A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND MAY 2007 – APRIL 2009

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Confidentiality   Public

Preface

The Finnish Air Force Command (FINAFCOM), Armaments Division, initiated and supported this work. The editor is indebted to the following individuals who helped in the preparation of the review (organisations and individuals in alphabetical order – the reference list refers to paragraph-specific contributions):

Espoo 7th April 2009

Editor

Contents

13.1   Introduction

The year 2009 marks the 91st anniversary of the Finnish Air Force (FINAF) – one of the oldest independent air forces in the world. It was founded as an independent service on the 6th March 1918 [FINAF 2009]. The fixed wing aircraft inventory of the FINAF at the time of writing this review is summarised in *Fig. 1*.
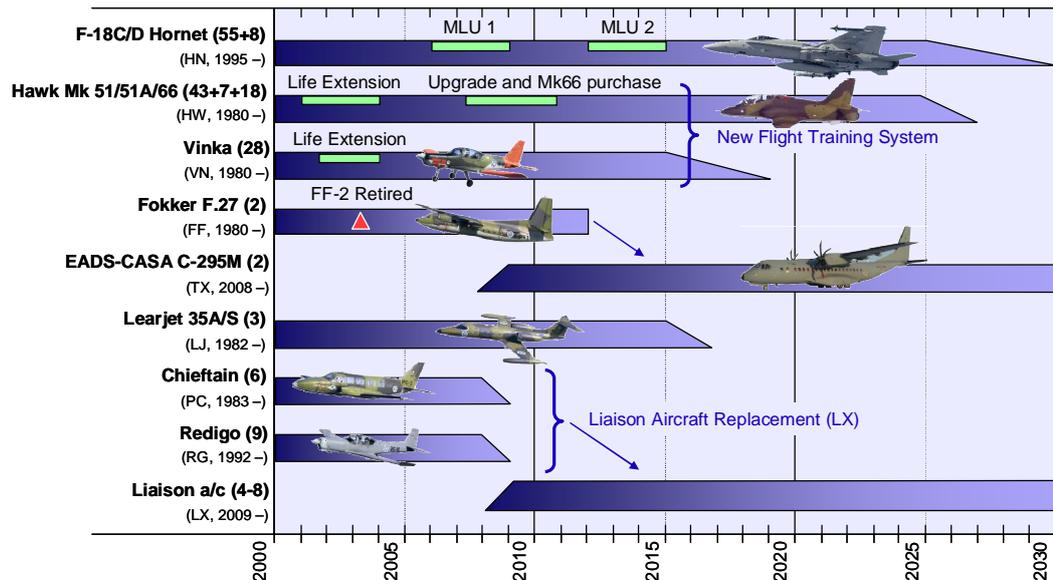
Figure 1:   *An overview of the fixed wing aircraft inventory of the Finnish Air Force (FINAF). Courtesy of the FINAF.*

In addition to the fixed wing air vehicles of the FINAF, Patria is responsible for assembling 50 NH90 helicopters for Sweden, Finland and other operators. The Finnish assembly line is the first NH90 assembly line established outside the NAHEMA countries, being the 4th operational assembly line for the NH90, beside the ones based in France, Germany and Italy. The first Patria assembled NH90 helicopter was delivered in September 2008 to the Swedish customer (the Swedish Defence Material Establishment – FMV) by NHIndustries. The first delivery to the Finnish Defence Forces (FDF) took place in March 2008 [Patria 2007; Patria 2008c].]. At the end of 2008, a total of 5 helicopters (IOC – Initial Operational Configuration) were delivered to the FDF and four helicopters (IOC+) are being delivered during the year 2009 [MIL 2009].

Before going into highlights of the structural integrity management activities, a brief update of the FINAF's fighter aircraft and associated pilot training aircraft is provided below.

