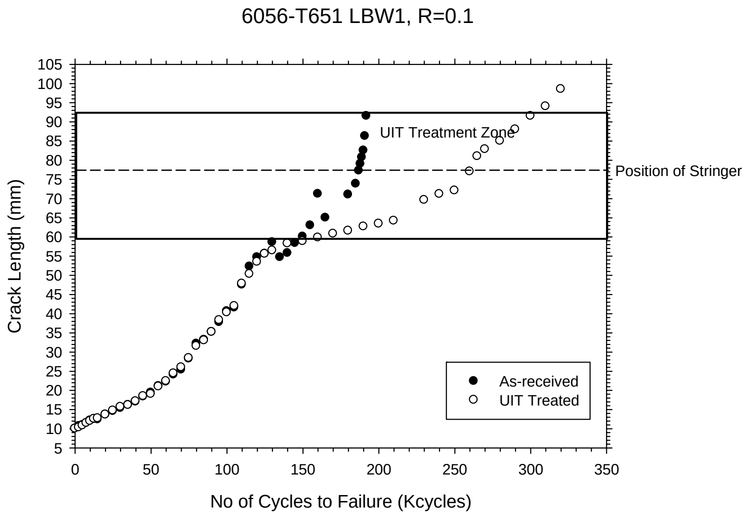


Figure.34b Comparison of crack growth between as-received and UIT treated panel of 6056-T651 LBW tested at a maximum stress of 90 MPa

2.6.12 Fatigue crack growth discrepancies with stress ratio (C A Rodopoulos, Sheffield Hallam University)

The accurate estimation of the fatigue lives of metallic structural components in highly demanding environments is still a challenge for the designer. Military aircraft are often required to achieve long lives under demanding operational conditions consisting of highly complex and variable spectra. As a result there has been an increasing use of titanium in primary structural members due to its high strength, light weight, and good fatigue and fracture toughness properties. Indeed, some bulkheads in the F-22, the Super Hornet, the Swiss F/A-18, and the F35 Joint Strike Fighter are made of titanium. In the F-22, titanium accounts for ~ 36%, by weight, of all structural materials used in the aircraft.

It was recently reported that crack growth data, obtained for D6ac, solution treated and over-aged (STOA) condition Ti-6Al-4V and 4340 steels, obtained using CT specimens tested under the ASTM constant R load reducing technique, exhibited that there is no R ratio dependence, and hence no closure, in the Paris Region (Region II). As a result damage tolerance codes based on the principle of closure can lead to erroneous results. The concept of the Fatigue Damage Map was introduced in order to define the propagation loci of the material, [38] Figure 35a shows the points defining the loci which are then turned into da/dN vs crack length, Figure 35b.

