Review of aeronautical fatigue investigations in the Netherlands during the period March 2003 – March 2005

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1.1 INTRODUCTION

The present review gives a summary of the work performed in the Netherlands in the field of aeronautical fatigue during the period from March 2003 until March 2005. The various contributions to this review come from the following sources:

- The National Aerospace Laboratory NLR
- The Faculty of Aerospace Engineering, Delft University of Technology (TU Delft)
- Stork Fokker AESP BV.

The names of the principal investigators and their affiliations are presented between brackets at the end of each topic title.

1.2 LOADS

1.2.1 Computer aided sequencing of aircraft loads and stresses for fatigue analysis and testing, CLASS (R. Houwink, NLR)

NLR has continued to develop the CLASS computer program. The CLASS program generates a sequence of loads or stresses automatically for an arbitrary aircraft structure, and was presented in the ICAF 2001 meeting. The CLASS program reduces the effort to generate flight-by-flight load and stress sequences for fatigue analysis and testing. CLASS has been used for aeroplanes (Airbus A380, A400M), for components (Airbus and Dassault movables), landing gears (F-16) and for helicopter parts (NH90 tail).
Class is operational at Stork Fokker AESP and at Airbus Germany and is currently being considered to become an all-Airbus preferred tool. A schematic of the CLASS program is given in figure 1.

1.2.2 Analysis of SD loads on aircraft in two-dimensional atmospheric turbulence (R. Houwink, NLR)

Under contract with Airbus Germany, further developments were made to the PSD procedure to calculate aircraft loads in 2D atmospheric turbulence. The PSD method, programmed in MATLAB and using input from MSC/NASTRAN analyses, was extended to include a full aeroelastic aircraft model with a linearised lateral flight control system. Also, a version of this procedure was developed to calculate the aircraft loads due to wake-vortex encounter, modelled as a 3D discrete gust problem. For the latter development use was made of the vortex-wake model developed as part of the EU project S-wake.

1.2.3 Load database system for fatigue analysis (R. Houwink, NLR)

A load database system is being developed to allow fast generation of fatigue load and stress spectra for different usage and configurations of one type of aircraft. It will provide input for CLASS (see 1.2.1) and subsequent fatigue analyses. Input in the database are results of manufacturer's load analyses for static and dynamic conditions.
Pre-calculated loads and stress-to-loads ratio's (SLR) are stored in neutral interface (NI) points for a grid of Point-In-the-Sky (PITS) and configuration parameters (covering flight envelope of the aircraft). Load and stress data in NI and PITS are delivered in advance by detailed load and stress analysis programs for all relevant conditions. Load/ stress spectra are generated for mission profiles and environmental data by interpolation in the database and further processed by CLASS into load or stress sequences for fatigue analysis. A schematic of the database is given in figure 2.

1.2.4 F-16 Landing Gear loads (P.A. van Gelder, NLR)

In support of the Dutch Industry (Stork SP Aerospace) NLR has carried out an analysis with respect to the potential benefits of (semi-)active damping control. With the use of simulation models results have been obtained for different conditions and configurations of F-16 landing gear, see figure 3. Also, a procedure to determine fatigue loads and fatigue load-sequences has been established in order to determine fatigue life consequences according to the Damage Tolerance concept in addition to the usually applied Safe-Life philosophy.
From the results it is found that the effects of damping control will strongly depend on the flight condition and aircraft configuration. Since the fatigue life of the nose landing gear is governed by lateral loads, damping control (of vertical loads) will hardly affect this. Damping control of the main landing gear was most effective for peak-load reduction during taxiing and fatigue-life extension of heavy configurations.

1.2.5 F-16 wing loads (P.A. van Gelder, NLR)

In support of the ongoing work in the area of Fatigue Life Monitoring for the Royal Netherlands Air Force (RNLAF), NLR is developing a procedure which couples state-of-the-art Computational Fluid Dynamics (CFD) codes (Euler, Navier-Stokes) with refined Finite Element Models (FEM) in order to calculate loads and stresses. The result from a realistic test case, of an F-16 configuration with and without a wing-tip missile for a 'heavy' manoeuvre case ($N_Z = 9$, Mach = 0.90, Sealevel), has been presented at the IFASD (International Forum on Aeroelasticity and Structural Dynamics) conference from 4-6 June 2003 in Amsterdam (NL) (Ref. 1). Currently these results are being verified with in-flight wing-deformation measurements.

1.2.6 Strain correlation at F-16 ASIP points with strain gauge results (R. Houwink, NLR)

The F-16 aircraft of RNLAF are equipped with strain gauges in 5 control points, in order to obtain information about the fatigue life of the aircraft in practice. The strain gauges form part of the FACE system developed at NLR for loads and fatigue monitoring purposes. Currently an investigation is being carried out to correlate the strains at the location of the FACE strain gauges to the strains in a number of ASIP control points. The strains in the FACE and ASIP points are analysed for a number of design load cases, using an FE Model of the F-16. A correlation analysis and regression analysis are carried out to describe the strains in the ASIP points as functions of those in the FACE points. It is intended to use the results of the analysis to obtain an improved prediction of the fatigue life of the structure near the ASIP points, by using the crack severity index (CSI) per ASIP point, rather than the CSI for a representative FACE strain gauge location only.

1.3 FATIGUE LOADS/USAGE MONITORING OF MILITARY AIRCRAFT

1.3.1 Structural fatigue load and usage monitoring of F-16 aircraft (F.C. te Winkel, NLR)

Structural load monitoring of the RNLAF/F-16 fleet is carried out by NLR as a routine programme since the early 1990s. In the past a more sophisticated electronic device capable of in-flight data reduction of a strain gauge signal replaced the ex-factory mechanical strain recorder. A representative sample from each squadron was instrumented. Later hardware upgrades made it possible to record some flight and engine parameters as well.
In the late 1990s a completely new fatigue monitoring system specified by NLR was developed by RADA and this was named FACE (Fatigue analysing & Air Combat Evaluation system). Main features are: a) increase to five strain gauge locations, two indicative for wing root and "outer" wing bending, two at the rear fuselage dealing with horizontal and vertical tail loads, and one in the fuselage centre section indicative for fuselage bending; b) a flexible selection of flight, engine, and avionics parameters available via the MUX-BUS; and c) fleet wide implementation allowing more extensive load monitoring of each individual aircraft.
A relational database application was developed for storing, managing and processing the raw measured FACE data, combined with flight operational data obtained from the RNLAF computerised maintenance/debriefing system CAMS. In the last years more emphasis has been given to a user-friendly interface for presentation of the results directly to the air staff by means of an interactive interface.

NLR is performs a similar loads and usage monitoring programme for the Belgian Air Force. For both Air Forces an intensive measuring campaign was started to collect Loads and Environment Spectrum Survey data for LM Aero to provide an update of the Fleet Structural Maintenance Plan. For the RNLAF this additional measuring programme has been completed. For the BAF this programme is in the final stages. Further it may be noted that the PoAF and USNAVY are also going to use the FACE instrumentation.

1.3.2 Maritime Patrol Aircraft, P-3 Orion (A.A. ten Have, R.P.G. Veul, NLR)

NLR has developed software to perform fatigue life calculations for the P-3 Orion maritime patrol aircraft. The software provides the operator with a validated fatigue life indicator based on the most critical wing location. The software package is currently in use by the Royal Netherlands Navy RNLN (as “PLEBOI”), The Spanish Air Force SAF (as “SAFORI”) and the Portuguese Air Force PoAF (as “POLICAL”). In ad-hoc applications it has also been used for usage and fatigue damage comparisons between Royal Norwegian Airforce RNoAF, USNavy, Royal Australian Airforce RAAF and Canadian Forces CF.
For the European Orion operators RNLN, SAF, PoAF and RNoAF, NLR has either specified, designed, co-developed, installed or implemented an improved P-3 Orion structural data recorder system to support the theoretical fatigue life calculations. For this purpose NLR recently developed a simple finite element model of the Orion wing, enabling application of proprietary stress-to-load ratios for direct fatigue damage calculations at specified wing locations.
The NLR specified data-acquisition system has advanced capabilities compared to similar systems in use with the USNavy, RAAF and CF, since it also measures wing loading on the ground (e.g. during taxiing) and has no dead-band zone in the c.g. and strain counting algorithms. NLR is also involved in the routine data extraction, storage and analysis process for the majority of the European P-3 Orion operators.
The RNLN Orion aircraft have recently been sold to Germany (8 A/C) and Portugal (5 A/C). On fatigue related issues, NLR will be involved in the aircraft transition process from RNLN to Germany/Portugal.

1.3.3 Transport aircraft C-130H-30 Hercules (M.J. Bos, NLR)

NLR has been tasked to develop and sustain a loads & usage monitoring programme for the C-130H-30 Hercules fleet of the Royal Netherlands Air Force. Within the framework of this project, both aircraft of the fleet have been equipped with a data acquisition system that samples the altitude, differential cabin pressure, airspeed and vertical acceleration. Together with flight administrative data (take-off and landing weight, mission type, etc.) from various other sources, the recorded data are stored in a relational database.
In parallel, Lockheed Martin has developed a set of so-called data blocks that quantify fatigue damage key values for a number of critical locations (‘control points’) of the C-130 airframe, covering the entire operating range of the RNLAF C-130H-30 flight envelope and configurations. These locations have been selected by LM Aero, based on structural test and service experience. They are the same as those used on the C-130J Structural Health Monitoring System and cover the outer wing, centre wing, forward, centre and aft fuselage. NLR has constructed a fatigue life monitoring system - the so-called Data Block Method - around these data blocks, using the measured flight profiles as input. This system now serves as a high-level management tool for the RNLAF to:

- keep track of the consumed fatigue life
- assess the severity of specific missions and mission types
- evaluate and possibly optimize the usage of the C-130 fleet
- assess/anticipate required structural modifications programs or individual aircraft Fatigue Life Extended (FLE) updates
- provide the OEM with high-quality data in case of modification programs
- rationalize decisions regarding tailnumber selection in the case of out-of-area deployment, fleet downsizing, etc.

The Data Block Method uses a data base of fatigue damage values for each possible point-in-the-sky, ground event (taxi, roll-out, take-off, etc.) and GAG-cycle. The underlying stress-spectra are based on extensive L/ESS measurements that have been performed in the past (world-wide baseline). The underlying Kt factors for each of the control points have been estimated from fatigue test data. The damage values for a complete flight are added together to obtain the total damage according to a linear

fatigue damage algorithm. A 50% probability crack would be anticipated if the sum of accumulated damage is equal to 1.
In principle the Data Block Method cannot be used to optimise the prescribed ASIP inspection intervals. It employs a Miner-approach to fatigue damage rather than using a non-linear method for crack growth prediction. The Data Block Method should therefore be regarded as a tool to determine the economic life for the individual aircraft of the fleet. It is felt, however, that to some extent and in a relative way it also provides information regarding the safe crack growth life of the various components that are covered by the control points.