13.1.1 Valmet Vinka

Previous activities related to the Valmet Vinka primary trainer of the FINAF were outlined in e.g. [ICAF 2007 Chapter 13.3]. Patria is monitoring the structural life consumption of each primary trainer, each of which is equipped with a g counter. The severity of usage (in view of structural life consumption i.e. the g counter status) is more benign than that on the basis of LEP assumptions, *Fig. 2*.
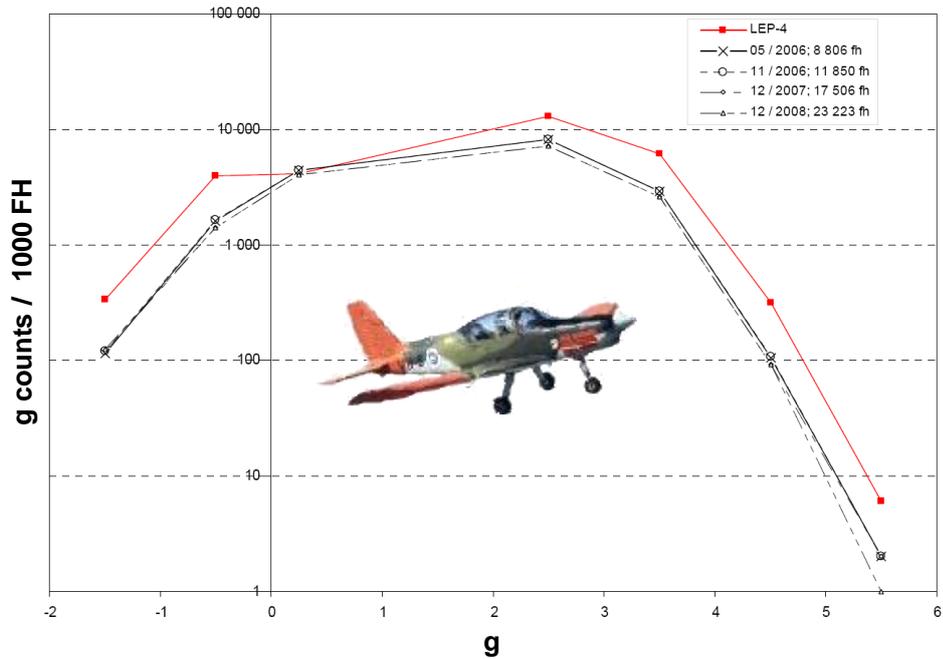
Figure 2:   *The g counts per 1000 FH of the Valmet Vinka. The spectrum representing the LEP design assumptions (**LEP-4**). The post LEP g counter spectrum as of May 2006 (**-x-**), as of November 2006 (**-○-**), as of December 2007 (**- ◊-**) and as of December 2008 (**- ▲ -**). All curves (excluding the red LEP-4) represent the fleet average from all Vinkas, as ranked according to the a/c centre of gravity normal acceleration. Courtesy of Patria Aviation Oy.*

Recommendations regarding the rotation of individual tailnumbers from more severe usage to a milder one and vice versa have been made by Patria to obtain a more even rate of structural life expended. Individual aircraft have been assigned to "fleet leader" roles to provide e.g. early warnings of possible structural fatigue scenarios [Pirtola 2009].

