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Review of aeronautical fatigue investigations in the Netherlands during the period March 2001 - March 2003

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ABSTRACT

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Summary

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1.1 INTRODUCTION

The present review gives a brief summary of the work performed in the Netherlands in the field of aeronautical fatigue, during the period from March 2001 until March 2003. 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 Aerospace Fokker Services
- Stork Aerospace Fokker Aerostructures.

The names of the principal investigators and their affiliation 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 (R. Houwink, NLR)

In support of Stork Fokker Aerostructures, at NLR the computer program CLASS has been developed which generates a sequence of loads or stresses automatically for an arbitrary aircraft structure. The program is based on the concept of condition codes, developed at NLR and used for instance for the Fokker 100 fatigue testing programmes in the early-eighties. Input data include the build-up of one or more typical flights by a number of segment/load type combinations, and load exceedance curves for each flight segment. These input data have to be generated by the manufacturer in advance after a thorough mission analysis of the aircraft under consideration. Condition codes are determined after identifying the relevant load events in a mission and discretisation of the corresponding exceedance curves. Load and stress sequences are derived from the condition code sequence using a working factor table, unit load distributions and stress coefficients. An updated version of the CLASS program was delivered to Airbus Germany and is being tested for application to transport aircraft in development.

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

Under contract with Airbus a method has been developed to calculate aircraft loads due to two-dimensional atmospheric vertical turbulence. The method is based on the results of investigations by Noback at NLR around 1990 and is the sequel to a FORTRAN demonstration program from 1991, updated in 2001 for application to a simplified A340 half model. The 2D turbulence modelling can be expected to yield more accurate results for larger aircraft, as it takes into account the lateral variation of the gust velocity. The current method is a Power Spectral Density procedure programmed in MATLAB. It uses results of a MSC/NASTRAN gust analysis for a full aeroelastic model as input data and generates loads and acceleration PSD spectra as well as design and correlated loads for a number of structural cuts. The program was applied to analyse effects of 2D atmospheric turbulence for A340 and A380 full aeroelastic study models. The models, interfaces to read NASTRAN files, and modules to generate cut loads were provided by Airbus Germany.

1.2.3 Fatigue load/usage monitoring of military aircraft

a. 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 nineties. 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 of each squadron was instrumented and final results were extrapolated to each individual aircraft to gain insight in the severity of operational usage. Later hardware upgrades made it possible to record some flight and engine parameters as well.

In recent years a completely new fatigue monitoring system specified by NLR was developed by RADA by extending their ACE pilot debriefing system with loads and usage monitoring functionality: FACE (Fatigue analysing & Air Combat Evaluation system). Main features are: the 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; a flexible selection of flight, engine, and avionics parameters available via the MUX-BUS; and fleetwide 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, see figure 1. Recently it became feasible to provide the end-users with the resulting fleet management information by means of an iterative interface (Ref. 1).

NLR is setting up a similar loads and usage monitoring programme for the Belgian Air Force, for which the formation system is being modified to facilitate both air forces. For both air forces an intensive measuring campaign will start shortly to collect Loads and Environment Spectrum Survey data for LM Aero to provide an update of the Fleet Structural Maintenance Plan.

b. 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"). For the above three European Orion operators, NLR has designed, installed and implemented a structural data recorder system to support the theoretical fatigue life calculations. NLR is also involved in the routine data extraction, storage and analysis process.

NLR also acts as On-site Rep at Lockheed, Marietta, Ga. for the RNLN in a multi-national full-scale fatigue testing programme of the P-3 Orion. The NLR contributions to this so-called "SLAP" programme consist of material characterisation tests on a more corrosion resistant material, and fatigue life and crack growth calculations for the different operational usage patterns of the SLAP-participants, i.e. US Navy, RAAF and Canadian Forces. Also, NLR participates in a co-development of an individual aircraft fatigue tracking programme for the Orion.

c. Transport aircraft (M.J. Bos, NLR)

The 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 recently 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 will be stored in a relational database that is currently being defined.

In parallel, Lockheed Martin is developing a set of so-called data blocks that quantify fatigue damage key values for a number of critical locations of the C-130 airframe, covering the entire operating range of the RNLAF C-130H-30 flight envelope and configurations. NLR will construct a fatigue life monitoring system around these data blocks, using the measured flight profiles as input. This system will serve as a high-level management tool for the RNLAF, to enable the comparison of mission types in terms of severity, to provide inputs to the evaluation of future fleet usage scenarios, and to rationalise decisions regarding:
- individual aircraft Fatigue Life Extended (FLE) updates
- tail number selection in the case of deployment, structural modification programmes, fleet downsizing, etc.

d. Counting methods (M.J. Bos, NLR)

Elaborating on its experience with rainflow load cycle counting that has been built up in the past, NLR is actively seeking to extend its knowledge in this field. It is a well-established fact that the way in which a counted load spectrum is resequenced has a significant effect on the results of a crack growth analysis. Resequencing therefore has to be done very carefully. Recently, a method has been studied in which the counted spectrum is arranged as a series of cycles such that the sequence of peaks is the same as in the uncounted spectrum. The result can be used directly in a crack growth analysis, without the need of generating a rainflow matrix. The resolution of the original load sequence is therefore not affected. Since the considered counting method preserves the original sequence of load peaks, crack growth retardation due to incidental overloads can properly be accounted for when used in conjunction with classical crack growth retardation models such as those due to Willenborg or Wheeler.

e. 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 has developed 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. As a concrete test case, an analysis has been carried out for the difference in wing-loading for an F-16 configuration with or without a wing-tip missile for a ‘heavy’ manoeuvre case, described by a normal load factor $N_Z = 9$ at zero altitude and Mach = 0.90.

1.2.4 Helicopters

a. 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. This AIDA system also replaces the formerly installed engine cycle counter. To date, more than 10,000 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.

b. Chinook and Apache helicopters (A.A. ten Have, NLR)

NLR has supported the RNLAF with structural integrity issues concerning the Chinook and Apache helicopter types. The activities concern the development of fatigue live monitoring concepts, aiming at optimising economy, safety and maintenance aspects (Ref. 2).

A three-year (2001-2003) Chinook pilot project for structural load and usage monitoring is ongoing, and will be ready by the end of 2003. By then it is planned that associated activities are in place to cover structural integrity issues for the Apache helicopter.

1.2.5 Prognostics and Health Management (H.H. Ottens, NLR)

A Prognostics and Health Management, PHM, will be incorporated in the Joint Strike Fighter, JSF. The Dutch PHM Consortium, DPC, consisting of Perot Nederland (specialised in adaptive and learning software development), TNO-TPD (sensor development) and NLR (load and usage monitoring) 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.