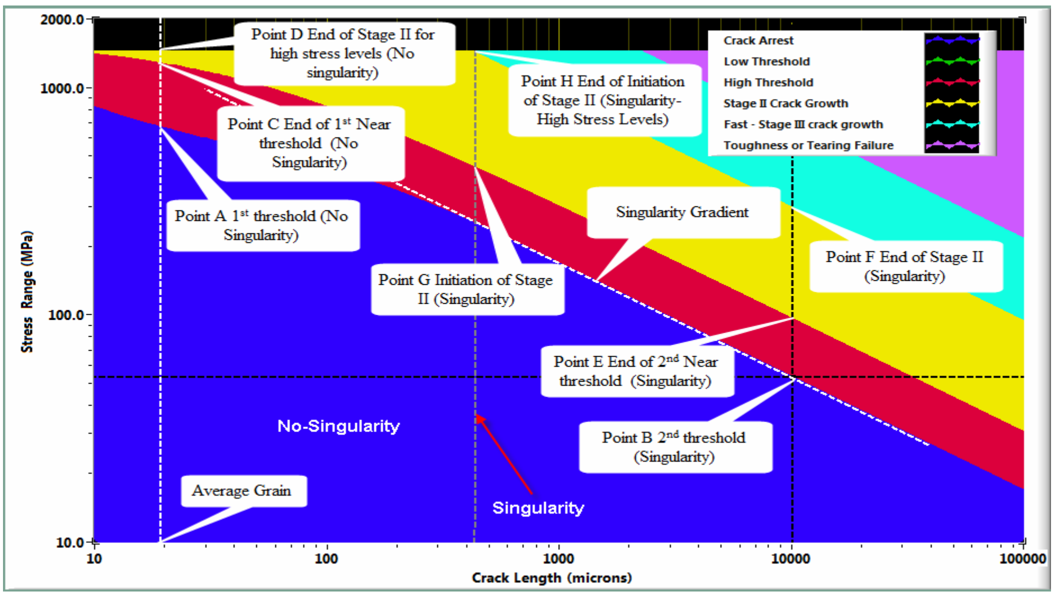


Figure 35a Snap shot from FDM Ver. 1.08 (stress range vs crack length) for 4340 at R=0 and selection of the 8 points

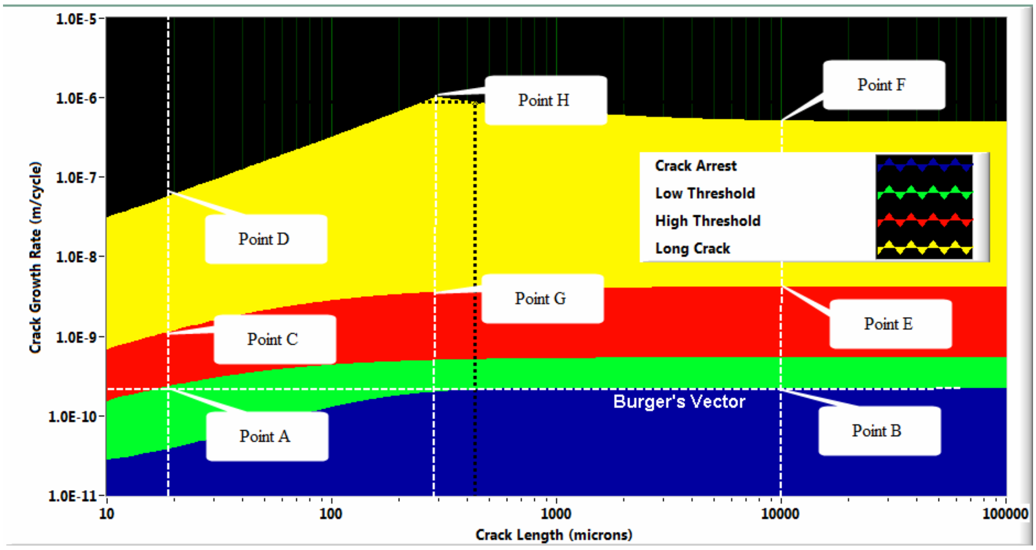


Figure 35b Snap shot from FDM Ver. 1.08 (crack growth rate vs crack length) for 4340 at R=0 and selection of the 8 points

The points are then used to construct the propagation loci, see Figure 36. It is worth noting that the propagation loci is a material property and independent of geometry or loading conditions. Close examination of Figure 36, reveals that there is an overlapping area for all stress ratios; the size of this area is shown in Figure 37. To provide an explanation towards the tendency of the selected materials to appear independent of stress ratio, the loci for 2024-T351 a material with strong R-dependency is also included, Figure 38. The comparison demonstrates the small potential of 2024-T351 to exhibit R-independence.