13.1.2   Hawk Mk51/51A and Mk66

The structural fatigue consumption of the FINAF Mk51/51A Hawks is summarised in *Fig. 3*.
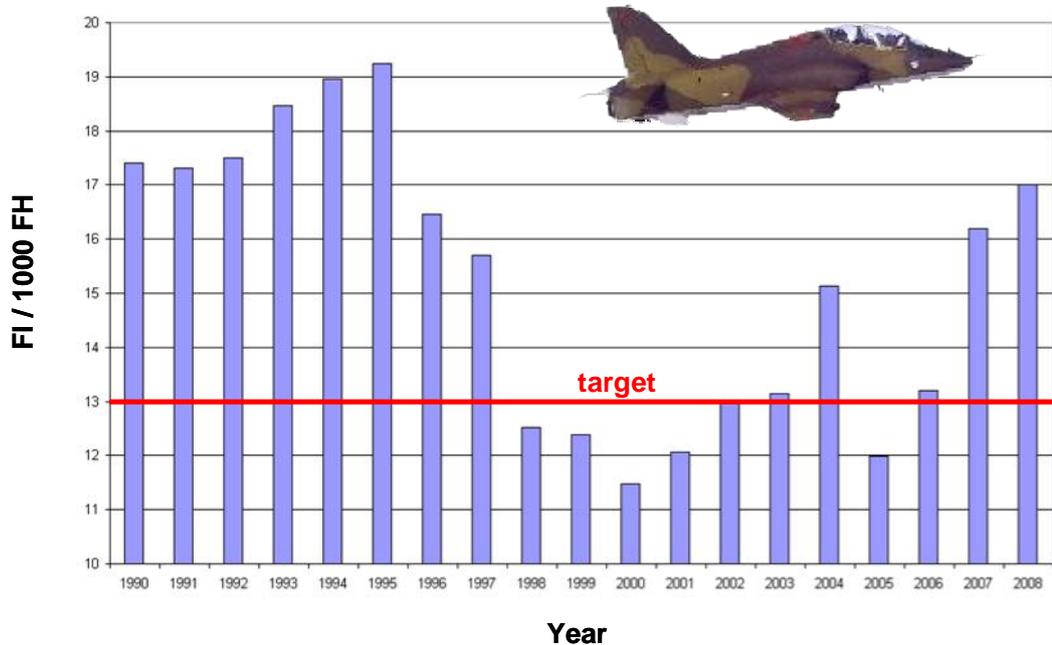
Figure 3:   *Fatigue Index (FI) development of the FINAF Hawks (Mk51 & Mk51A) at the end of November 2008 (fleet average; data from all 57 aircraft included, as ranked according to the a/c centre of gravity normal acceleration. Note that the FINAF Hawks were concentrated to Kauhava at the end of 2005. Courtesy of the FINAF.*

The FINAF boosted its 49 Mk.51/51A Hawk jet trainer fleet by purchasing 18 second-hand BAES Hawk Mk.66 jet trainers with maintenance tools and spares from Switzerland. The FINAF's current Hawks will reach the end of their lifespan by 2019. The Swiss airframes have flown less than one fifth of their maximum flight hours, which translates into 15 years of operation in the FINAF service. The same number of flight hours could be attained by 9 new Hawk-category aircraft. The purchase allows the FINAF more time to plan its future flight training arrangements and enables cooperation in this field with other European air forces [FINAF 2009].

Of the 49 Mk.51/51A jets – all undergone an extensive structural life extension modification at Patria [ICAF 2001; 2003; 2005; 2007] – selected Mk51/51A jets (12 aircraft) and the Mk.66 jets (18 aircraft) will be upgraded by Patria to further increase the quality of fighter training by the modern avionics and glass cockpits as well as by creating mission planning, recording and debriefing capabilities. These modernisations improve training efficiency and enable the Hawks' use in certain training purposes in which Hornet interceptors now have been used [Patria 2008b; Patria 2009]. The first Hawk jet trainer modernised by Patria with a glass cockpit performed its first flight in September 2008 in Jämsä, Finland.

The FINAF and Patria have teamed up to establish an international flight training centre called the Nordic Pilot Training Centre (NPTC). The NPTC will offer military flight training to foreign customers utilising upgraded FINAF Hawk aircraft operated by the FINAF's Training Air Wing at Kauhava air base. The renewed aircraft further enhance the possibilities to offer high quality pilot training not only to the Finnish military pilots but also to foreign pilots in the Kauhava based training centre in the future. The advantages of Kauhava include airspace, which is extensive by European standards and more than sufficient for tactical and weapons training. The NPTC training

syllabi will be tailored to ensure that each customer can be offered training to deliver just the competence they require and bring pilots up to a level that enables them to convert to modern fighters upon completion of training [FINAF 2009; Patria 2008a].

13.1.3   F-18C/D Hornet

The FINAF's F-18C/D Hornet fighter fleet, with the trained personnel for different tasks in international operations, is already fully compatible with the systems of the other European countries. To further enhance the performance of the Hornet air defence fighter, the aircraft are being furnished with the Mid-Life Upgrade (MLU) 1 and 2 to further enhance the performance of the fighter by e.g. furnishing the aircraft with air-to-ground capability, introducing the Joint Helmet Mounted Cueing System (JHMCS) and procuring new air-to-air missiles. Simultaneously, the development of the command and control system and the air base systems will be carried out [FINAF 2009].