1.3 FIBRE-METAL LAMINATES (J. Schijve, TU Delft)

Historical aspects of the development of materials for aircraft structures are covered in the Plantema Memorial Lecture presented by Professor Boud Vogelesang in the opening session of the Symposium. It includes the development of the fibre-metal laminate concepts and the application of ARALL and GLARE. In view of the development of these concepts, reference should also be made to a book written by the late Professor Ad Vlot (Ref. 3). The development started with bonding of thin sheets to arrive at a more damage tolerant laminate. Later on, fibres were introduced in the adhesive layers, originally aramid fibres (ARALL) and later advanced glass fibres (GLARE). The book by Ad Vlot gives the inside story of ups and downs during several decades of developing a new material concept by a small group of people, under the inspiring and persevering guidance of Boud Vogelesang. Finally a highly fatigue resistant and damage tolerant material was obtained.

A major milestone is the application of GLARE on the Airbus 380. Various aspects of the application of Glare were covered during a Conference on GLARE in honour of the retirement of Professor Boud Vogelesang, the promoter of fibre-metal laminates. Contributions presented during this conference have been published in two books (Refs. 4,5). The books deal with technical and non-technical issues associated with the introduction of GLARE in aviation, e.g. weight saving, economical aspects, airworthiness regulations, inspections, maintenance, etc.

Standardised fibre-metal laminates are now available and production procedures have been developed. Full information can be obtained from the Fibre-Metal Laminates Centre of Competence (FMLC) in Delft. Research is still continued in co-operation with Delft University and the National Aerospace Laboratory NLR. Research covers work on analytical problems, experimental investigations and production topics. Research drivers are various applications and further improvements of GLARE options. Research has been started on FML grades with improved strength performances. Data so far are encouraging, including the fatigue performances of these products. An example of analytical work is presented in a paper by Alderliesten and Woerden in theICAF Symposium that will be held during the week.

1.4 ENGINES

1.4.1 Engine usage monitoring

a. Pratt & Whitney F100 engine (M.F.J. Koolloos, 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.

From 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 in 1999 by Pratt & Whitney. To date, more than 95% of the RNLAF F-16 fleet is instrumented with the FACE data acquisition system.
Ad-hoc campaign measurements will always allow other parameters to be temporarily monitored.

b. 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.

1.4.2 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).

A slip system based creep model, describing all three stages of creep behaviour, has been implemented in the finite element code MSC.Marc. Furthermore, a method to predict Low Cycle Fatigue life, also based on slip system shear stresses, has been defined. In this way a fully 3D life assessment can be performed on any gas turbine component. The model parameters for the single crystal superalloy CM186LC have been determined from a large number of creep and fatigue tests. The models have been validated on simple test bars, and their capability to predict single crystal material behaviour has been evaluated for actual gas turbine components. The F100-PW-220 first stage turbine blade has been used to demonstrate the prediction of fatigue life in single crystal components, see figure 2.

1.5 FATIGUE AND DAMAGE TOLERANCE STUDIES

1.5.1 Riveted joints

a. Effect of riveting die end on fatigue performance (M. van der Geest, Fokker Aerostructures)

A comparative test programme has been done for three types of riveting, in order to check the possible effect of the use of flat die ends on the fatigue performance of riveted joints. The types of riveting are:
1) Manual riveting with concave die ends (reference series, indirect riveting)
2) Manual riveting with flat die ends (indirect riveting)
2a) Manual riveting with flat die ends (direct riveting)
3) Automatic riveting with flat die ends.

Single lap joints were prepared from 4.0 mm thick 7175-T7351 aluminium plate, anodised and painted; 2017A rivets for manual riveting; and 7050 rivets for automatic riveting. The rivets had solid protruding heads, and the lap joint assembly was with interfay sealant and wet-installed rivets. Figure 3 shows the fatigue test results.

b. Effect of application of chamfer below fastener head (M. van der Geest, (Fokker Aerostructures)

Comparative fatigue tests were done to investigate the fatigue behaviour of assemblies with full or reduced hole chamfer under the fastener head. The test programme included three types of fasteners, namely titanium shear bolts, Hi-lites and Lockbolts, for four configurations:

- One series with high pinloading and a small fastener diameter (Ø 4.8 mm)
- One series with low pinloading and a small fastener diameter (Ø 4.8 mm)
- One series with high pinloading and a large fastener diameter (Ø 7.9 mm)
- One series with low pinloading and a large fastener diameter (Ø 7.9 mm).

The specimens were made using 7175-T7351 plate, anodised and painted, and in thicknesses in the range 2.5-6.5 mm. The low pin load specimens had a pad up configuration. The high pin load specimens were double lap joints. Assembly was with interfay sealant and wet-installed fasteners. Figure 4 shows typical results.

1.5.2 Influence of wire electrical discharge machining on fatigue of high strength stainless steel (L. Velterop, NLR)

S-N curves were determined for wire-EDM machined and abrasive jet machined specimens of PH 15-7Mo steel. Figure 5 shows the results. At longer lives the influence of wire-EDM was detrimental, but only beyond 10^6 cycles. On the basis of metallographic observations it was concluded that the detrimental influence of wire-EDM cannot be reduced by modifying the EDM process. Instead there has to be a finishing treatment, e.g. grinding, polishing or chemical milling, to remove the wire-EDM modified surface layer, especially brittle untempered martensite (Ref. 6).

1.5.3 Effect of Phosphoric-Sulphuric Acid anodising on fatigue of 7075-T6 aluminium (L. Velterop, NLR)

As part of a broader investigation into the suitability of Phosphoric-Sulphuric Acid (PSA) anodising to replace chromic acid anodising (Ref. 7), S-N curves were determined for PSA and chromic acid anodised 7075-T6 clad. Figure 6 show the results: the S-N curves were the same. It was concluded that PSA anodising can replace chromic acid anodising, but only if the corrosion protection by PSA is improved.

1.5.4 Effect of Diamond-Like-Carbon coatings on fatigue of 7475-T761 aluminium (W.G.J. ‘t Hart, NLR)

Wear-resistant Diamond-Like-Carbon (DCL) coatings were applied by chemical vapour deposition to both clad and bare 7475-T761 sheet. Before application of the DLC coating the specimens were covered with a homogeneous nickel strike 10-14 µm thick. The DCL coating was about 1.5 µm thick. Figure 7 shows S-N results for fatigue specimens with Kt = 1.06 and tested at R = 0.1. The DLC coating was very detrimental in comparison to the fatigue strength of bare 7475-T761, but much less so compared to clad 7475-T761. Cracks in the DLC coating resulted in many fatigue origins at higher stresses and shorter lives, see figure 7b. Further, it should be noted that the coating process was done at temperatures resulting in a 50% strength reduction of the 7475-T761 sheet (Ref. 8).