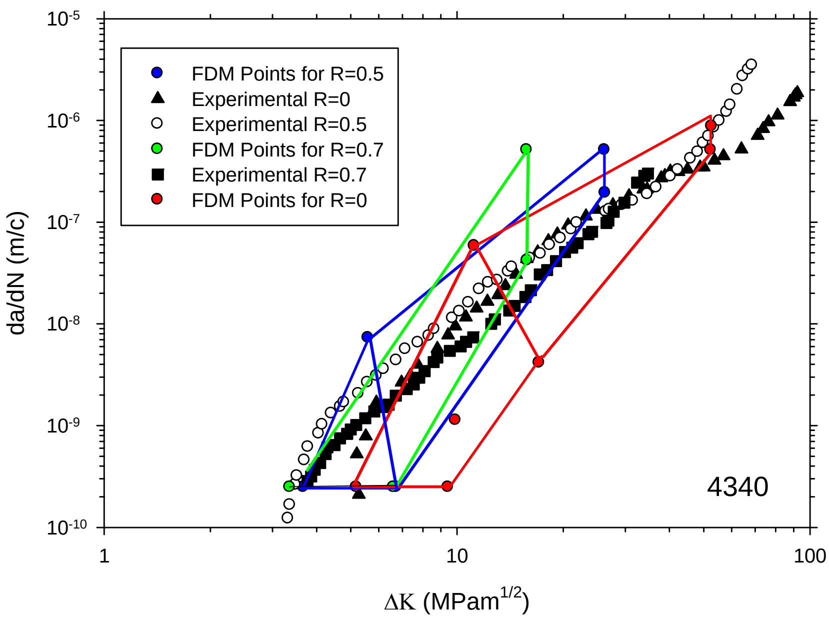


Figure 36 Propagation loci vs SIF for 4340 for different stress ratios. Experimental results taken from several manufacturers are also plotted for comparison

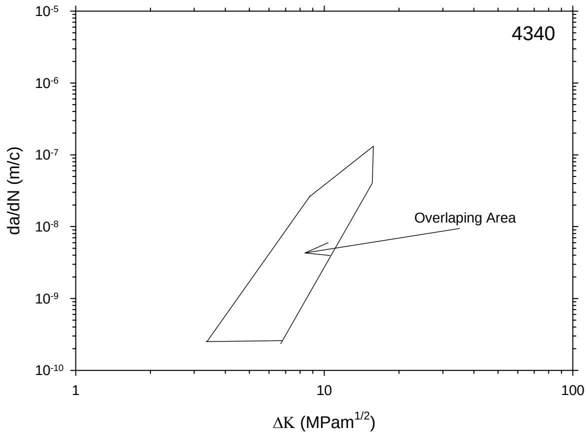


Figure 37 Overlapping area for 4340 Steel

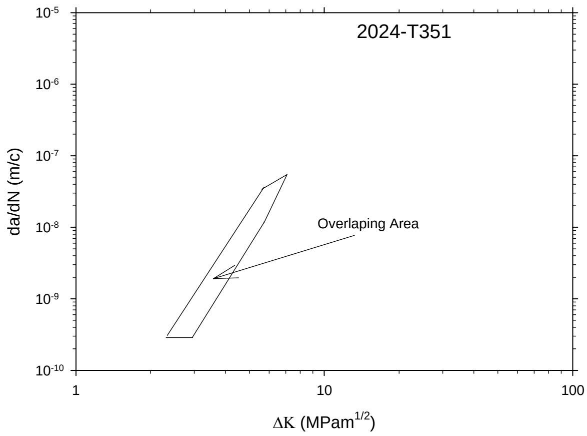


Figure 38 Overlapping area for 2024-T351

2.7 FATIGUE OF METALLIC STRUCTURAL FEATURES

2.7.1 "VAREX" – Process – A new cost efficient method for cold working fastener holes in aluminium aircraft structures (E G Reese, A Dowson, T Jones, Airbus)

Fatigue vulnerable areas on aircraft structures are often concentrated around fastener or open hole locations. Fatigue enhancement methods are often applied to these critical locations prior to joint assembly to retard the potential for in-service crack initiation and growth.

Cold expansion of holes ('cold-working') is a fatigue enhancement technique that is used extensively on metallic aircraft components to enhance the fatigue performance of a structural assembly. In addition, the cold expansion process is also incorporated into the structural design philosophy as a means of reducing the weight and cost of the structure.

Cold expansion is undertaken by expanding a hole radially to an extent whereby the surround of the hole is plastically deformed. The cold expansion results in a zone of high residual compressive hoop stress in the bulk material surrounding the hole. During aircraft service, the resultant residual compressive zone counteracts and reduces any tensile fatigue stresses that are normally associated with crack initiation and growth thereby improving the overall fatigue performance of the structure.