1.3.4 Lynx helicopter (A.A. ten Have, NLR)

To achieve Lynx life extension and to monitor and control maintenance of the main rotor and sponson loads, the RNLN has performed a fleetwide installation of a multi-channel structural data recording system, called AIDA (Aircraft Integrated Data Acquisition system).
This AIDA system also replaces the formerly installed engine cycle counter. To date, more than 15,000 flight hours have been gathered with AIDA. These are being used for fleet planning and maintenance tasks. For the RNLN, AIDA clearly acts as a vital link for continuing usage of the Lynx fleet until full service introduction of its successor, the NH-90, has been achieved. In a support role, NLR safeguards validity of the various AIDA data processing steps.

1.3.5 Apache helicopter (D.J. Spiekhout, NLR)

In recent years the RNLAF has adopted the approach that for the different weapon systems available in the fleet some kind of load monitoring should be available. In agreement with the mentioned policy a pilot project has been started for the Apache helicopter to see if the already available recording equipment on board the helicopter can be used for the task of load monitoring.
For the Apache this means the recordings from the maintenance recorder. Besides the maintenance download a safety download also can be made available after a number of flights. On these safety downloads a large number of usage related parameters are present. The idea is to convert the flight regime recognition algorithms that were developed for the Chinook for use on the Apache.
In additio, exceedance curves for accelerations and for engine torque are to be investigated.
In support of these routine recordings, additional strain gage and vertical acceleration recordings have been made for a limited number of flights, including a number of ‘air display’ flights. The strain gage bridges were located in the aft fuselage of the helicopter. See also figures 4 and 5.

1.3.6 Chinook helicopter (A.A. ten Have, NLR)

Because the CH-47D Chinook is prone to fatigue, the Royal Netherlands Air Force (RNLAF) and the National Aerospace Laboratory (NLR) initiated a Structural Integrity Pilot Program to monitor and control aircraft degradation, in an effort to optimise the maintenance burden, operational availability and flight safety. An exceptional loading of the Chinook is given in figure 6.
Under the present research programme, three RNLAF Chinook airframes were instrumented, test flights (reference missions) were performed, followed by appr. 1,000 of operational flight hours. The objective was to investigate the feasibility of a global/local concept of load monitoring and to collect data for three specific research topics:
- comparison of RNLAF operational usage with Boeing design usage
- development of a Chinook Automatic Flight Regime Recognition (AFRR) algorithm
- development of an RNLAF Structural Integrity management tool (based on a damage index) for rotational as well as for non-rotational components
- development of a fatigue damage prediction tool (based on projected future usage).

Severe flight regimes with regard to fatigue damage (due to fuselage lateral bending) are:
a) hover and level flight with underslung load
b) high speed flight with 130 < v > 160 knots
c) heavy manoeuvring, such as roll reversals, evasive manoeuvres and quick stops and 45-60 degree AOB steep turns.

Measurements indicate that material stress due to lateral bending and local ‘hotspot’ stress are 10 to 20 times higher than material stress associated with airframe torsion and ground impact. The present RNLAF measurements match very well with the existing Boeing design data for the reference strain gage location, i.e. the local ‘hotspot’.

The results indicate that good insight can be gained into the character and the severity of the RNLAF CH-47D Chinook usage spectrum. As such, it will serve as a sound basis for the aforementioned research topics.
Detailed information and final results are published in a series of NLR CR reports (Ref 2, 3, 4, 5).

1.3.7 Prognostics and Health Management (D. J. Spiekhout, NLR)

A Prognostics and Health Management, PHM, system will be incorporated in the Joint Strike Fighter, JSF. The Dutch PHM Consortium, DPC, consists of Perot Nederland (specialised in adaptive and learning software development), TNO-TPD (sensor development) and NLR (load and usage monitoring). DPC has been awarded a contract to develop an Intelligent Help Environment, IHE, using PHM knowledge to assist the JSF support centre in solving problems and failures.
In the last two years NLR has been engaged in the Force Life Management project of the JSF. Goal is to support the future operator directly in order to get a good impression about the possibilities of the proposed system and the status of the implementation to date. Of course, changes have been made with respect to the originally proposed programme, and for the future operators it is useful to know these differences.
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1.3.8 MALE UAV (D.J. Spiekhout, NLR)

NLR is engaged in a programme to see if there is a need for usage monitoring in future UAV aircraft to be introduced in the fleet by the RNLAF. More specifically the question is to what extent there is a need for this kind of system, and for what components and systems and if this is cost-effective.

1.4 SERVICE LIFE ASSESSMENT AND EXTENSION PROGRAMMES

1.4.1 P-3 Orion Service Life Assessment Program (SLAP) spectra comparison (R.P.G. Veul, NLR)

The U.S. Navy (USN) and its Foreign Military Sale (FMS) partners (Canadian Forces (CF), Royal Australian Air Force (RAAF), Royal Netherlands Navy (RNLN)) have been conducting the Service Life Assessment Program (SLAP) to evaluate the fatigue life and damage tolerance characteristics of the P-3C.

a. comparison of the severity of usage spectra
As part of the NL work share contribution to the Service Life Assessment Program (SLAP) for the P-3C Orion aircraft, a USN/FMS spectra comparison was conducted at fourteen Fatigue Critical Areas (FCA). Fatigue analyses, using FAMS, and damage tolerance calculations, using FASTRAN, were used for the spectra comparison.
From the fatigue analyses the following conclusions were drawn. On average, the RAAF spectra show more than twice the life of the USN-85 spectrum, whereas the CF spectrum shows about 10 % and the RNLN spectrum about 50 % more life compared to the USN-85 spectrum.
From the damage tolerance analyses the following conclusions were drawn. The crack growth from a 0.005 inch initial flaw for the selected Analysis Areas (AA) is calculated. The unfactored life for the initial inspection interval and the repeated inspection interval for all analysed areas are calculated. For the lower wing surfaces retardation has a significant effect on the results, for the wing upper surfaces this effect does not play a role. For the nacelle location, FCA 622, retardation effect on the FSFT inspection interval results are clearly shown, while the stresses on the empennage and fuselage are too low to cause any beneficial effect.

b. comparison of analytical results with test data
A part of the FMS spectrum comparison programme consists of analytical calculations of the severity of different FMS spectra. These calculations have to be experimentally verified by coupon tests. NLR has performed a test programme using fatigue life coupon tests on FCA 301(wing root) and FCA 361 (Outer Wing WS 209 front spar lower cap/web attachment) subjected to FSFT, FMS (RAAF, CF, RNLN) and USN-50 (only FCA 361) spectra. Crack growth coupon tests have been performed on

FCA 301, FCA 361, and FCA 465 (outer side of inboard engine) subjected to FSFT and FMS spectra. The test program generated fatigue life data and crack growth data.
The fatigue life test results show that the analytical fatigue life prediction with FAMS is poor. FAMS over-predicts the lives for all spectra-location combinations, i.e. the cracks initiate sooner in tests than predicted by FAMS using a K_N of 3.45. The difference is larger for FCA 361 than FCA 301. The FAMS relative life values of the FMS spectra with respect to the FSFT spectra correlate well with the relative test life values for FCA 301 but less for FCA 361.
The FAMS computational procedure needs to be evaluated to explain or solve these issues.
The crack growth test results show that the FASTRAN prediction correlates well in the small crack region of 0.3 – 0.4 inch for all three areas. Above this crack length the deviation is large. The test set up is shown in figure 7 and some results are shown in figures 8 and 9.

c. tear down
The SLAP includes a destructive teardown and inspection of the Full Scale Fatigue Test (FSFT) article. The test article is divided into four major areas, Fuselage/empennage, Centre Wing, Left Hand Side (LHS) and Right Hand Side (RHS) wing. The NLR was contracted by NAVAIR to teardown and inspect the LHS wing (see figure 10).

The primary objective of the destructive teardown and inspection of the FSFT article was to obtain structural data for the re-baselining effort of the USN P-3C airframe. The inspection was focussed on assessing the extent of accumulated fatigue damage. Three tasks, i.e. disassembly task, NDI (Non Destructive Inspection) task and a coupon/fractography task, were defined to perform the teardown and inspection. The disassembly covers the complete dismantling of the wing. This included the removal and retaining of approximately 30,000 fasteners, and tagging and storing each part after dismantling (see figure 11).
NDI mainly consisted of BHEC (Bolt Hole Eddy Current) inspection. Up to WS 250, each hole in each layer was inspected with (single-layer) BHEC. From WS 250 up to the wing tip, the BHEC was done on an assembled structure (multi-layer BHEC). Other NDI methods used were visual inspection, Fluorescent Penetrant Inspection (FPI) and Eddy Current Surface Scan (ECSS).
Within the Coupon/Fractography task a total of about 5600 coupons were cut out of the disassembled parts (see figure 12). These coupons were broken open and inspected for cracks. In addition 16 LHS wing cracks were selected for detailed fractographic examination with the Scanning Electron Microscope (SEM).

The teardown and inspection of the LHS wing resulted in 1709 findings, which were entered into the teardown database. 1224 were related to NDI findings and 485 were related to actual cracks

1.4.2 Airbus A300/-600 Extended Service life (R. Geraedts, Stork Fokker AESP)

The Airbus A300 models B2 and B4 were developed in the early seventies for a design service goal of 48000 Flight Cycles (B2 model) and 40000/34000 FC (B4 models). In the early eighties the enlarged A300-600 was developed for a design service goal of 30000 FC. As the first aircraft reached their design life, an extended service goal was defined at up to 60000 FC for the A300 and 42500 FC for the A300-600 models.

Stork Fokker AESP is responsible for the design and production of the wing movable surfaces (Flaps, Slats, Ailerons, Spoilers and Airbrakes) of these Airbus models. To allow the extended utilisation for the wing movables, a review of the fatigue and damage tolerance capabilities and durability of these components was performed by Stork Fokker AESP. All the in-service experience was summarised and analysed. No significant general deterioration was found that could jeopardise the proposed extended utilisation. Detailed fatigue and damage tolerance analyses were made for critical areas. The necessity to make structural modifications, in particular with regard to Wide Spread Fatigue Damage, was investigated. No modifications appeared necessary. Based on fatigue and damage tolerance considerations (calculation and service experience) modifications to the maintenance programs were defined: additional tasks and revised inspection intervals and areas.