1.5.5 Fatigue crack growth tests on specimens of a Russian Al-alloy sheet material (J. Schijve, TU Delft)

Fatigue crack growth tests were carried out in co-operation with Professor Skorupa of the University of Mining and Metallurgy in Krakow (Ref. 9). The material was D16Cz, which is similar to 2124-T3. Centre-cracked specimens (M(T)), width 100 mm, thickness 4 mm, were tested under CA loading (several R-values) and VA loading covering CA loading with periodic overloads and underloads, and the miniFalstaff flight-simulation load history. Fractographic observations were made to obtain information about shear lip development, fatigue macro-bands and striations. The CA crack growth results agreed very well with data for 2024-T3 sheet material. The miniFalstaff crack growth data also agreed with results of a previous investigation on 2034-T3 sheet specimens. The fracture surfaces for all VA tests were predominately in the tensile mode with limited shear lip forming, see figure 8. This occurred in spite of high-amplitude cycles of OL or severe cycles in the miniFalstaff tests. This observation implies that crack growth prediction models cannot simply use CA base line data for severe load cycles, which in a CA test would produce crack growth in the shear mode.

1.5.6 Fatigue of a Friction Stir Welding (FSW) 2024-T3 stiffened panel (A.U. de Koning, NLR)

Figure 9 shows a 2024-T3 stiffened panel manufactured by Friction Stir Welding (FSW). In phase T-stiffeners, thickness 3 mm, were made by FSW. Subsequently, five of these stiffeners were welded onto a 500 mm wide 2024-T3 sheet panel. This was prepared for fatigue crack growth testing by cutting through the central stiffener and making a 40 mm centre crack in the panel. Fatigue crack growth tests were done for R = 0.1, with an S_{max} of 110 MPa. The test results are compared with ESACRACK predictions in figure 9b. The experimental behaviour lay well below the predicted values, and this is attributed to the beneficial effect of compressive stresses introduced by FSW. Post-test inspection of the panel did not reveal damage in the welds.

1.5.7 Certification of NH90 components (J. Laméris, NLR)

NLR has been actively involved in the period after 1995 in advising the Royal Netherlands Navy (RNLN) in their role as the official certification agency for those components of the all-composite NATO helicopter NH90 (RNLN) which are manufactured in the Netherlands. These components are the tail section, the doors and sponsons, made by Stork Aerospace Fokker Aerostructures, and the landing gear and intermediate gearbox manufactured by DAF Special Products. NLR's activities in the last two years consisted of reviewing and discussing the static and fatigue strength demonstration data package for flight clearance of the five prototypes. At this moment this work is now shifting to the review and discussion of the data being collected for the structural strength substantiation required for the certification of the production models.

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

Stochastic fatigue and crack growth analyses become more and more important, to account for the scatter found in material parameters, loading, etc. Many stochastic methods are available with which such a stochastic analysis can be made, of which a number of well known methods are the Monte-Carlo method (MC), Directional Simulation (DS), FORM and SORM. MC and DS are accurate, but inefficient in the case of small probabilities of failure ($p_f < 10^{-4}$), which is the case for most structural problems that are designed to be reliable. FORM and SORM are efficient but not accurate in the case of complex limit-states, such as: multiple design points (i.e. multiple optimums), multiple failure functions (series systems, parallel systems or combinations) and highly non-linear limit-states, when even a second-order approximation does not suffice.

Therefore a new stochastic method has been developed within the EU-project ADMIRE. This method has a broader application range and is in many cases (much) more efficient than other methods, i.e. requiring less computation time to reach a solution with comparable accuracy. The method is based on a directional sampling scheme in which the important directions, with the highest probability content, are sampled "exactly" and the other, less important directions, by means of a response surface approach. The response surface is constantly updated during sampling when extra information becomes available from the exact samplings, which makes the scheme adaptive. The method is therefore called Adaptive Directional Importance Sampling (ADIS).

The method has been implemented and severely tested on efficiency, accuracy and robustness with a large number of academic test cases covering a broad class of possible so-called limit-state functions. Moreover, the method has been applied successfully to two crack growth problems, including crack initiation, showing far better efficiency than standard sampling methods, while preserving accuracy. The method will be further explored within the EU-project ADMIRE.

1.5.9 Rotorcraft fatigue & flaw (damage) tolerance (J.P. Roos, NLR)

The Loads and Fatigue Department of NLR supports military operators and industry in the Netherlands regarding fatigue and structural integrity issues. It needed to expand its expertise to include rotorcraft to be able to cater for the anticipated increase in demand for support in these areas from our armed forces and national industry participating in the NH90 project. Civil airworthiness regulations and military and naval requirements concerning rotorcraft fatigue and flaw (damage) tolerance were reviewed in conjunction with other literature relevant to the subject. Rotorcraft specific sources of (potential) high-cycle and low-cycle fatigue were identified and described utilising actual helicopter data where available. Results are being documented in a report that will be completed in 2003.

1.5.10 Fatigue of Structures and Materials (J. Schijve, TU Delft)

In 2001 a textbook was published by Professor Schijve with the title "Fatigue of Structures and Materials". Exercises have been made available on a web site (Ref. 10). Professor Schijve was invited to present the opening lecture of the ECF-14 meeting in Krakow in September 2002 (Refs. 11,12) and to summarise the knowledge gained in the 20th century. The present state of the art is covered in this paper, which will also be published in a Journal (Ref. 13).

1.6 FULL SCALE FATIGUE TESTS

1.6.1 Testing of filament wound carbon/epoxy-metal flange drive shafts (W.J.G. 't Hart, NLR)

The objective of this programme was to demonstrate the performance of drive shaft components under torsional fatigue at room temperature and 100^0C. The drive shaft components were constructed of filament wound carbon/epoxy with metal end flanges, and were designed for ultimate load of 35 kN.m. Before fatigue testing the drive shafts were damaged by a 1 in. diameter impacter at an impact energy of 25 J. The fatigue tests were done at R = 0.1 and with maximum torsional fatigue load corresponding to 70% ultimate load. The tests concentrated on damage propagation from the impact site and the development of damage in the metal flanges and the composite-metal joint (Ref. 14). Figure 10 shows the test rig with a fatigue test component in situ.

1.6.2 Acoustic fatigue of a weapon bay door (Fokker Aerostructures, TU Delft, NLR)

Fokker Aerostructures, Delft University of Technology and the National Aerospace Laboratory (NLR) formed a team to promote the usage of new fibre metal laminates (FML) in the Joint Strike Fighter (JSF). The weapon bay door of the Boeing version of the JSF (X32) was selected to be an ideal component to demonstrate the good capabilities of fibre metal laminates with respect to acoustic fatigue. The goal of the project was to design, fabricate and test an FML-demonstrator model of the weapon bay door.

In the design phase of the project a finite element model of the weapon bay door was made to enable acoustic fatigue analyses. To validate the results of these analyses a full-scale fatigue test was conducted on the shaker facility of the NLR. The weapon bay door was placed in a rigid test frame and excited with an LDS shaker. The test frame was tightly mounted on the concrete floor of the test facility. Between the shaker and the weapon bay door an excitation accessory was placed to lead the vibration energy from the shaker into the door. The accessory was instrumented with a force sensor to measure the dynamic force and to control the shaker. A view of the test set-up is given in figure 11.