Airbus currently employ two cold expansion processes on metallic aircraft structures. Although these processes provide reasonable results in fatigue enhancement of Aluminium alloys, they exhibit disadvantages like e.g. inhomogeneous strain distribution around the hole or risk of crack formation near ridges – in particular with new generation Aluminium alloys.

Therefore, a new process, named the “Variable in-situ Expansion (VarEx)”-process, was developed at EADS Innovation Works. The tool employed allows the application of variable expansion levels; it provides a homogeneous strain distribution around the hole and allows the cold working of even difficult to expand Aluminium alloys like AA7xxx series up to high levels of applied expansion without crack formation, yielding an even better fatigue enhancement.

The paper to be presented at this year’s ICAF Symposium [39], will also address additional benefits like: a precise control of the expansion level, an ability to compensate for hole tolerances and wear entailed changes in tooling diameter, a simplified process control, a improved material exploitation at a reduced risk of crack formation, a potential for joining dissimilar materials (e.g. hybrid stacks), at significantly reduced costs.

2.7.2 The effect of controlled shot peening on the fatigue behaviour of 2024-T3 aluminium friction stir welds (C A Rodopoulos, Sheffield Hallam University)

This work [40] examines the microstructural and fatigue properties of Friction Stir Welds made in 2024-T3 aluminium alloy and provides extensive information concerning their cyclic stress-strain behaviour, residual stress distribution and crack initiation sites. To eliminate the cost associated with the removal of the flow arm by milling and other costs associated with the quality control of the welding process (residual stress distribution, micro-hardness profile, welding scar, etc), controlled shot peening is introduced. Tensile residual stresses introduced in the thermomechanical affected zone (TMAZ) during welding are found to become compressive after peening as shown in Figure 39, which also presents the effect of peening, both with and without skimming, on residual stresses in other FSW zones. The introduction of compressive residual stresses leads to the increase in the fatigue resistance of the weld beyond the values of the bare (parent) material, as shown in Figure 40.