In the Structures Working Group meeting the findings were discussed with operators and airworthiness authorities.

1.5 ENGINES

1.5.1 Pratt & Whitney F100 engine usage monitoring (D.J. Spiekhout, NLR)

Since 1991, NLR performs operational engine usage monitoring of the Pratt & Whitney F100 engines installed in F-16 aircraft. For this purpose a number of multi-channel data-acquisition systems have been installed in the RNLAF F-16 fleet, registering parameters such as pressure, altitude, calibrated airspeed, engine rotational speed and power lever angle.
Engine damage accumulation is then calculated from the recorded engine cycles using specific algorithms. Furthermore, flight time and hot time envelopes (time spent in certain Mach number versus altitude regions) are determined to gain more insight in the RNLAF F100 mission profile. On a routine basis, these operational RNLAF engine data are transferred to the engine manufacturer for evaluation purposes and could be used as a basis for tailored engine maintenance procedures, e.g. affecting inspection intervals or retirement lives.
Since 1997 the Fatigue analysing and Air Combat Evaluation system (FACE) is being introduced in RNLAF F-16 aircraft. FACE is a comprehensive maintenance management and flight debriefing system developed by RADA Electronic Industries Ltd in Israel. This system enables the recording of approximately 100 engine parameters, of which a representative selection has been determined by Pratt & Whitney. Ad-hoc campaign measurements will always allow other parameters to be temporarily monitored.

1.5.2 Rolls Royce Gem 42 engine (A.A. ten Have, NLR)

NLR supports the RNLN with Cycle Life control of their Lynx Gem engines on a routine basis and employing the NLR developed AIDA data acquisition system. Currently, the RNLN is the only Lynx operator benefiting from tailored exchange rate in Gem engine maintenance procedures. On short notice, NLR plans to support another operator of AIDA with cyclic life control, i.e. Germany.

1.5.3 Single crystal material modelling (T. Tinga, NLR)

As operating temperatures in gas turbines increase, the application of single crystal materials is increasing. The use of these special materials has consequences for the material testing, but also for the modelling and life prediction of this type of material. Therefore NLR has developed the capability to perform life predictions on single crystal gas turbine components subjected to both creep and low cycle fatigue (LCF).
The modelling of single crystal material behaviour was continued by extending the capabilities of the previously developed slip-system-based creep model in two directions. Firstly the model was transformed into a multi-scale micro-mechanical model (see figure 13), taking into account microstructural details of nickel-based superalloys. The two superalloy constituent phases (γ and γ') were modelled separately and the morphology of the microstructure can be specified. This enables the analysis of the material response to microstructural degradation (e.g. precipitate coarsening, rafting). The model was implemented in the FE code MSC.Marc.
Secondly a fracture mechanics based method to predict crack propagation in single crystal materials was developed. The stress intensity factors were calculated taking into account the material anisotropy, and a criterion for the direction of crack growth based on the slip system resolved shear stress was selected.

1.5.4 Life assessment of gas turbine components (T. Tinga, NLR)

An integrated analysis tool for gas turbine life assessment was developed (see figure 14). The tool combines the NLR Gas Turbine Simulation Program GSP (engine performance), computational fluid dynamics models (heat transfer), finite element models (thermal / mechanical loads) and lifing methods to perform life assessments on a variety of gas turbine components. The tool was applied to real components of a military turbofan engine, like discs, turbine blades, air seals and combustor liners. Depending on the failure mechanism of the specific component, the life assessment included creep, low cycle / thermal fatigue or fatigue crack growth analyses. Furthermore, specific material models and lifing methods for single crystal components were developed, taking into account the material anisotropy and the effect of distinct crystallographic planes on crack propagation.

1.6 FIBRE-METAL LAMINATES

The historical development of Fibre Metal Laminates for aircraft structural materials has been presented at the previous Symposium in the Plantema Memorial Lecture by professor Boud Vogelesang (Ref 6). The continued research on Fibre Metal Laminates at TU Delft during the last two years covers analytical and experimental investigations and manufacturing related topics. A major contribution to the development of GLARE from laboratory status to aircraft application is given by Beumler, who addressed the certification aspects of strength properties in undamaged and fatigue damaged GLARE structures (Ref 7).

1.6.1 Fatigue initiation and propagation in FML's (J.J. Homan, R.C. Alderliesten, TU Delft)

Analytical investigations into fatigue initiation and crack propagation in GLARE have resulted recently in analytical prediction methods validated by extensive test programmes. The analytical approach for calculation of fatigue initiation in GLARE will be published in the International Journal of Fatigue by Homan (Ref 8). The analytical method for crack propagation calculation of the 'through crack' configuration in GLARE (equal crack lengths in all aluminium layers), including the phenomenon of interface delamination, has been developed by Alderliesten (Ref 9), see also figure 15. The model is presented in a paper in the Poster Session.
The analytical method for crack propagation calculation of cracks in subsurface layers in GLARE, as shown in figure 16, induced by combined bending + tension loading, including the phenomenon of interface delamination, was developed by Randell (Ref 10). The method is presented in a paper in the Symposium.

1.6.2 Residual Stresses in GLARE Laminates due to Cold Expansion (C. Rans, TU Delft)

A numerical investigation of the residual stresses in GLARE owing to the cold expansion process has been performed by Rans (Ref 11) in co-operation with Carleton University, Ottawa, Canada. Parallel studies in aluminium 2024-T3 provided good agreement with analytical models and finite element studies performed by other authors. Rans also investigated the rivet forming process in monolithic aluminium and GLARE. This is presented in a paper in the poster Session. See also figure 17.

1.6.3 Analysis of Fatigue Cracks in Mechanically Fastened Joints (J.J.M. de Rijck, TU Delft)

An experimental and numerical investigation into fatigue crack growth in mechanically fastened joints has been performed by De Rijck (Ref 12). The investigation covered the extension of the neutral line method, the development of stress intensity factors of joints, and the residual strength of GLARE joints.

1.6.4 Certification tests of HSS GLARE (P. Nijhuis, NLR

For the Airbus A380 freighter a new variant of GLARE is considered, the so-called High Static Strength (HSS) GLARE. HSS GLARE is built up of thin 7475-T761 aluminium alloy sheets and Cytec FM906 prepreg layers. The laminate is cured at a temperature of 180 °C and is more stable over a wider temperature range than standard GLARE. The Al 7475-T761 alloy gives the laminate higher static strength properties than the standard GLARE, which is built up with Al 2024-T3 alloy sheets. NLR has performed a large number of mechanical tests on HSS GLARE within the framework of an Airbus qualification and allowables programme for this material.
As part of this programme, fatigue crack growth, fatigue initiation and residual strength tests were carried out on three different spliced and un-spliced HSS GLARE lay-ups at room temperature, -30° and -55 °C. The results are described in Ref 13.

1.6.5 Investigation of riveted and bonded repair concepts for GLARE (W.G.J. 't Hart, NLR)

For application of GLARE in fuselage structures, effective repair procedures have to be available for incorporation in structural repair manuals (SRM).
In a repair programme 1000 mm wide panels with cut-outs of 200 mm x 350 mm were repaired with different repair materials and fastener types. Riveted repairs as well as bonded repairs were considered. Constant amplitude fatigue tests were performed at a stress ratio of R=0.1,and fatigue crack initiation at critical fastener locations was checked with the Eddy current inspection technique. For bonded patch

repairs (with a smaller cut-out), the Fokker bondtester was used for monitoring delamination initiation. After fatigue testing for 80,000 cycles the residual strength was determined to demonstrate the effectiveness of the repair. Most tests were done at room temperature, but for a limited number of test panels the effect of outdoor exposure was investigated also.

1.7 FATIGUE AND DAMAGE TOLERANCE STUDIES

1.7.1 Reliability analysis of structural components (F.P. Grooteman, NLR)

Traditionally, most aircraft components are designed according to two different philosophies: the *Safe Life* and *Damage Tolerance* approach. Both concepts cover a different part of the lifetime and are based on so-called deterministic models, in which the model parameters are constants (single-valued). In order to compensate for neglecting the natural variability of the model parameters (e.g. scatter in material parameters) and other uncertainties, scatter and safety factors are applied explicitly and implicitly (e.g. by means of an assumed initial crack length). The results obtained with both approaches can be very conservative, although the reliability of the design remains unknown.
Another, better, way of dealing with this variability of the model parameters is by means of a stochastic analysis, adding an extra dimension to the deterministic analysis, by introducing a range of values that can occur together with their chance of occurrence. However, performing a stochastic Damage Tolerance or Durability analysis does not make much sense, since the most important stochastic parameter, initial crack length distribution, is unknown.
An alternative life approach called SLAP (Stochastic Life APproach) has been developed by which the lifetime and inspection scheme of a component can be determined in a stochastic manner, covering the crack initiation period as well as the crack growth period in a realistic way. The approach can serve as an alternative to the current approaches, especially the Safe-Life and Damage Tolerance approaches, resulting in more realistic predictions of the lifetime and inspection scheme.
Instead of starting the life analysis at the start of the service life, another approach is to start the analysis at the end of the service life by constructing the failure distribution. This distribution (unlike the EIFS distribution) can be verified afterwards using inspection data that becomes available during the service life. In the design stage this distribution will be unknown, but with a limited number of tests and/or experience from the past a conservative lower bound can be generated. Based on this distribution a conservative estimate of the inspection scheme can be obtained guaranteeing the required safety level.
In order to subsequently reduce the inspection effort, the obtained conservative failure distribution has to be updated when service life information (failure data: cracks found and non-failure data: service time) becomes available. Even before reaching the initial inspection the current service lives of the various components can be used to obtain an improved estimate of the failure distribution and subsequently the inspection scheme, thereby reducing the conservatism of the approach. In this way an **adaptive** scheme can be constructed leading to a minimal inspection effort for the required safety level.
The approach consists of three steps:

- Construct the failure distribution or a conservative estimate
- Backward crack growth analyses to determine the initial inspection time and corresponding crack size distribution
- Forward crack growth analyses, including inspections to determine the probability of failure.

Grooteman (Ref 14) gives more details, discussing the approach for a realistic application. It is emphasised here that the approach is adaptive and the obtained results should be updated by repeating the analysis when service life information becomes available, thereby improving the failure distribution and inspection scheme.