The dynamic properties of the weapon bay door were determined by performing modal analysis measurements. The measured and calculated natural frequencies and mode shapes showed a good agreement, which means that the finite element model is representative for the dynamic behaviour of the weapon bay door.

To measure the response of the weapon bay door during the fatigue test, several accelerometers and strain gauges were mounted on the weapon bay door. The sensors were connected to an FFT analyser to measure the vibration energy as a function of the frequency. During the fatigue test, acceleration levels of 100 g were measured on the weapon bay door, which caused an overall sound pressure level of 120 dB(A) in the test chamber. The test was stopped after 9% frequency drop of the first natural frequency. After visual inspection, damage was found at the position where the shaker force is led into the door. The lifetime of the weapon bay door was significantly longer than the required service life, showing the superior capabilities of the fibre metal laminate with respect to fatigue (Ref. 15).

1.7 FATIGUE PROBLEMS IN SERVICE

1.7.1 Airbus A300/-600 extended service goal (N.J. Fraterman, 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 the 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 programmes 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.

1.7.2 Fatigue failure of a helicopter rotor hub (R.J.H. Wanhill, NLR)

A Lynx helicopter from the Royal Netherlands Navy lost a rotor blade during preparation for take-off. The blade loss was due to failure of a rotor hub arm by fatigue. The arm was integral to the titanium alloy rotor hub. An extensive material-based failure analysis covered the hub manufacture, service damage and estimates of service stresses. There was no evidence for failure owing to poor material properties. However, fractographic and fracture mechanics analyses of the service failure, a full-scale test failure and specimen test failures indicated that the service fatigue stress history could have been more severe than anticipated (Ref. 16). This possibility was subsequently supported by a separate investigation of the assumed and actual fatigue loads and stresses.

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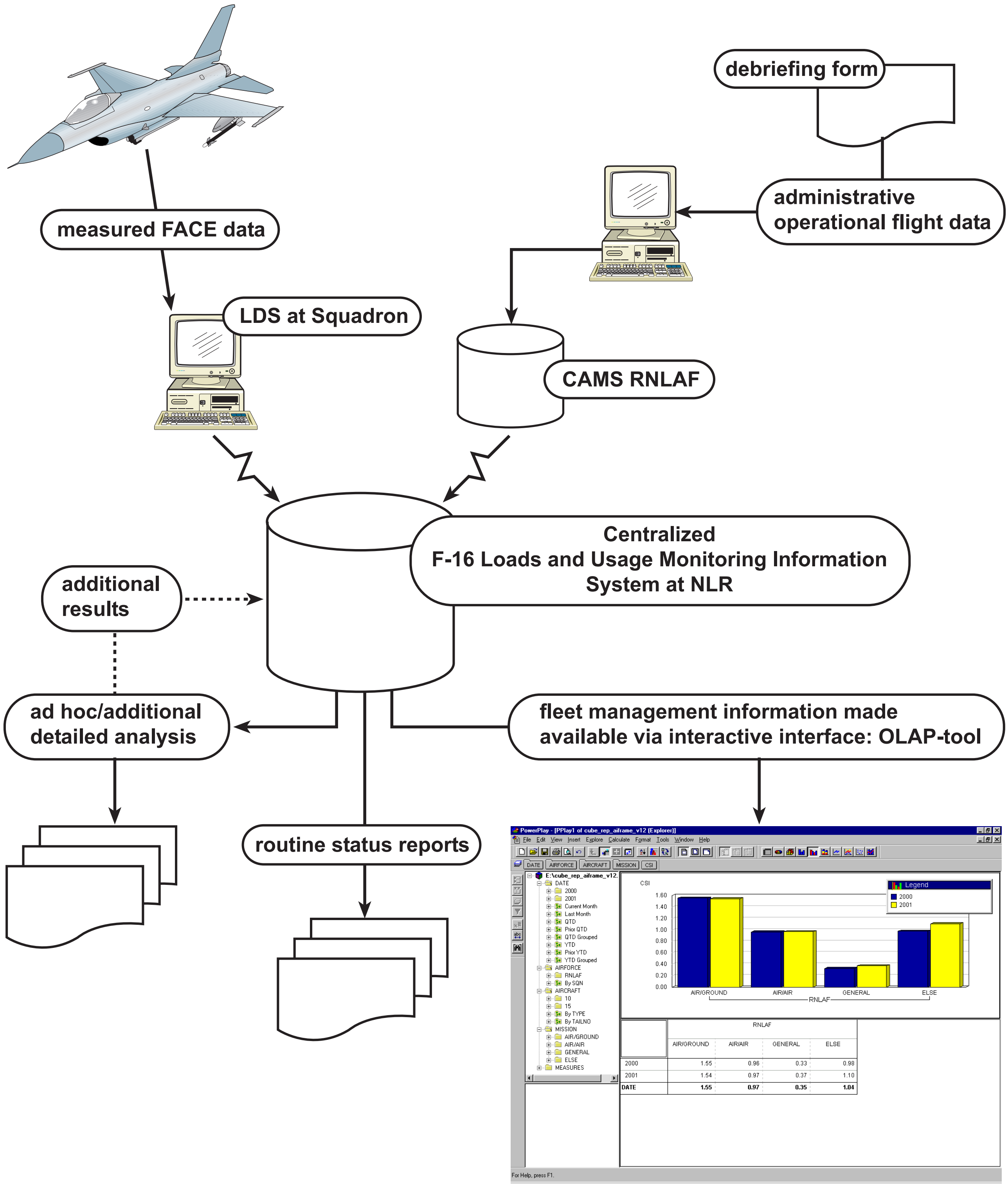

Fig. 1 Relational database application for FACE and CAMS (see subsection 1.2.3a)

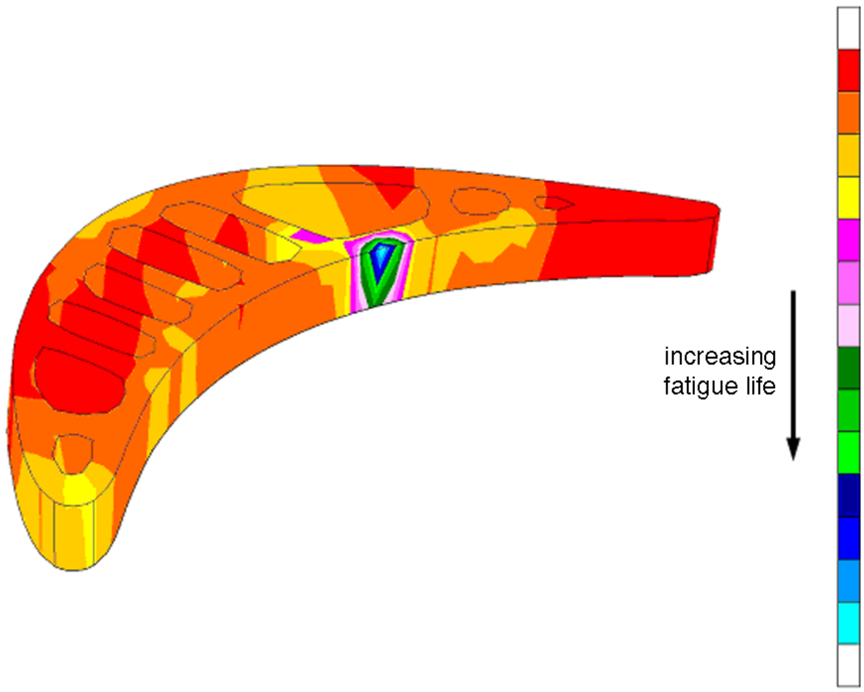

Fig. 2 Calculated fatigue life distribution (cycles) in a single crystal turbine blade (cross-section at half span; see subsection 1.4.2)