The current structural life consumption of the FINAF Hornet fleet is shown in **Fig. 4**. As can be seen, the aircraft's usage is more severe than the design target. The yellow lines provide estimated durability value extremes (in flight hours – FH) as ranked per individual tailnumbers corresponding to the most severe (3591 FH) and most benign (7623 FH) flying.
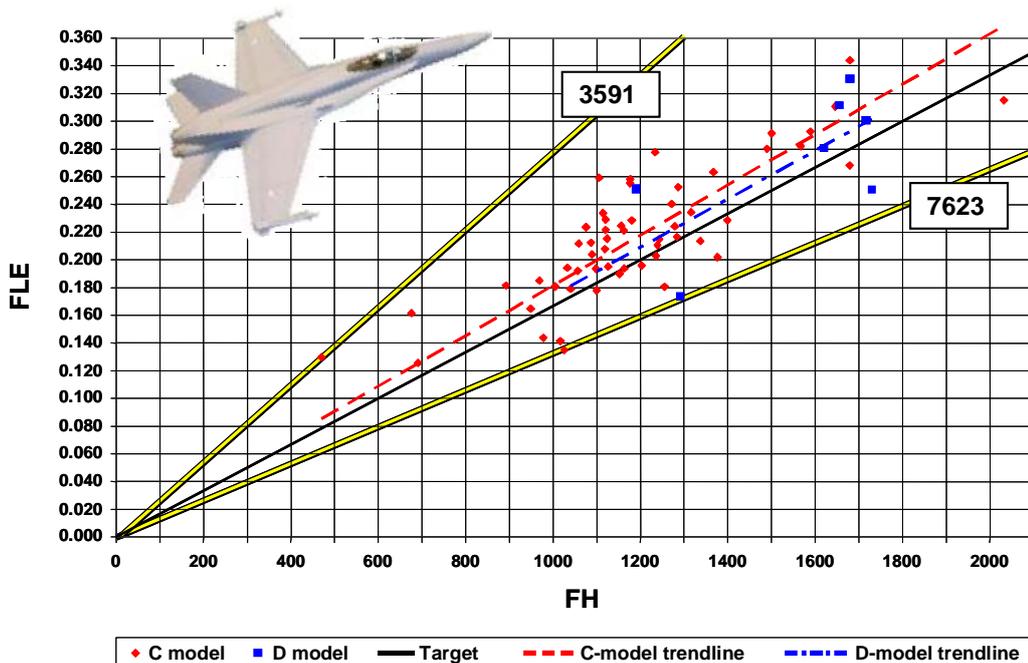
Figure 4:   *Summary of the wing root fatigue life expended (FLE) of the FINAF F-18 fleet at the end of August 2008 (data from all 64 aircraft included, as ranked according to the data obtained from the current onboard strain recording system. Courtesy of the FINAF.*

13.1.4   Scope of the review

This national review on aeronautical fatigue concentrates on the fixed wing aircraft inventory of the FINAF related to fighter jets and associated pilot training aircraft. The FINAF inventory today includes 63 F-18C/D Hornet fighters, 67 Mk.51/51A Hawk jet trainers (including the 18 Mk66 aircraft from Switzerland) and 28 Valmet Vinka primary trainers. During the writing of this review, approximately 88 000 FH have been flown with the Hornets, 221 000 FH with the Mk51/51A Hawks and 142 000 FH with the Vinkas.

No FINAF aircraft of these type designations have been lost due to structural issues.

The severity of the Finnish usage in view of structural fatigue with the two jets of noteworthy manoeuvring capability can be seen in *Fig. 3* (Hawk) and *Fig. 4* (Hornet). Figs 3 and 4 clearly demonstrate the need to maintain, further develop and apply concrete and systematic efforts to cope with the structural deterioration effects of these two aircraft types.

During 2005, the International Committee on Aeronautical Fatigue (ICAF) formally welcomed Finland as a full member of the ICAF, making Finland the 13th full member. This Finnish national review of current aeronautical fatigue investigations up to April 2009 – although the 5th review but the 2nd review as a full member – was compiled by Aslak Siljander (VTT).

The review comprises inputs from the organisations listed below (in alphabetical order).