1.7.2 ADMIRE (M.F.J. Koolloos, NLR)

In the framework of the European project ADMIRE (Advanced Design Concepts and Maintenance by Integrated Risk Evaluation for Aerostructures) the NLR has developed a great deal of expertise on the area of stochastic damage tolerance methods. A large number of fatigue tests on simple lap joints were done to assess the stochastic fatigue behaviour. The test results were used to evaluate the EIFS concept with a newly developed integrated short crack / long crack model. Moreover, a new stochastic method called Adaptive Directional Importance Sampling (ADIS) was developed. The method, which is used as a shell around an existing deterministic code, can be applied to account for the natural variability of the parameters and other uncertainties during a fatigue analysis.

1.7.3 Fatigue properties of explosively formed titanium alloys (L. 't Hoen-Velterop)

Explosive forming is a technique that can be applied to form titanium alloys at room temperature. This low temperature results in reduced forming costs and reduced finishing work because there is no need for decontamination. Besides forming, explosive techniques can also be used for welding and cladding, where the low temperatures reduce the forming of intermetallic compounds, thereby enabling the joining of materials that cannot be joint by fusion welding techniques. In co-operation with TNO-PML, who did the explosive forming, the static and fatigue properties of explosively formed Ti-6242 were investigated and compared with the properties of the base material and superplastic formed material. Additionally, a few fatigue experiments were performed on the oxidation resistant titanium alloy β21S. The results showed that static mechanical properties of explosively formed materials were similar to those of the base material, while forming caused a small reduction in fatigue strength. The forming technique used had hardly any influence on the reduction in fatigue life with respect to the base material (see figure 18).
Preliminary results obtained on the explosively clad Ti-6Al-4V indicate that the defects present at the interface of the first generation cladded materials cause a reduction in fatigue life. Further research aims to improve the cladding process and thereby improve the fatigue performance of clad titanium alloys.
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1.7.4 Bonded Repair for Aircraft Structures (H.J.M Woerden, TU Delft)

In 2004, the research into bonded repair for aircraft structures was divided into separate projects. Bonded repair for ageing aircraft is investigated in cooperation with the United States Air Force Academy in the so-called "Repair Project" and focusses currently on bonded repair durability (Ref 15, Ref 16). See Figure 19.
Bonded (and advanced mechanically fastened) repair for commercial aviation is investigated in the 5th Framework European project "IARCAS" (Improve and Assess Repair Capability of Aircraft Structures) (Ref 17), see figure 20. The latter involves a project in which 14 European partners, including all Airbus branches, strive to reduce the downtime and increase the inspection interval of aircraft through the use and development of new and advanced repair materials, new repair methods (bonding), improved calculation methods and extension of allowable damage limits.
In both projects much experimental, analytical, and finite element modelling work has been performed in 2004 by TU Delft. The most important results in the projects are:

"Repair Project":
- Patch and aircraft structure surface pre-treatment has to be carefully controlled and performed correctly so that it does not become a cause for durability problems.
- Temperature and moisture have a significant effect on adhesive bond line properties, but due to the small load transfer length needed, compared to the bond line length available, the effect on patching effectiveness is minimal; a bonded patch repair is inherently fail-safe in this respect.
- The behaviour of the damaged aluminium aircraft structure at differing temperature and moisture levels seems to be the most influential factor for bonded repair effectiveness.

"IARCAS":
- Bonded repair offers a significant fatigue life improvement over conventional, riveted repairs, not only for ideally pre-treated configurations (CAA or PAA), but also for in-field pre-treatment solutions (grit blast-silane).
- Methods like flap-peening, interference fit, and increased rivet squeeze force offer some improvement in fatigue life for mechanically fastened repairs, but not even close to the improvement seen for bonded repairs.
- Glare repair doublers/patches can improve fatigue life compared to aluminium doublers by changing the crack initiation location.

1.7.5 Prediction of fatigue crack growth under variable-amplitude (VA) loading (J. Schijve, TU Delft)

The co-operation with professor Skorupa of the University of Mining and Metallurgy in Krakow was continued. The prediction model is a modification of well-known strip yield models. The modification was proposed by professor Skorupa. A paper was published (Ref 18) on the results of simple VA tests and miniFalstaff tests on sheet specimens of the Russian alloy D16Cz (similar to 2124). The paper does not yet include predictions. However, the fractographic observations indicate that is it not correct to adopt the CA data for predicting the crack length increments of large cycles in the VA tests owing to incompatible crack front orientations. The investigation will be continued.

1.7.6 Statistical Distribution Functions and Fatigue of Structures (J. Schijve, TU Delft)

A comparison has been made between three statistical distribution functions: (1) the log(N)-normal distribution function, (2) the 3-parameter Weibull distribution function, and (3) the log(N-N0)-normal distribution function. The third one is a normal distribution of log(N-N0), a function which was largely overlooked in the literature. The second and the third function both contain a statistical minimum of the fatigue life (N0) as a 3rd parameter, although mathematically in a different way. Both functions gave a good data fit of the results of 30 similar tests with a skew distribution, but it still has to be recognized that the distribution function is actually unknown. The physical significance of the estimated N0-value remains unclear. A major problem of fatigue life distribution functions is the extrapolation to low probabilities of failure, which cannot be supported by relevant experimental data.

In Ref 19, a summary is presented of different sources for scatter in laboratory test series and scatter of fatigue lives in service under practical circumstances. Although laboratory test data can be informative, it remains a difficult issue to account for scatter to be expected in service. Unfortunately, theories with a physical and rational basis for this problem do not exist.

1.7.7 Damage tolerance analysis of helicopters (M.J. Bos, NLR)

NLR has recently started a programme on helicopter damage tolerance. This programme - dubbed ‘HeliDamTol’ - aims to improve the capability to predict in-service fatigue crack growth in helicopter airframe components. A recent round-robin analytical exercise has shown that the present predictive capability of industry and institutes around the world is insufficient. The results indicated a large variation in the crack growth predictions, most of them being unconservative.

Based on the results of a literature survey, NLR has opted to investigate the fatigue crack growth behaviour in the near-threshold ΔK vs. da/dN regime and, at a later stage, to develop a methodology to easily convert a recorded history of flight parameters to a stress sequence at any desired location in the airframe. The objectives of the research of the near-threshold behaviour are to gain basic understanding of the load interaction effects in this regime under variable amplitude loading conditions and to generate inputs for the definition of improved fatigue crack growth models. The study is limited to conventional aluminium alloys that are used in the airframes of helicopter types that are currently flown or are about to be flown by the RNLAF and RNLN. The stress spectra will reflect the typical usage by these operators of those helicopter types.

The project involves both experimental and analytical work. Compact-tension specimen tests are currently conducted to determine the constant amplitude fatigue crack growth threshold values for a range of stress ratios R, from 0.1 through 0.8. For this purpose both the constant R load reduction method and the constant Kmax load reduction method are used. Load shedding is applied carefully in order to minimize load history effects.

Once the material-specific threshold values have been established, the effect of interspersed high-amplitude low-cycle loads will be determined. From past experience it is known that low stress intensity fatigue fracture is probably controlled by the maximum extent of crack tip cyclic plasticity, which for block programme loading is determined by the largest load excursion per flight block. This implies that constant amplitude fatigue crack growth rate data and the constant amplitude threshold stress intensity factor range, ΔKth, may be insufficient or inappropriate for predicting fatigue crack growth under variable amplitude loading. As a first step, compact-tension specimen tests will be conducted with simple underload sequences. The simplified stress sequences will be representative of real helicopter spectra, with many low-amplitude high R cycles and incidental high-amplitude low R underloads. The number of low-amplitude cycles in a block of loads will be systematically varied.

After that, similar experiments will be conducted with more realistic stress sequences, obtained from actual in-flight measurements.
The experimental work will include fractography and crack closure measurements. The results will be used as inputs to, and validation of, the theoretical modelling work. This will also consist of a non-linear FE analysis effort to study the effect of the crack tip constraint on crack closure under variable amplitude loading typical for helicopter airframe components.
For the definition of a reliable prediction tool an existing method will be updated. Possible (and available) candidates are the strip-yield model as implemented in NASGRO and ESACRACK and the CORPUS model that is implemented in the NLR in-house package CRAGRO. These models will be used to predict the experimental data. Depending on the nature of the prediction errors (i.e. whether deviations occur in the threshold regime, Paris regime or high da/dN regime) one or more of the models will be adjusted according to physical arguments, empirical data and/or the results of non-linear FE analyses.
Part of the exercise will be to incorporate the improved model in an initial release of a tool that can be used for the prediction and/or assessment of operational damage. This tool will also include other elements, such as an FRR and/or neural network module to translate operational usage data to stress spectra, and will be based on a risk & reliability assessment approach.
For the validation of the new models experiments will be conducted on realistic test articles that are representative of actual helicopter airframe components. Again, in-flight measured stress sequences will be applied. The experimental results will be compared with those obtained from analysis.

1.8 FULL SCALE FATIGUE TESTS

1.8.1 Fatigue certification of NH90 helicopter components (B. Vos, Stork Fokker AESP)

For the NH90 programme Stork Fokker AESP is responsible for the fatigue strength substantiation of the following components:
- Landing gear Pintle Axle: safe life item in 300M steel.
- Tail structure: hybrid structure of CRFP skins, spars & ribs and 7075 bracketry.
- Cabin Sliding Door – fuselage: fail safe item in Al 7075 and Ti-6-4 bracketry attachment (loss of door is catastrophic).

The certification of the pintle axle and the cabin sliding door will be done by analysis and are in progress. Detail fatigue tests for the particular bracket-to-CRFP attachment are in progress.

1.8.2 Tail structure full scale fatigue test (J.P. Roos, NLR)

As part of the ongoing NH90 certification effort, the NH90 tail module under Stork Fokker AESP responsibility will have to be subjected to a combined fatigue/damage tolerance test in accordance with FAR 29.571. Barely Visible Impact Damages (BVID) and production flaws that are at the threshold of detection capability are duly considered. The test is performed at NLR and supervised by Military Airworthiness Authority recognized NLR designates. The first 1000 hours of testing have been completed and clear the first series aircraft for delivery. With the FAR 29.571 flight loads survey in its final stages NLR designates and Stork Fokker AESP are now closely co-operating to finalize the fatigue spectrum. Once the new NLR test facility in Marknesse has been completed, the entire test stand will be moved from the old Schiphol facility to this new location. The final qualification fatigue test that clears the series aircraft for a full life of 10.000 flight hours (24000 flights) will be started soon after. The test set-up is given in figure 21.

1.8.3 Megaliner barrel tests (H. Hersbach, NLR)

Airbus Germany has carried out a test programme on a Megaliner barrel (see figures 22 and 23). This test was carried out at the Airbus facilities in Hamburg and was done in co-operation with Stork Fokker AESP and NLR. Stork Fokker AESP was responsible for the design and production of the GLARE structure, NLR participated in performing the test.