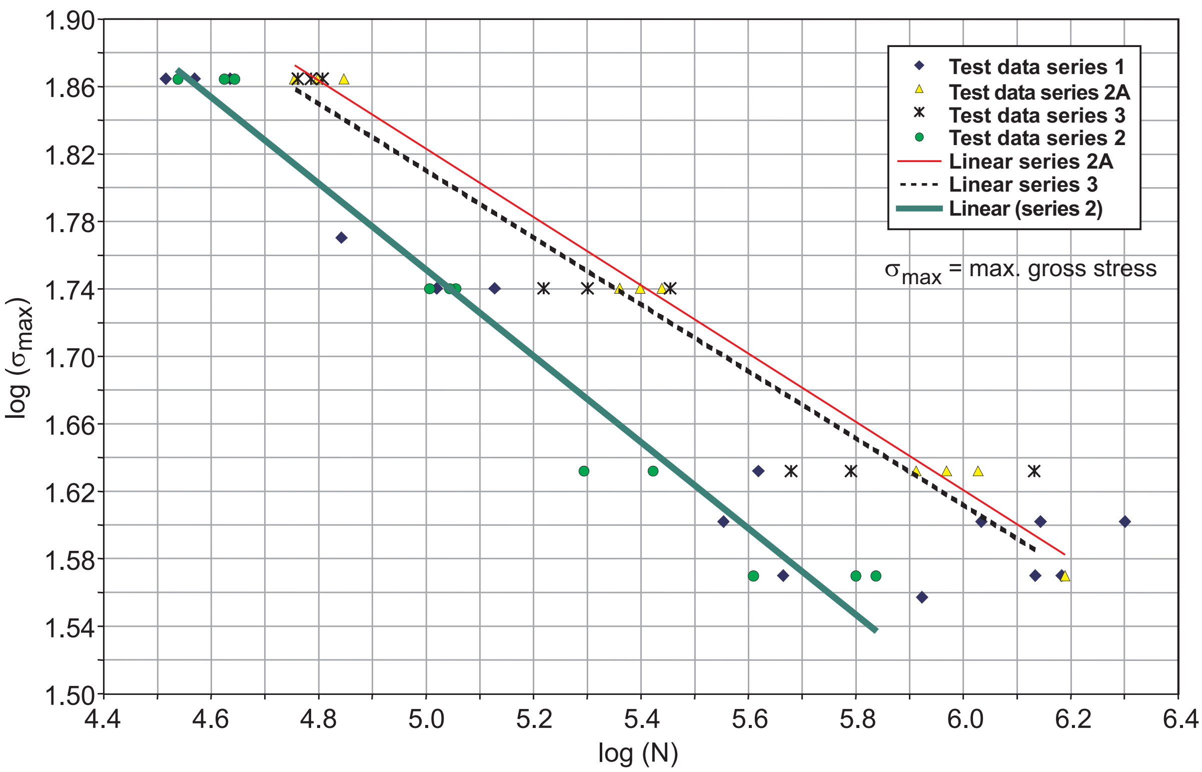

Fig. 3 Fatigue test results for riveted lap joints (subsection 1.5.1a)

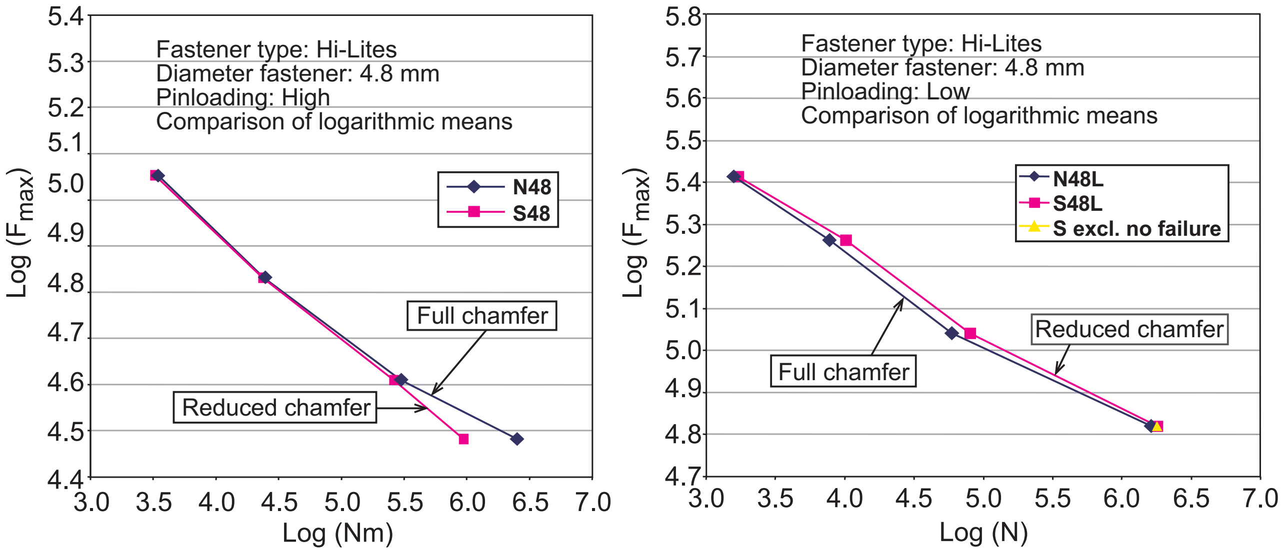

Fig. 4 **Example fatigue test results for high and low pin loaded joints (subsection 1.5.1b)**