Emmecon	Emmecon Oy., P. O. Box 35, FI-53851 Lappeenranta, Finland (http://www.emmecon.fi/)
FINAFAMC	The Finnish Air Force, Air Materiel Command, P. O. Box 210, FI-33101 Tampere, Finland (http://www.ilmavoimat.fi/index_en.php)
FINAFCOM	The Finnish Air Force Command, Armaments Division, Aircraft Section, P. O. Box 30, FI-41161 Tikkakoski; Finland (http://www.ilmavoimat.fi/index_en.php)
Finflo	Finflo Oy, Tekniikantie 12, FI-02150 Espoo, Finland (http://www.finflo.fi/)
Insta	Insta Group Oy, P.O. Box 80, FI-33901 Tampere, Finland (www.insta.fi)
Patria	Patria Aviation Oy, Aeronautical Engineering, FI-35600 Halli, Finland (http://www.patria.fi/index2.htm)
TKK	Helsinki University of Technology, Department of Applied Mechanics, Faculty of Engineering and Architecture, Aeronautical Engineering, Structures Group, P. O. Box 4300, FI-02015 TKK, Finland (http://www.lls.hut.fi)
TUT/DSP	Tampere University of Technology, Department of Signal Processing, Korkeakoulunkatu 1, FI-33720 Tampere, Finland (http://sp.cs.tut.fi)
TUT/DMS	Tampere University of Technology, Department of Materials Science, Korkeakoulunkatu 6, FI-33720 Tampere, Finland (http://www.tut.fi)
TUT/IHA	Tampere University of Technology, Department of Intelligent Hydraulics and Automation, P.O. Box 589, FI-33101 Tampere, Finland (http://www.iha.tut.fi/research/aircraft/)
VTT	VTT Machine and Vehicle Industries, P. O. Box 1000, FI-02044 VTT, Finland (http://www.vtt.fi/?lang=en)

13.2   Current activities: ASIMP 2007 – 2009

The Aircraft Structural Integrity Management Program (ASIMP) 2007 – 2009, as briefly outlined in [ICAF 2007 Chapter 13.8], has progressed in all fronts. The Framework Agreement [FA 2007] was signed by the research partners in June 2007. The research efforts under the various sub-programs are well underway. An attempt is provided below to provide highlights of the ASIMP 2007 – 2009 achievements thus far, including those from the parallel research programs[1].