The overall objectives of the Megaliner Barrel Project were:
- Validation of the structural model (FEM) used for stress analysis.
- Verify design concepts that are typical for large aircraft design.
- Verify the structural behaviour of new materials (fatigue & static)

- Verify new manufacturing concepts with respect to feasibility, risk and cost.

Examples of new design concepts tested in the barrel are the influence of a double deck, skin-frame attachment, floor beam attachment, stringer/coupling and door reinforcement.
Examples of new materials are GLARE for skin material, CFRP for floor beams, 6056/6013 aluminium alloys for lower skins, 2524 alloy for skin material, new high strength aluminium alloys for stringers.
Examples of new manufacturing concepts are GLARE manufacturing concepts, concept of welding stringers to the fuselage skin (6056 and 6013 alloys).

The validation of GLARE structures was successful. The test revealed several structural flaws. NDI inspection methods for GLARE were tested and improved.

Unfortunately the test could not be continued as planned up to 60000 flights, but was ended at 45402 flights due to the fact that at that time the start of the full scale fatigue test on the A-380 specimen was foreseen.

1.8.4 Dassault Falcon F7X metal flaps, airbrakes, spoiler, and CFRP aileron (J. Waleson, Stork Fokker AESP)

Stork Fokker AESP is responsible for the design and tests of the Dassault Falcon F7X metal flaps, airbrakes, spoiler, and CFRP aileron. Full-scale fatigue and damage tolerance tests to be performed at NLR are defined for flaps, spoiler, and aileron. (see figure 24). Flaps are tested at fixed maximum extension on the wing. Spoiler and aileron are tested at fixed deployment angle in component tests.

Element fatigue tests at SKF-SARMA were defined for flap roller bearings and tracks. (see figure 25) Roller load is variable. It appeared that the temperature in the test is too high due to constant motion. Therefore the rollers have to be greased regularly in the test.

Tests at Aubert et Duval are defined to determine S-N curves, crack growth curves (Middle Tension Sample for R=-1, Compact Tension for R=0.1), and fracture toughness of material E16NCD13 of flap integral roller shafts.

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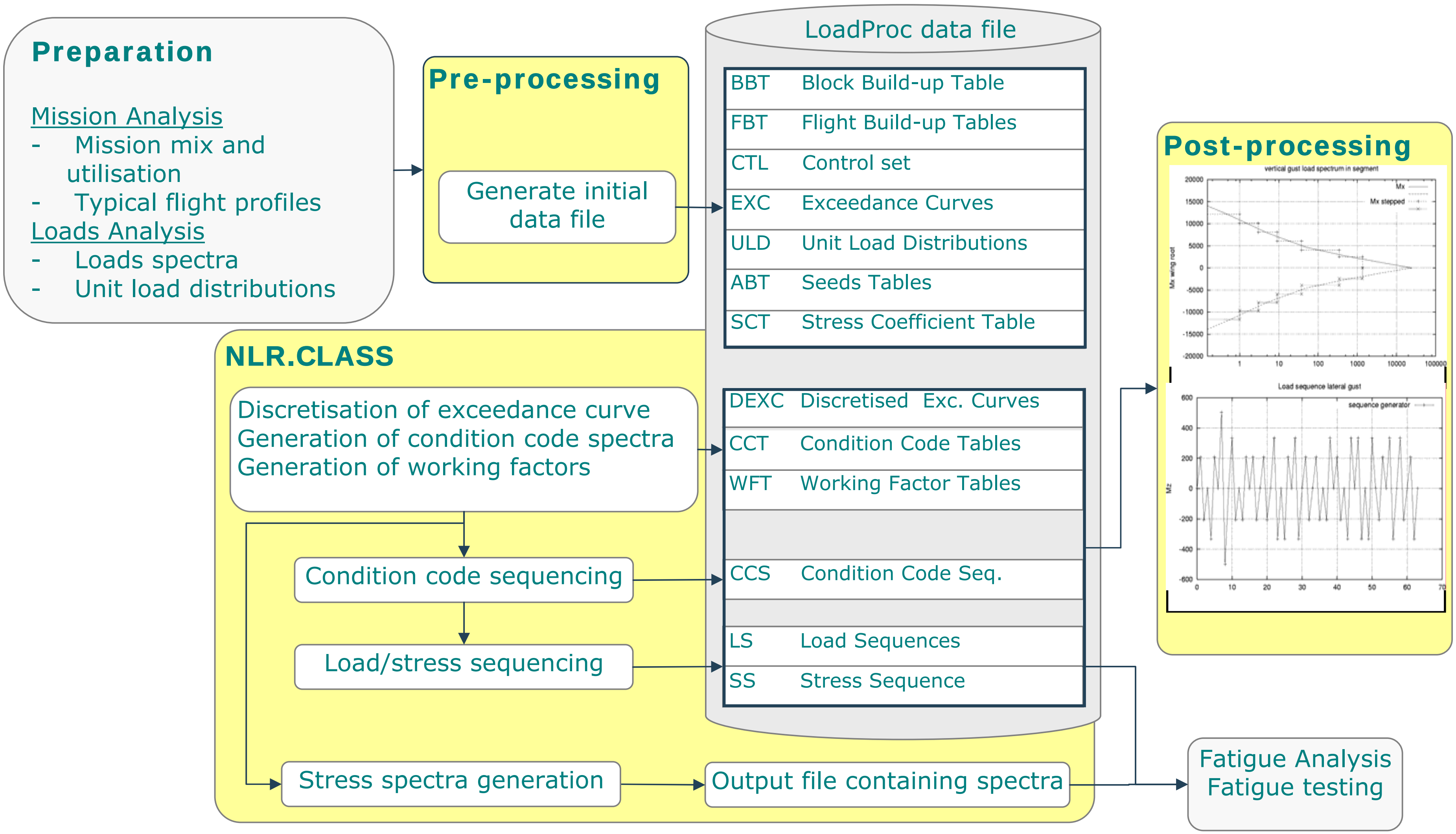
Figure 1 Flow diagram of the CLASS programme for generation of sequences for loads or stresses for aircraft structures



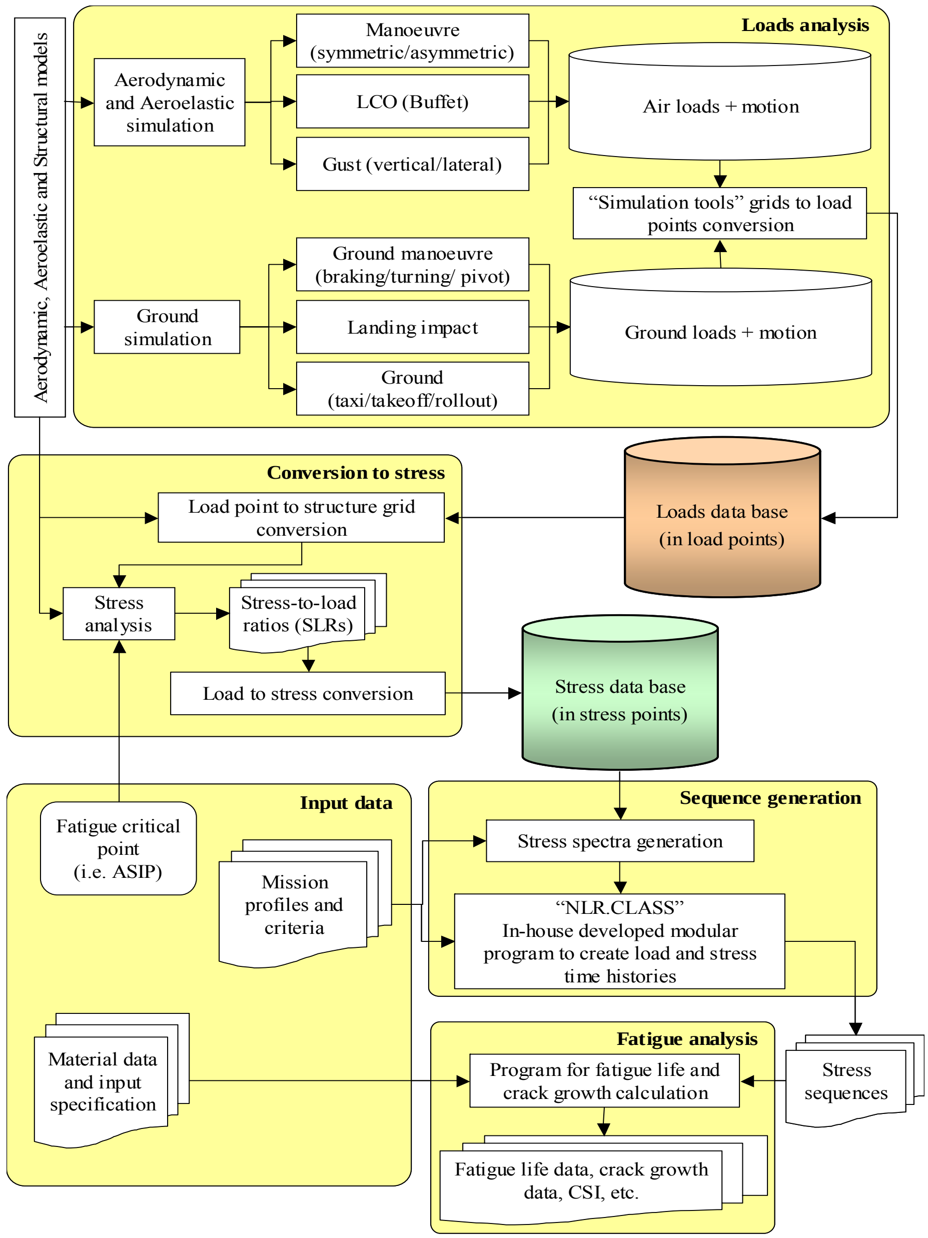


Figure 2 Schematic for a load database system for fatigue analysis

Figure 3 F-16 aircraft with extended landing gears

Figure 4 Apache helicopter

Figure 5 Instrumentation for strain and acceleration measurements in an Apache helicopter