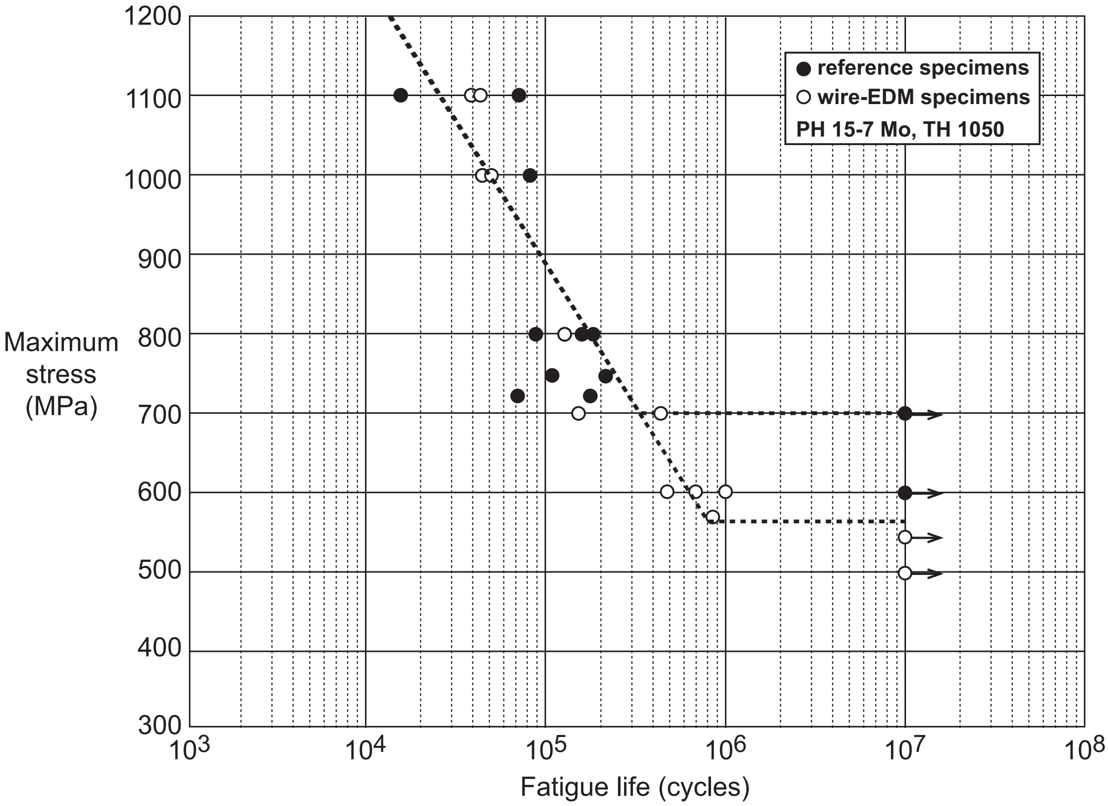

Fig. 5 **Effect of wire-EDM on fatigue of PH 15-7 Mo stainless steel (reference specimens were abrasive jet machined, K_t = 1.06, R = 0.1: see subsection 1.5.2)**

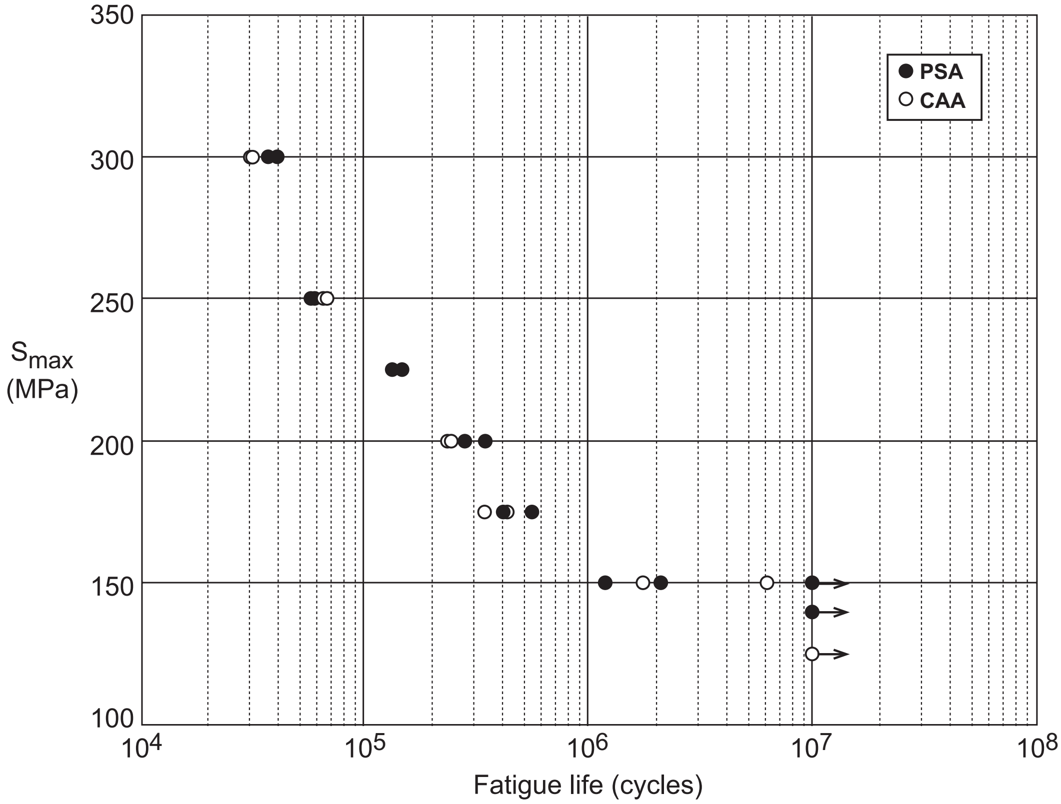

Fig. 6 Comparison of PSA anodised and chromic acid anodised 7075-T6 clad fatigue specimens, K_t = 1.06, R = 0.1: (see subsection 1.5.3)