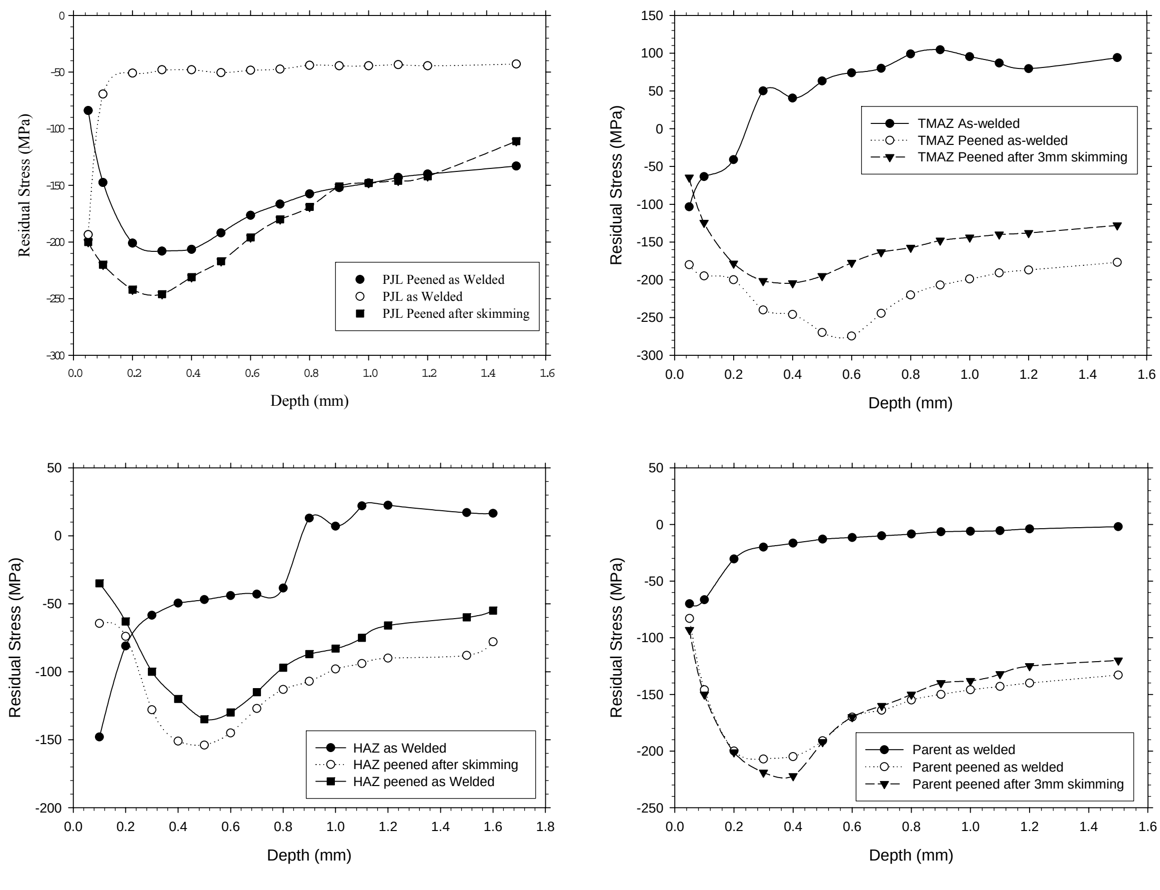


Figure 39 Re-distribution of residual stresses in FSW zones including parent material after shot peening.

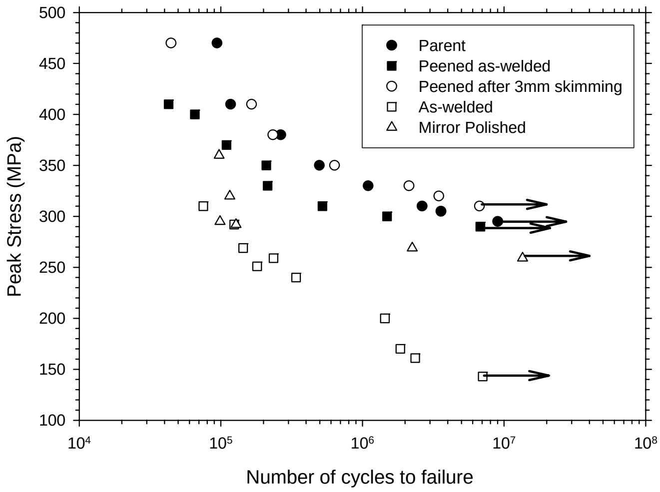


Figure 40 Effect of shot peening, mirror polishing against as-welded and skimmed weld on fatigue life.

2.7.3 Crystallographic texture and the definition of Effective Structural Unit Size in Titanium products (M R Bache, Swansea University)

The majority of the Swansea research portfolio continues to support aero-engine applications through their role as a Rolls-Royce University Technology Centre (UTC) in Materials. A fundamental understanding of the fatigue behaviour of titanium alloys and the so-called dwell effect has been extended through recent empirical studies of both commercial and model large grain alloy variants [41,42].

In ref 43**,** microstructure and micro-texture assessments of two titanium alloy product forms, namely Ti 6Al 4V cross-rolled plate and Ti 834 forged disc, are described. A banded, two-component texture was noted in the Ti 6/4 plate. In contrast, Ti 834 illustrated more extensive, randomly distributed zones, with each zone often containing a distinct crystallographic orientation. In either case, fatigue crack initiation and in particular the formation of densely facetted regions were intimately related to these areas of common orientation. Thus, it is proposed that mechanical performance may be controlled by effective structural units (ESUs) that extend well beyond the size of typical microstructural features such as individual primary α grains or even prior β grains.

This work has emphasised the essential use of electron back-scattered diffraction (EBSD) orientation mapping for the evaluation of ESU in titanium alloy microstructures. Standard metallographic sections and associated optical characterisation alone are insufficient to predict mechanical response or form the basis of crystal plasticity models.