13.2.1   Loads and stresses

13.2.1.1   Computational fluid dynamics (CFD) – update

Previous CFD activities (flow simulations) have been reported e.g. in [ICAF 2007 Chapter 13.5.1.2]. The main purpose of the flow simulations is to obtain structural loads to be used as inputs for other analyses i.e. structural analyses – FEA. The flow simulations are being made at Finflo Ltd. utilising an in-house software FINFLO [Siikonen 2000]. The maintenance of the FINFLO environment and cooperation with other users of the code are also conducted at Finflo Ltd. A 6-DOF model (e.g. of the FINAF F-18C Hornet and Hawk Mk51 aircraft) has been implemented into FINFLO and various store separation cases have been analysed. The 6-DOF model is based on the Chimera technique. A fourth-order Runge-Kutta method is applied for the solution of the kinematics. Several over-set (Chimera) grids can be used to model external stores. The method is parallelised using MPI (Message Patching Interface), but owing to the large amount of data in message passing, the efficiency is not as good as in a case of structured multi-block grids. An example of the store separation for the FINAF Hawk Mk51 is shown in *Fig. 5* [Ilkko 2007].
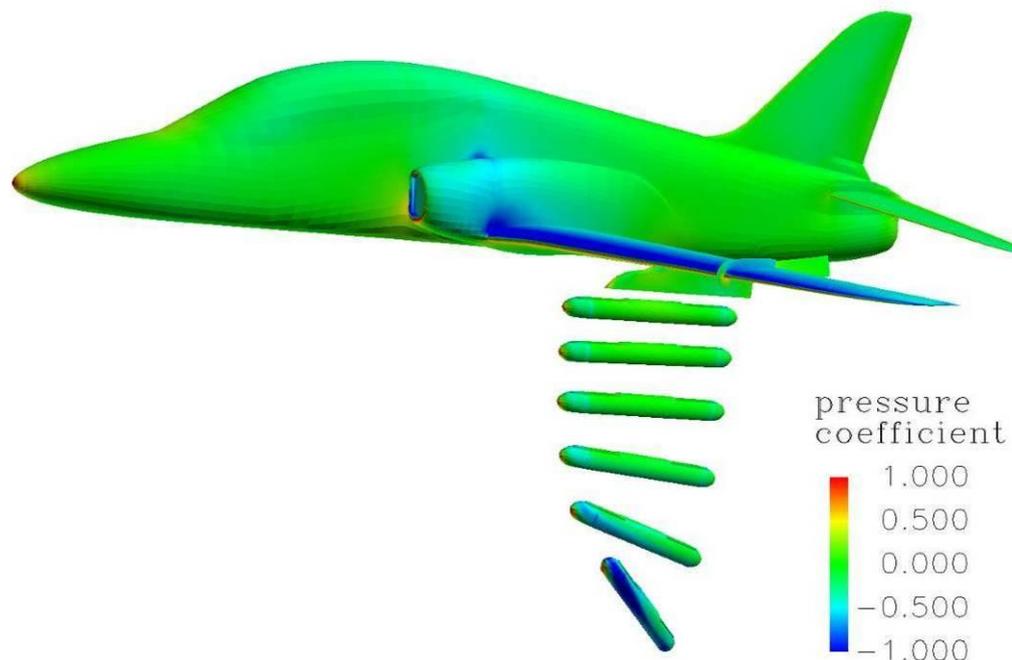
Figure 5:   *An example of an external store separation from BAe Hawk Mk 51. The aircraft is in a static position but the store is flying freely. Flow conditions are: Ma=0.288, AoA=5.17° and altitude 1000 m. Pressure coefficient distribution is visualised on the surfaces of the store and the aircraft. The movement of the store is drawn at intervals of 0.1 s. Courtesy of Finflo Ltd.*

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[1] The Hornet Operational Loads Measurement (HOLM) program, as described previously in [ICAF 2007 Chapter 13.5.1.1], launched by the FINAF during autumn 1998, has progressed successfully until the planned completion, which took place in September 2007.

The usual approach in practical CFD is to apply Reynolds-averaged equations. Detached Eddy Simulation (DES) is a promising approach at high angles of attack (AoA) and at high Reynolds numbers (Re). Cooperation with Helsinki University of Technology has started in order to apply DES for the F-18C aircraft. An example of the DES results is the flow structure over a delta wing in *Fig. 6*.
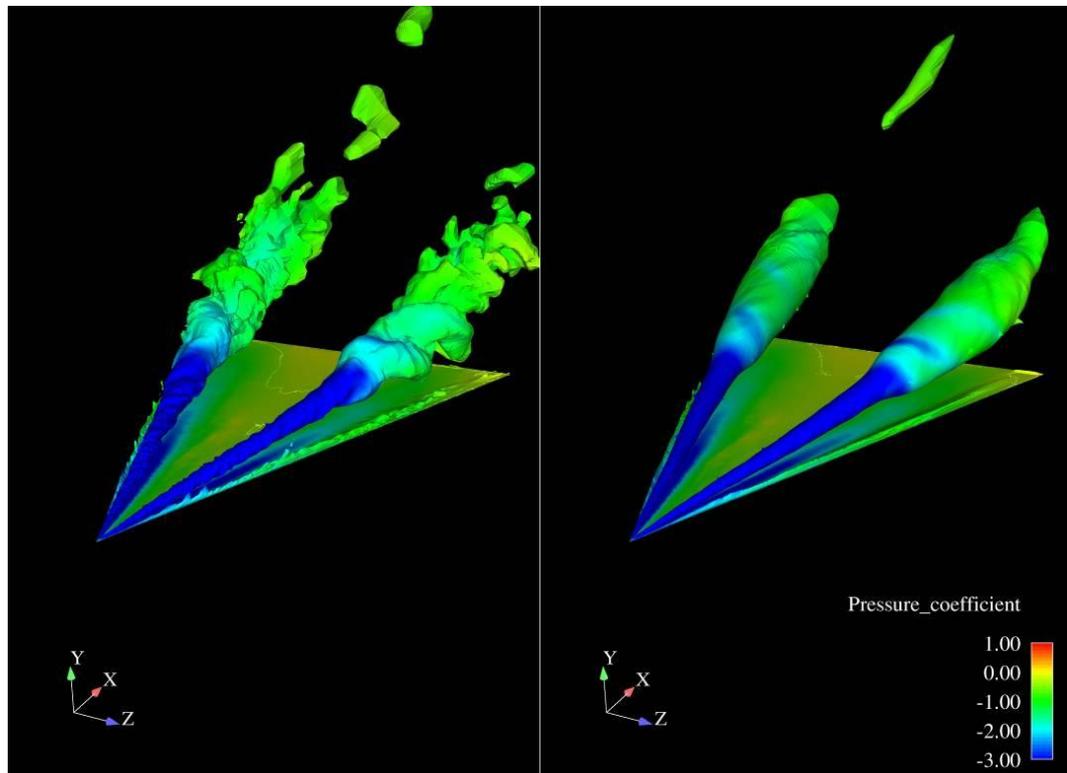
Figure 6: *Detached Eddy Simulation (DES) results of a 70° delta wing with a sharp leading edge at $\alpha=27°$ and $Re_c=1.56x10^6$. Instantaneous (**left**) and time-averaged (**right**) iso-surfaces of entropy coloured by pressure coefficient are presented. Courtesy of Finflo Ltd.*