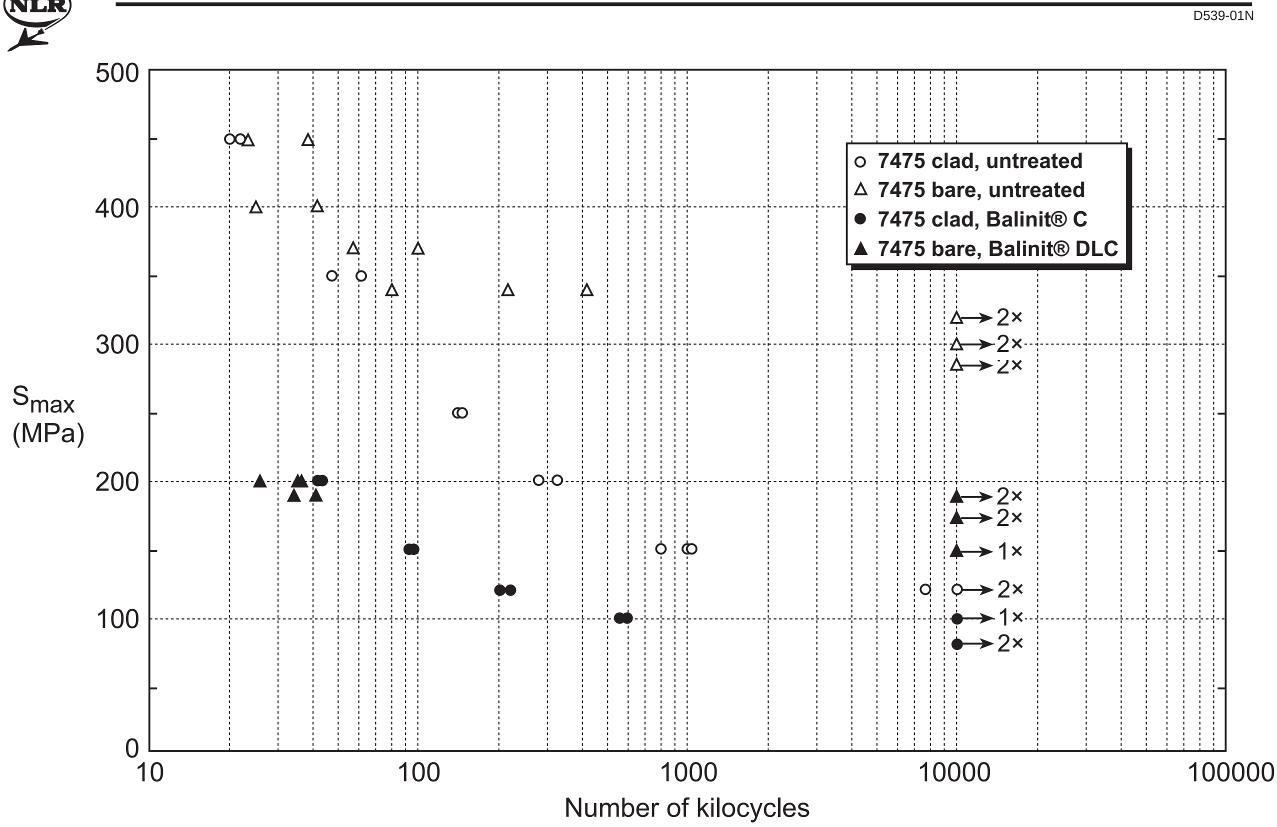

Fig. 7a Fatigue test results for 7475-T761 clad and bare sheet, with and without Diamond-Like-Carbon (DLC) coatings (see subsection 1.5.4)

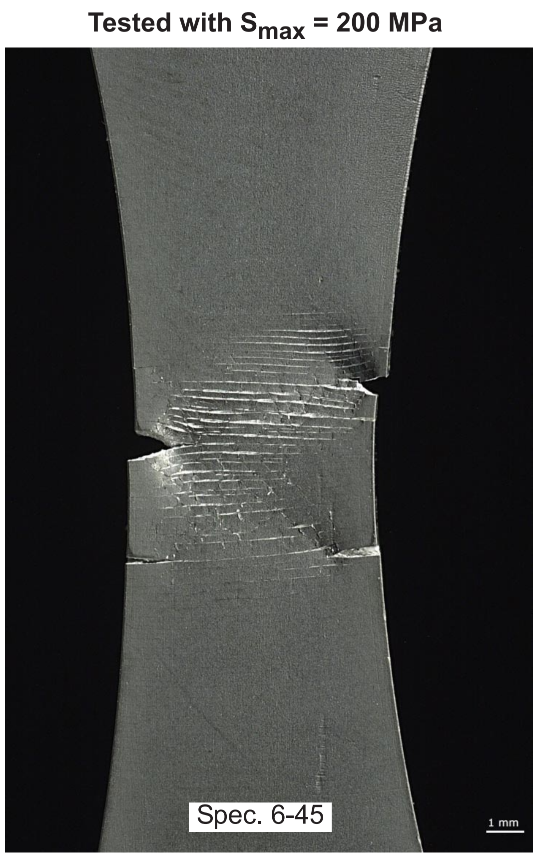

Fig. 7b Example of multiple fatigue crack initiation in a DLC coated specimen [Ref. 8]

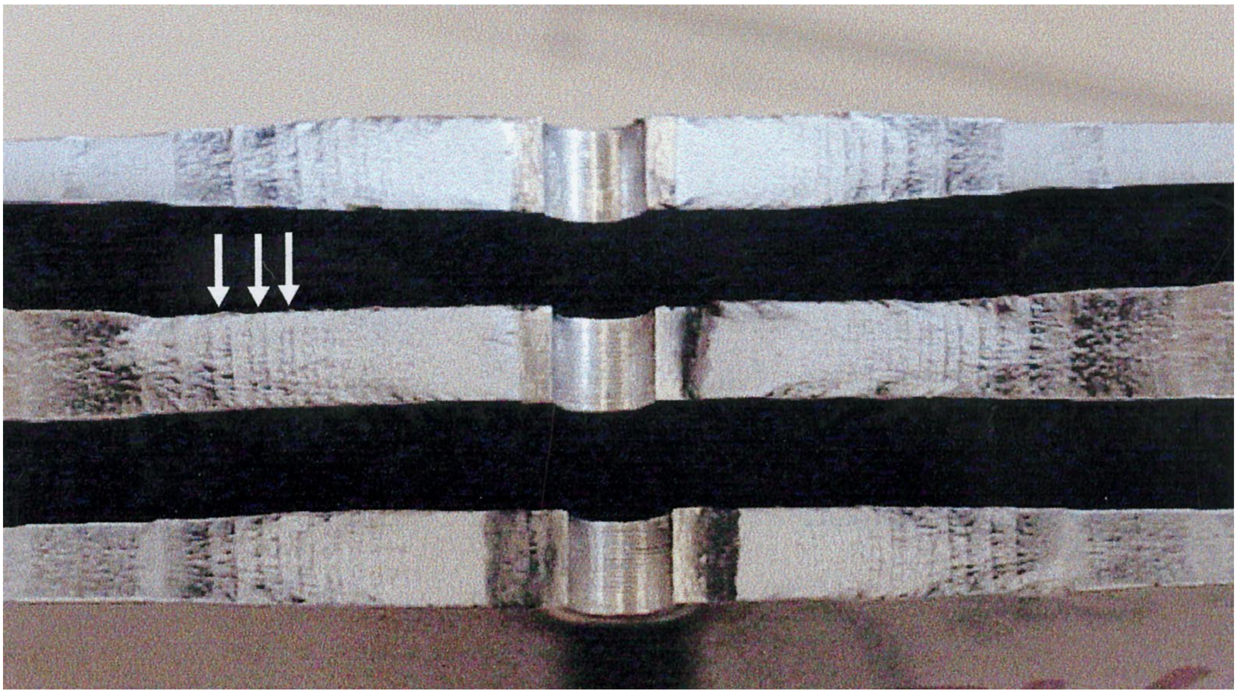

Fig. 8 Fracture surfaces of the three specimens tested with the miniFalstaff load history and S_{max} = 247.5, 220 and 230 MPa respectively (top to bottom). The arrows indicate pairs of growth bands associated with the two flights in which the most severe loads are applied (see subsection 1.5.5)