2.7.4 Microplasticity and fatigue crack initiation in Titanium alloys (F Dunne and D Hills, University of Oxford)

The project aims are to understand where, why and how fatigue cracks initiate by relating crystal plasticity modelling with detailed microscopy (SEM, EBSD). The generation of geometrically necessary dislocations, the formation of persistent slip bands and the local initiation of micro-cracking are to be examined and used to develop physically based initiation criteria. A very general set of three-dimensional crystal plasticity models has now been developed enabling fcc, bcc and hcp crystal structure to be analysed. In Titanium alloys in particular, the role of c+a slip (in addition to basal and prismatic) has been addressed and shown, at least in the pseudo-single phase system considered, not to be of great significance in facet nucleation. Microstructures and textures of two forms of Rolls-Royce Titanium alloy have been characterized and a FIBbing technique used to produce micro-grids on sample surfaces at sub-grain level. Samples with differing crystallographies have been prepared and testing is due to commence shortly. Single crystal bcc tantalum four-point bend tests have been carried out by Angus Wilkinson's group to characterize lattice curvature and the length scale effect. FE models have been developed and are currently being used to assess the ability of such models to capture correctly local grain reorientation. Currently, combined bcc/hcp crystal models are being developed to enable investigations into the role of the alpha/transformed beta phases in facet nucleation. In addition, the crystal models are providing insight into the effects of peening on crack nucleation in T900 discs.

2.7.5 High to Low Cycle Fatigue in Two-Phase Steel (F Dunne, University of Oxford)

Experiments by collaborators at Kyushu University, Japan have observed the interesting phenomenon of cycles of apparently high cycle fatigue (elastic response) leading subsequently to a cyclic plastic response without any change in loading. The number of cycles necessary to reach the transition depends on the stress applied (though always below the macroscopic yield stress). We are using our crystal models, enhanced to capture double yield, to investigate localised (grain by grain) plastic deformation and to attempt to explain the macroscopically observed behaviour. We will also use the models to investigate fatigue crack nucleation in samples in which a geometric stress raiser is both very small and very large compared to the grain size.

2.7.6 Fatigue crack initiation prediction (A Korsunsky, University of Oxford)

Energy dissipation during cyclic deformation offers a rational basis for the prediction of crack initiation. However, since during low cycle fatigue little evidence of this may be available at the macroscopic scale, microscopic investigation of local plasticity and damage is necessary. Cyclic deformation behaviour of key engineering alloys is being studied via a combination of experimental characterisation and numerical modelling. Synchrotron X-ray diffraction provides a unique non-destructive means of characterising elastic strains (and therefore of computing stresses) at the surface and in the bulk, while digital image correlation provides a means of total strain evaluation (at sample surface). Micron-sized X-ray beams are used to investigate intra- and inter-granular stresses. Length-scale dependent finite element and dislocation dynamics models are developed and used to interpret experimental observations.

2.7.7 Contact evolution based fretting fatigue prediction (D Hills and D Nowell, University of Oxford)

This project started in the summer of 2007 and is funded by the EPSRC. It is being undertaken in collaboration with the Nottingham Transmissions UTC. The objective is to combine fretting fatigue and fretting wear models to provide improved life predictions for components subject to fretting (such as shaft splines or blade roots). Oxford work is concentrating on the application of contact asymptotics to characterise fretting fatigue behaviour of partially or fully worn contacts. Work completed so far has included the development of theoretical solutions for fully worn contacts together with an efficient numerical approach which can tackle the transient problem. The experimental phase of the work is now underway.

2.7.8 High temperature fretting fatigue (D Hills and D Nowell, University of Oxford)

Work has been undertaken to design, build, and commission a high temperature fretting fatigue rig, which is now being used for investigating fretting fatigue performance of nickel superalloys in contact with single crystal pads. The rig was fully commissioned in modified form in early 2007 and a number of fretting wear tests have been successfully carried out. During 2008 a number of minor problems with the hydraulic actuators and control systems have delayed the experimental work. However, the rig is now working again and a number of experiments have been carried out since early September. The next stage will be to define the experimental programme in more detail in consultation with Rolls-Royce. Matthew Davies is undertaking his Eng.D. work in this area, concentrating on modelling aspects.