Figure 6 A Chinook helicopter in an unconventional loading condition

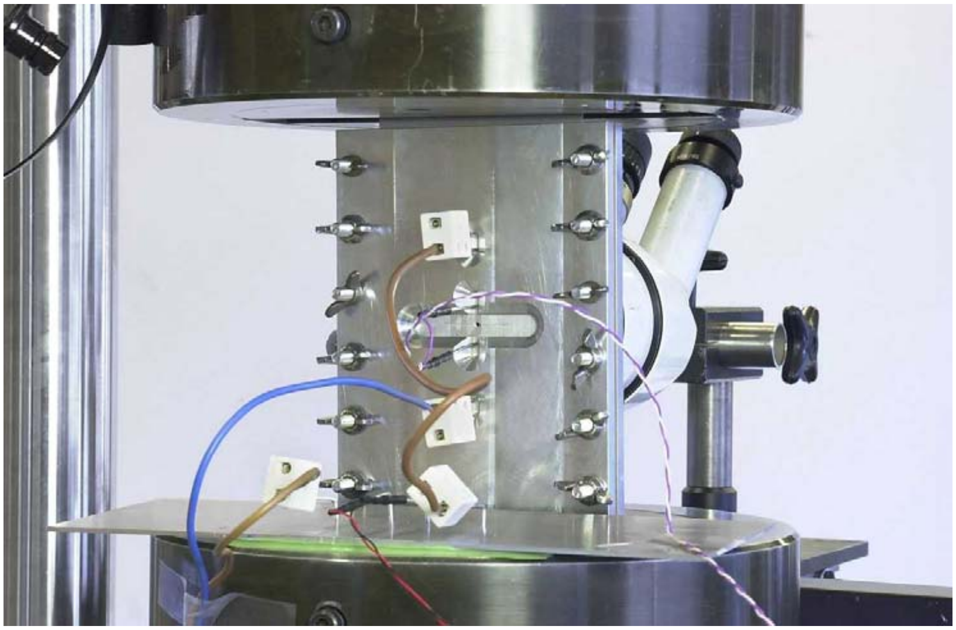


Figure 7 Test set-up for comparison experimental and analytical crack growth data in the framework of the service life assessment programme for the P3-C Orion aircraft

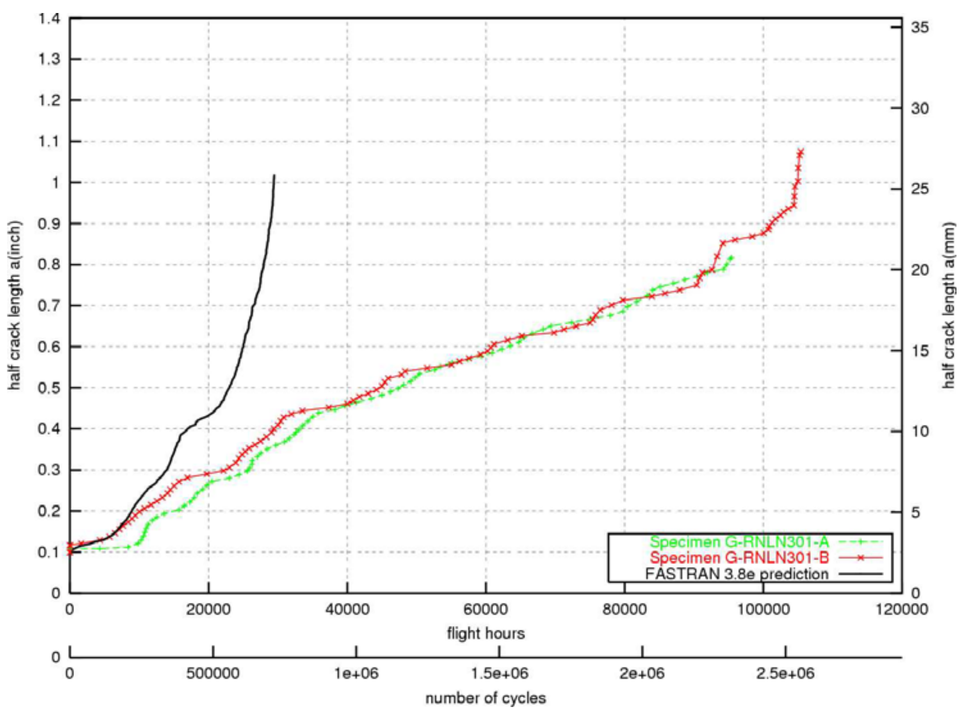


Figure 8 Comparison of crack growth data for P3-C Orion FCA 301 Front spar lower cap at OW WS 65 (wing root). (Black is analysis, Red and Green are experiments)

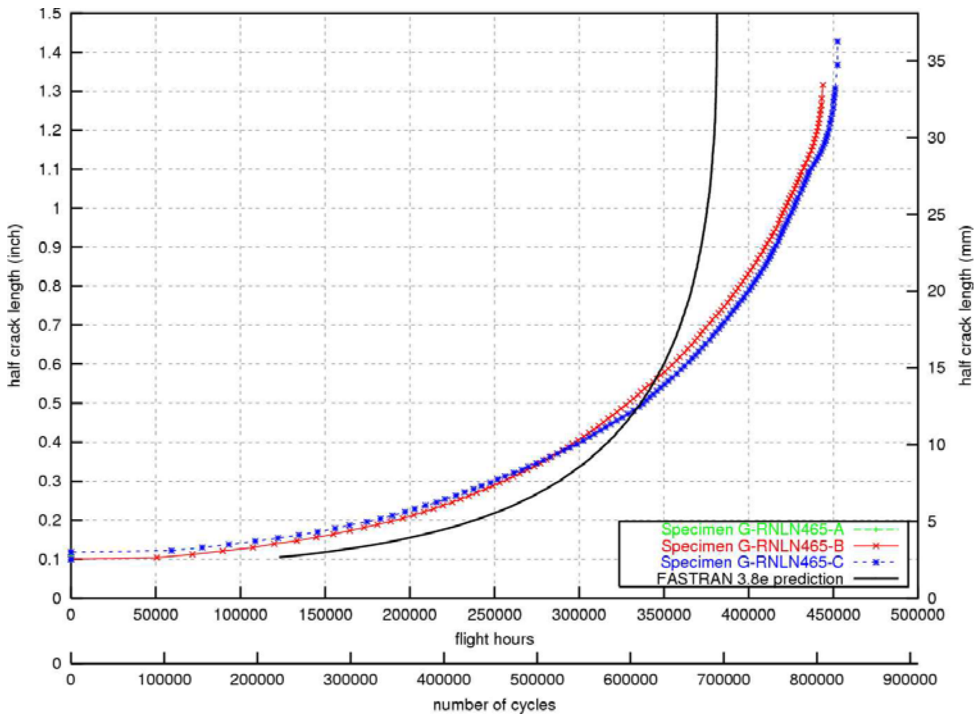


Figure 9 Comparison of crack growth data for P3-C Orion OW WS 209 Spanwise Splice at panels 3 & 4 (outer side of inboard engine) (Black is analysis, Red and Blue are experiments)

Figure 10 Part of the P3-C Orion ready for the teardown

Figure 11 Removing the fasteners to be able to inspect the fastener holes

Figure 12 Fastener holes specimen broken open to inspect the hole using microscope

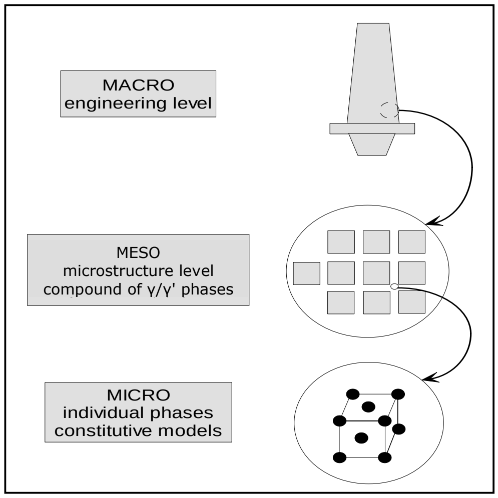


Figure 13 Schematic view of the different levels for investigation of crack forming

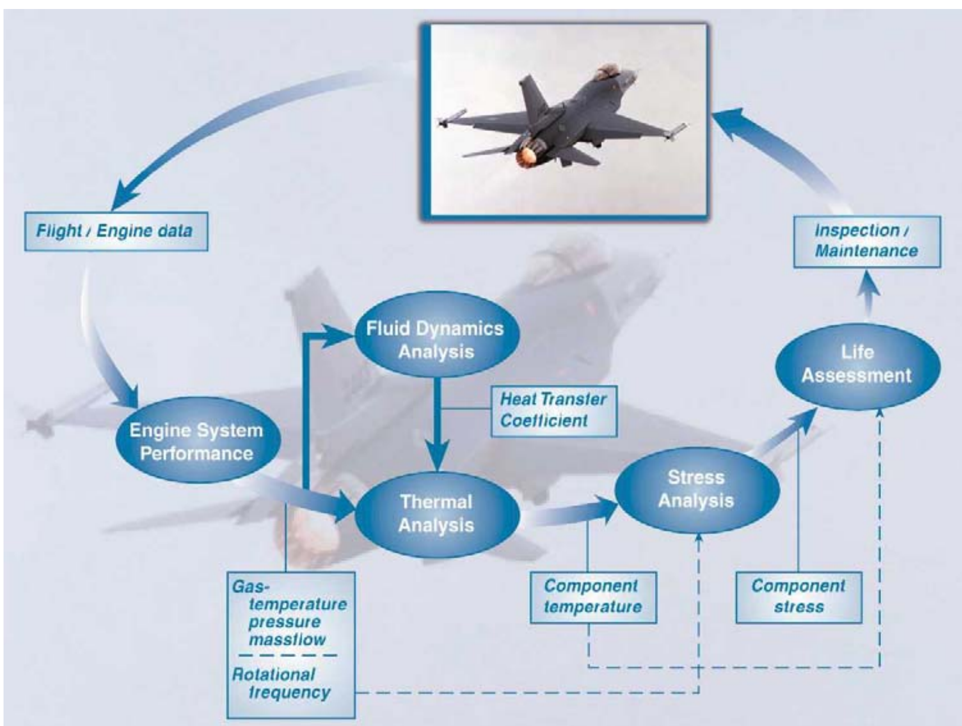
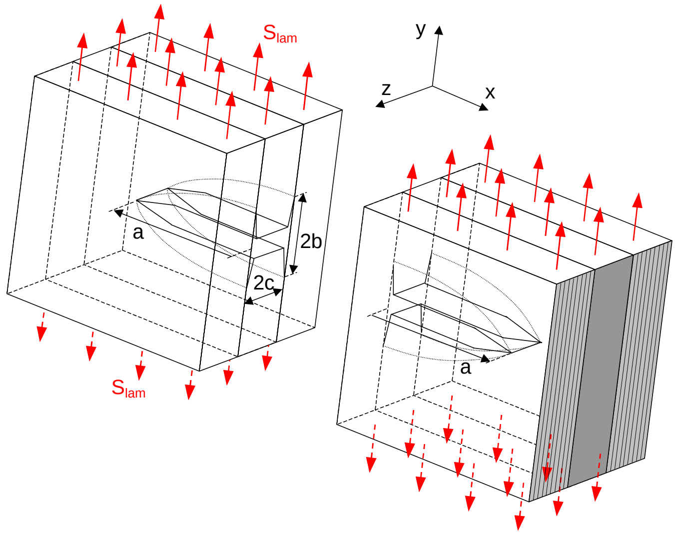
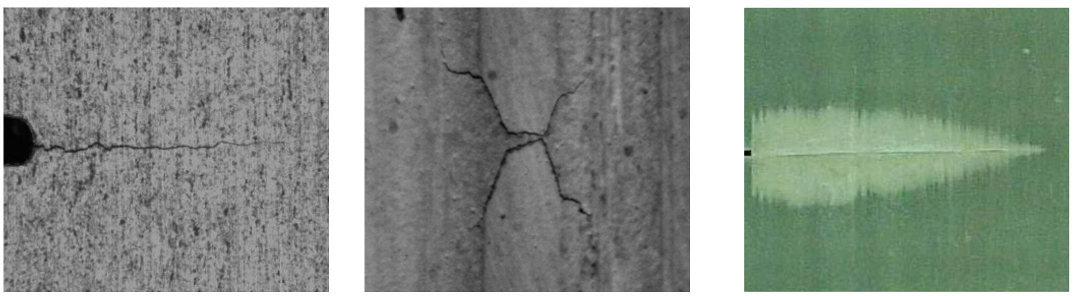