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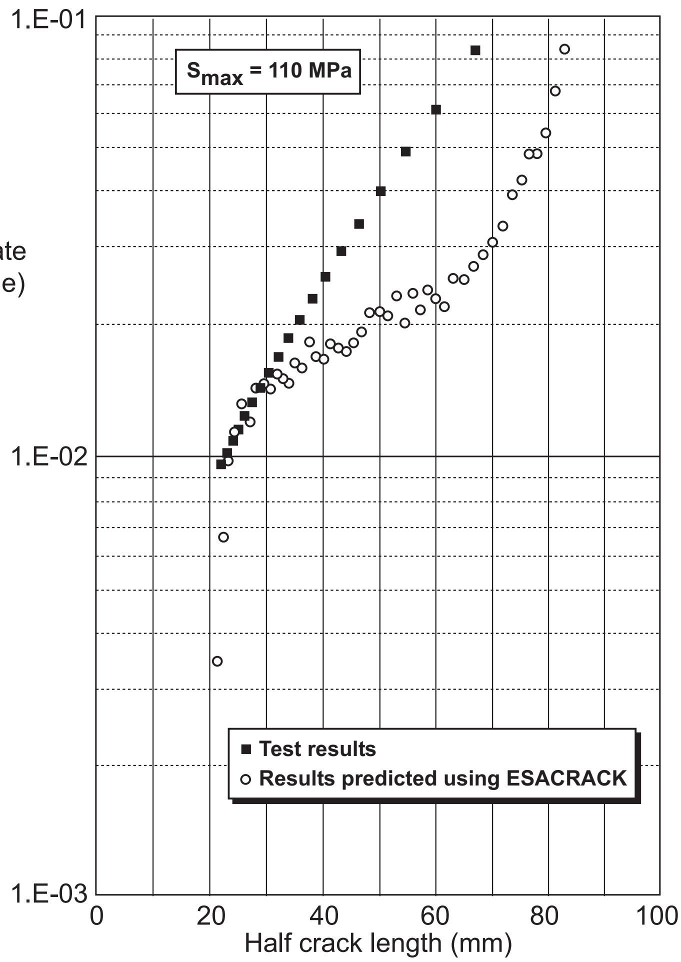
a) Stiffened panel manufactured by FSW



b) Fatigue crack growth rates in FSW panel

Fig. 9 Panel configuration and fatigue crack growth results for a Friction Stir Welded (FSW) T-stiffened 2024-T3 panel with a center crack cutting through the central stiffener (see subsection 1.5.6)

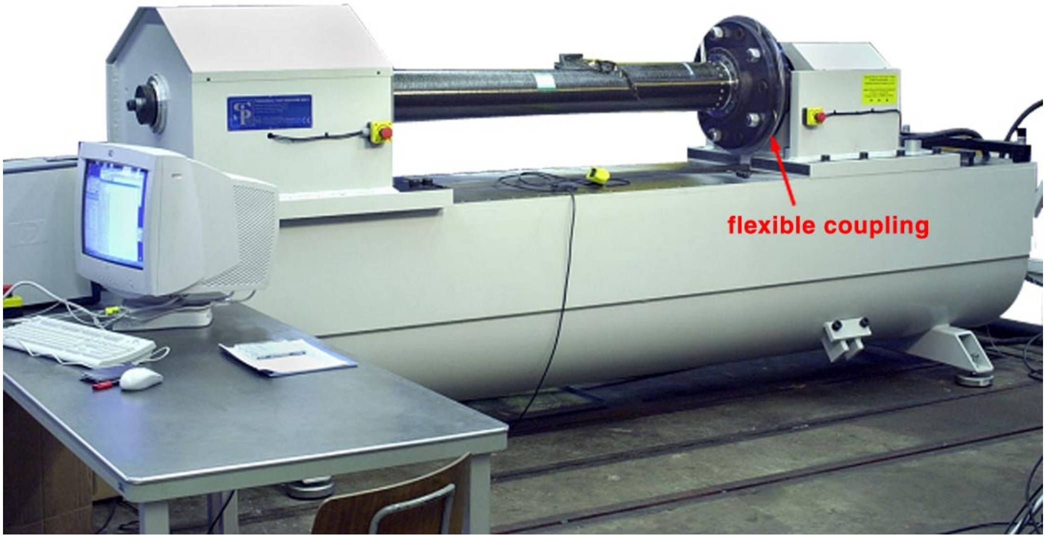


Fig. 10 Torsional fatigue testing of filament wound carbon/epoxy - metal flange drive shafts (see subsection 1.6.1)

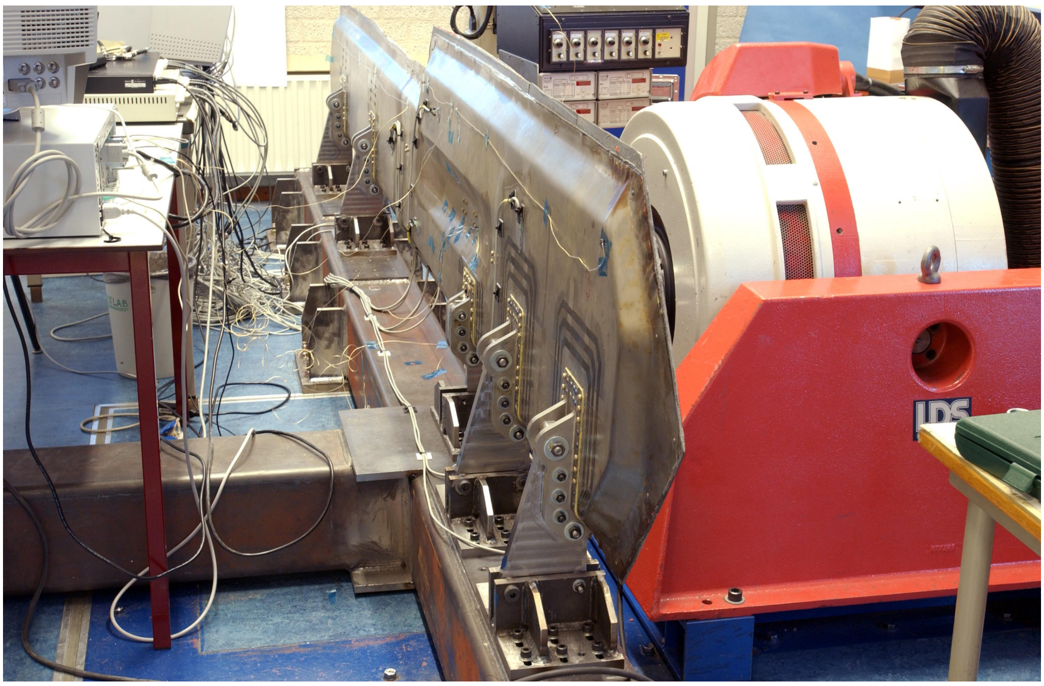


Fig. 11 Test set-up for acoustic fatigue of a Fibre Metal Laminate (FML) weapon bay door (see subsection 1.6.2)