2.7.9 Environment and time dependent effects on the fatigue response of an advanced nickel-based super alloy (M R Bache, Swansea University).

A series of DTI and TSB funded projects have helped optimise the process route for the nickel based super alloy RR1000, the UK's most advanced high temperature alloy for rotating disc components (compressor and turbine), including forging, inertia welding, heat treatment and final machining operations. The control of microstructure to provide fatigue resistance at the highly stressed bore cob while offering preferential creep resistance at locations around the rim has been achieved via specialist dual microstructure heat treatments.

The fatigue behaviour of RR1000 has been characterised [44] using double edge notch specimens incorporating shot peening. Evaluations were conducted at two test temperatures, 300°C and 650°C, employing baseline and dwell waveforms. The effects of air and vacuum environments plus prior exposure at 650°C were also assessed. It was demonstrated that surface oxidation does not control performance at the test conditions of interest. Rather, the modification to stabilised peak and mean stresses resulting from either thermal relaxation of peened stresses or a time dependent shake down of stress under mechanical loading governs ultimate behaviour.

2.8 OTHER ASPECTS OF FATIGUE

2.8.1 Damage caused by transportation (A Fox, QinetiQ, Farnborough)

Transportation by land, sea or air can expose aircraft components to potentially damaging levels of vibration. The way in which components are packaged and protected can be critical; so that fatigue life is not consumed outside normal aircraft operations. Examples where components could be at risk include the transportation of UAVs to remote deployment sites or the shipping of replacement aircraft parts to worldwide locations.

Vibration levels associated with some modes of transportation are severe and the need to understand the risk of causing physical damage, consuming fatigue life or reducing reliability/functionality is important, particularly because transportation is often an unmonitored exercise. The issue has attracted increased attention due to the increasing numbers of UAVs, of many different sizes, coming into service and the need to provide confidence that damage is not being accrued outside normal flight operations. Unlike typical manned aircraft, such vehicles often undergo significant amounts of transportation, of different types, including possibly traversing quite rough terrain to the launch site. Faced with the problem of advising UK MOD on the specification of qualification requirements for a particular vehicle, QinetiQ has developed a proven process for understanding and quantifying the detrimental effects of transportation.

This work has now been developed for general application and a draft leaflet has been prepared for inclusion in a future issue of Def Stan 00-970.

2.8.2 Teardown inspection programmes (D Taylor, QinetiQ, Farnborough)

Teardown inspection programmes continue to be a core element of ageing aircraft structural audits in the UK. Recent programmes include the front fuselage from a Harrier AV8B and wing from a GR5 variant, Tornado F3 centre fuselage and VC10 wings and fuselage. The Harrier programmes of course have added the extra element of Composite construction. The wing programme is continuing, but the front fuselage inspection revealed that the structure, which in general is relatively thin skinned, displayed little evidence of degradation. In fact, most teardown inspections have revealed that old airframes can be in remarkably good condition.

It is noteworthy that every project is different, and must be tailored to specific desired requirements, in order to make them cost effective; it is not possible to simply examine every detail in a complete airframe. Thus, teardown inspections can contribute to several purposes such as validation of fatigue analysis and inspection procedures as well as searching for hitherto unknown degradation by fatigue, corrosion etc.

In addition, they act as an audit of maintenance and repair procedures and modification embodiment. One interesting aspect to emerge is the evidence of inadvertent damage incurred during some inspections; this needs to be borne in mind when developing difficult inspections and even modifications.

A lot of practical experience has been gained over many years with structural teardown inspections, and this is now being applied into the relatively new area of system teardown programmes. QinetiQ is currently carrying out such investigations on 2 ageing aircraft types and the structures knowledge is proving very helpful. Of course there is an extended family of failure modes to consider, but for mechanical systems in particular, structures expertise, such as NDT, corrosion and forensic engineering is still used extensively, and, perhaps not surprisingly, fatigue can still be an issue.

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