Figure 14 Different disciplines involved in the life assessment of gas turbine components



Fatigue crack geometry in Glare



Fatigue crack in aluminium layer of Glare

Crack and delamination at interfaces

Delamination after etching aluminium

Figure 15 Fatigue crack growth in Glare.

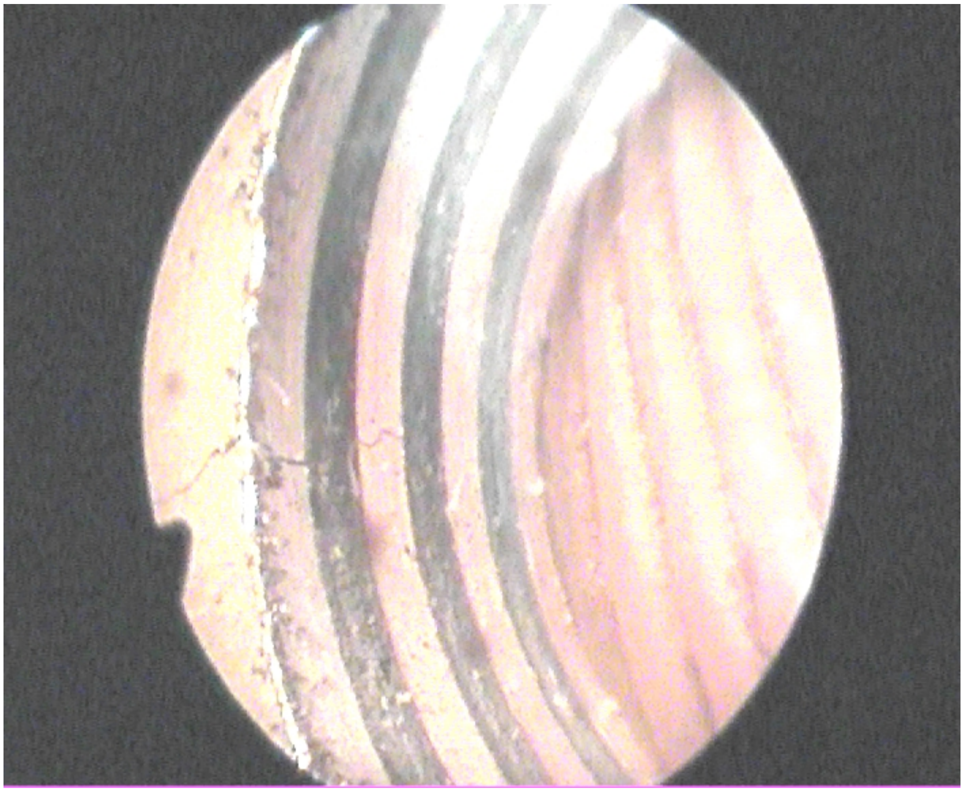
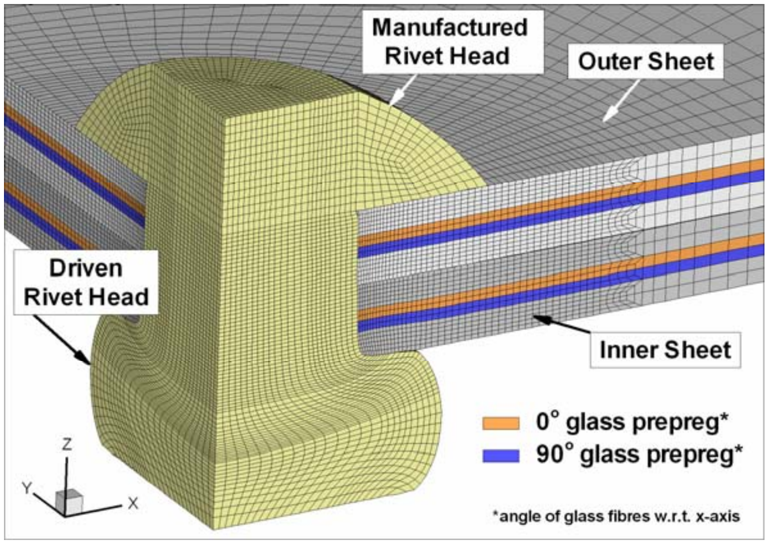
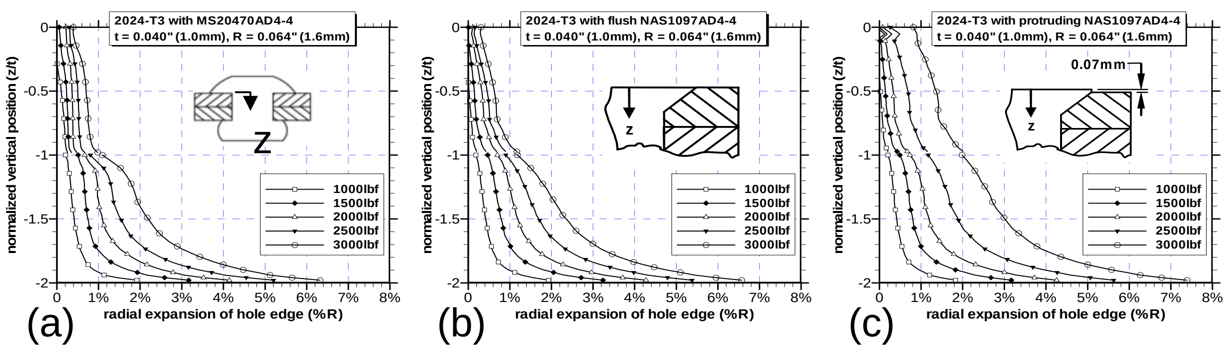


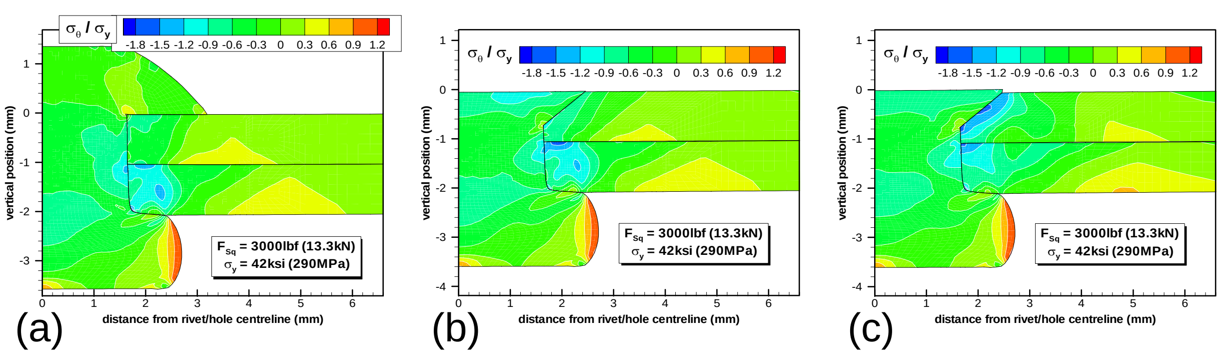
Figure 16 Fatigue cracks in surface and subsurface layers of Glare in a combined bending-tension specimen



Typical deformed mesh for quarter-symmetry rivet forming model showing lay-up orientation used for GLARE3-2/1-0.3 sheets



Comparison of radial expansion levels in 2024-T3 for (a) universal rivet; (b) perfectly flush countersunk rivet; (c) 0.07 mm protruding countersunk rivet



Comparison of residual tangential stress distribution in 2024-T3 for (a) universal rivet; (b) flush countersunk rivet; (c) 0.07 mm protruding countersunk rivet

Figure 17 Rivet forming in different rivet configurations

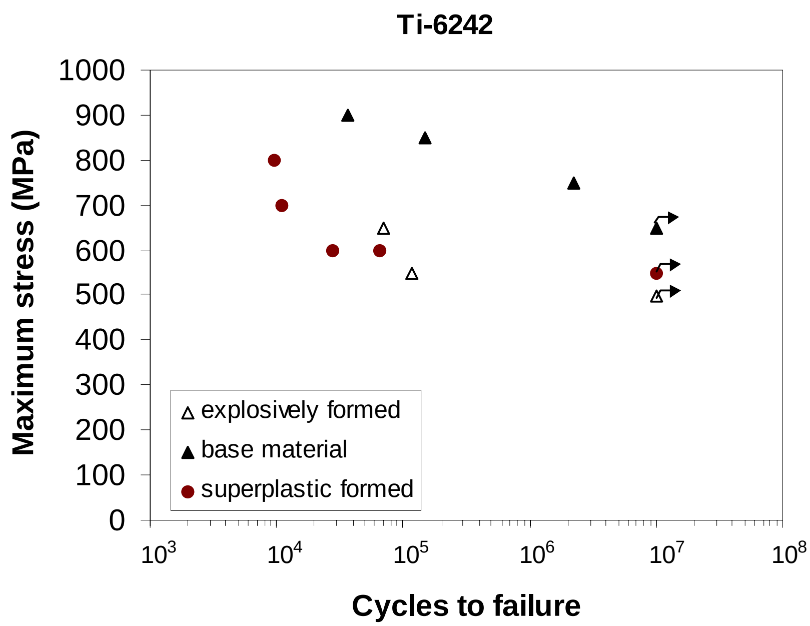
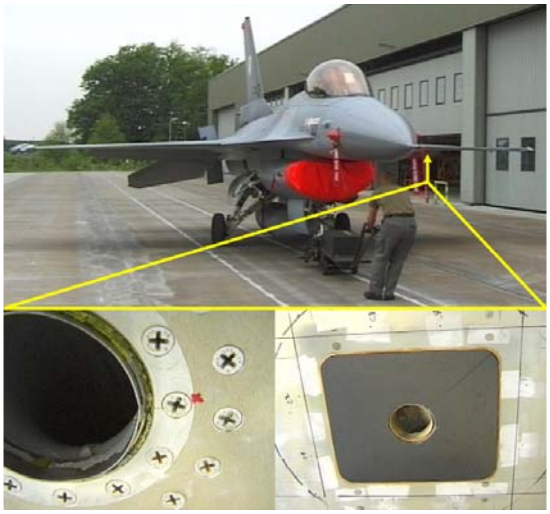
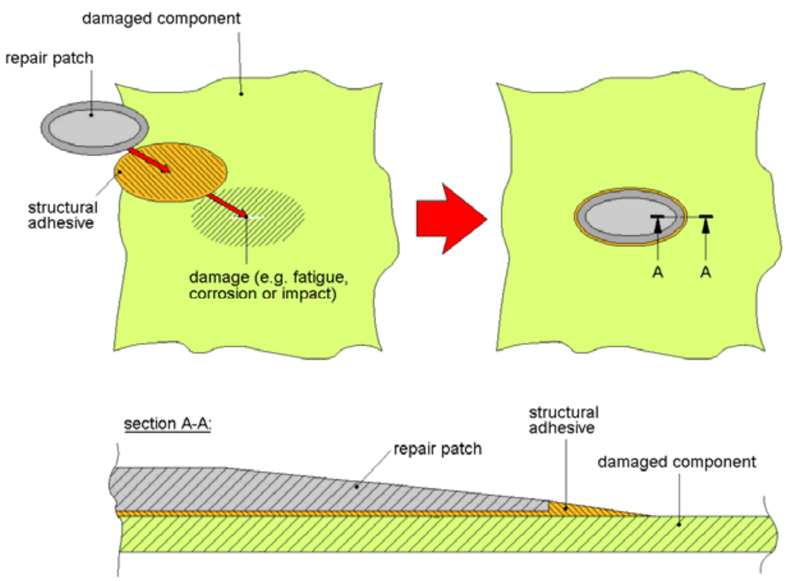
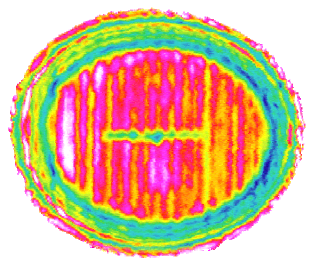


Figure 18 Constant amplitude fatigue test results (R=0.1) on smooth Ti-6242 samples. Base material data were obtained from the Technical University Hamburg-Harburg



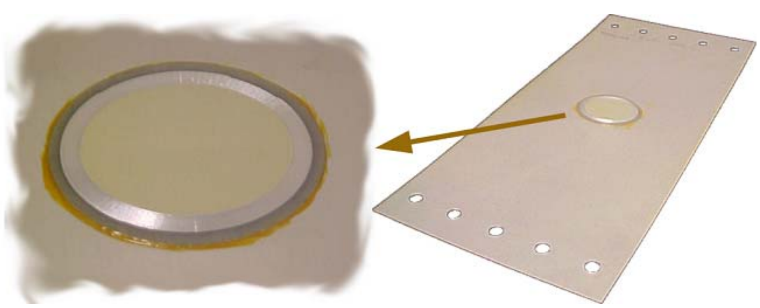
military application





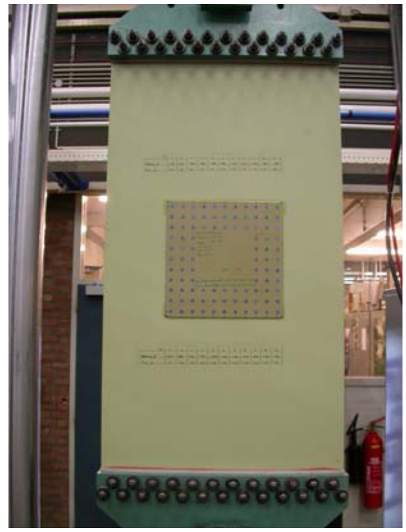
C-scan image of bonded repair

Lay-up of repair with tapering

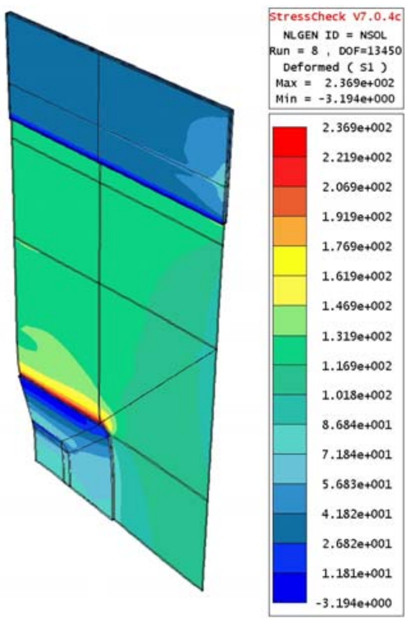


Example of specimen with repair

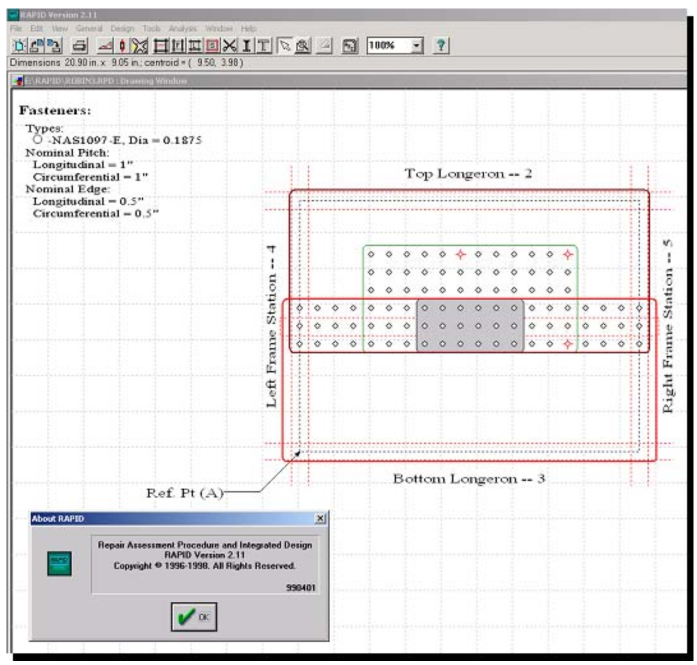
Figure 19 Patch repair for military applications



Bonded and riveted patch repair



Finite element analysis results



Rapid program model

Figure 20 IARCAS, Improve and Assess Repair Capability of Aircraft Structures

Figure 21 NH 90 helicopter tail section, fatigue test set-up

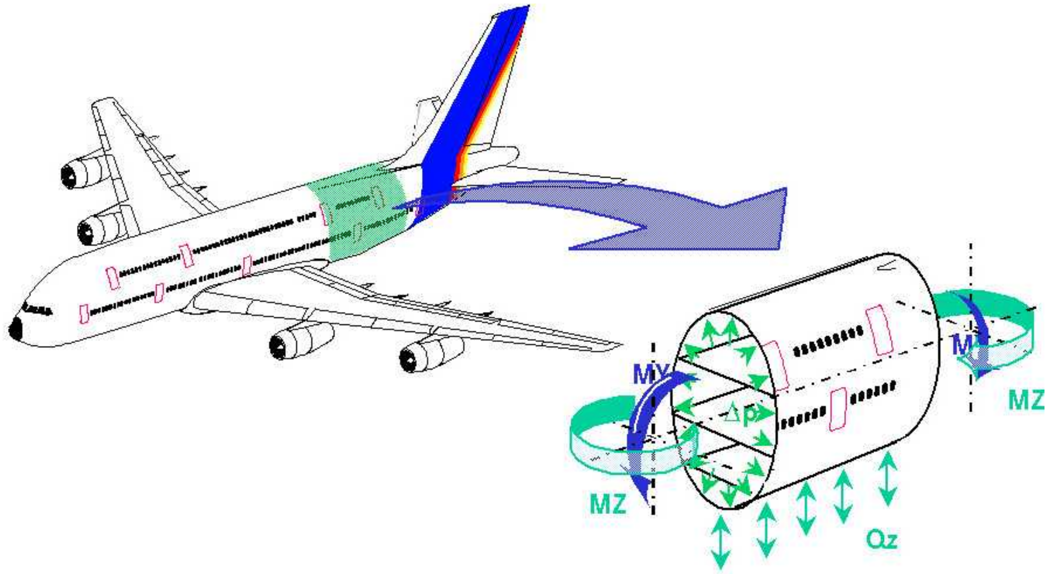


Figure 22 Location of the fuselage barrel section

Figure 23 Assembly of barrel specimen completed

Figure 24 Dassault Falcon F7X aileron fatigue test set-up

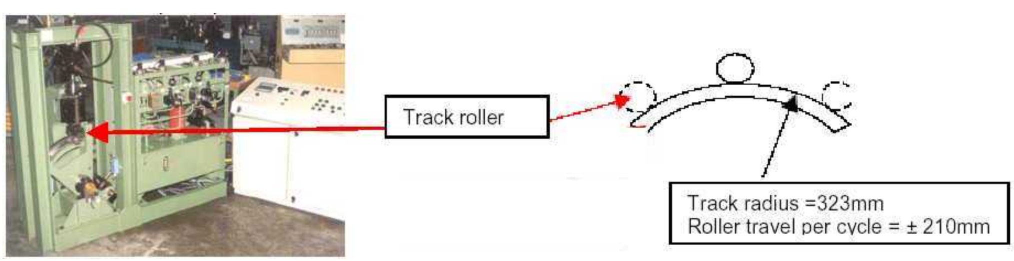


Figure 25 Dassault Falcon F7X track roller test set-up