Fluid structure interaction (FSI), i.e. coupling with FEA has been made so far explicitly by iterating between NASTRAN and FINFLO [ICAF 2007 Chapter 13.5.1.2]. In a new project, made in cooperation with Patria Aviation Ltd. this coupling is made using a simplified compliance matrix based on the original matrix from NASTRAN [Malmi 2008]. Using the simplified matrix the FSI problem will be solved inside FINFLO and the iterations needed with NASTRAN are minimized.

Cooperation between Finflo Ltd. (Finland) and CFS Engineering (Switzerland) is continuing. Meetings have been arranged to handle technical aspects and general CFD development. Current CFD studies concentrate on the influence of the wing tip missiles.

13.2.1.2 Flight simulations

Previous activities of the flight simulations to support the structural fatigue life management have been highlighted in e.g. [ICAF 2007 Chapter 13.6.3.1.1]. For years the FINAF has been funding the development of the low-cost flight simulation software which has been (and will be) utilised among the national research network in various projects (e.g. Chapter 13.3.3). Modular design allows different aircraft models to be implemented into simulations. Among the most important ones is the F-18C aircraft model.

The associated elements (software / hardware) have been upgraded when needed in order to maintain the simulation capability in a level corresponding to the actual flying of the FINAF aircraft. The following provides an update of the activities:

- Configuration and interface management, including software updates (e.g. compatibility aspects with new versions of COTS (commercial off-the-shelf) elements such as Matlab/Simulink) and user support
- Implementation of the flight control system (FCS) of the F-18 Hornet control laws (v10.7) to facilitate realistic simulations i.e. correspondence between simulations and actual flights
- Update of the aerodynamic model of the F-18 Hornet and its implementation in the simulation scheme [Kaarlonen & Öström 2008].
- The engine model is being improved by TKK [Soimakallio & Vesaoja 2008] in view of e.g. from steady-state thrust [ICAF 2003 Chapter 4.1] to more realistic (dynamic) thrust features.
- Trimming routine development to properly initialise the aircraft for simulation in selected flight conditions
- Post-processing features' improvements to e.g. improve the quality of the visualisations of the simulated flights
- VRML visualisations' improvements to enhance graphicness and animations for the "debriefings"
- HUD display development and implementation to provide the "pilot's view" during the visualisations of the simulations (see *Fig. 9*). The HUD implemented can be tailored to the user's preferences.
- Improvements in the inverse simulation capability [Öström 2007, Öström 2007b, Karelahti, Virtanen, Öström 2007, Karelahti, Virtanen, Öström 2008]

An overview of the low-cost HUTFLY2 simulator is provided in *Fig. 7*.
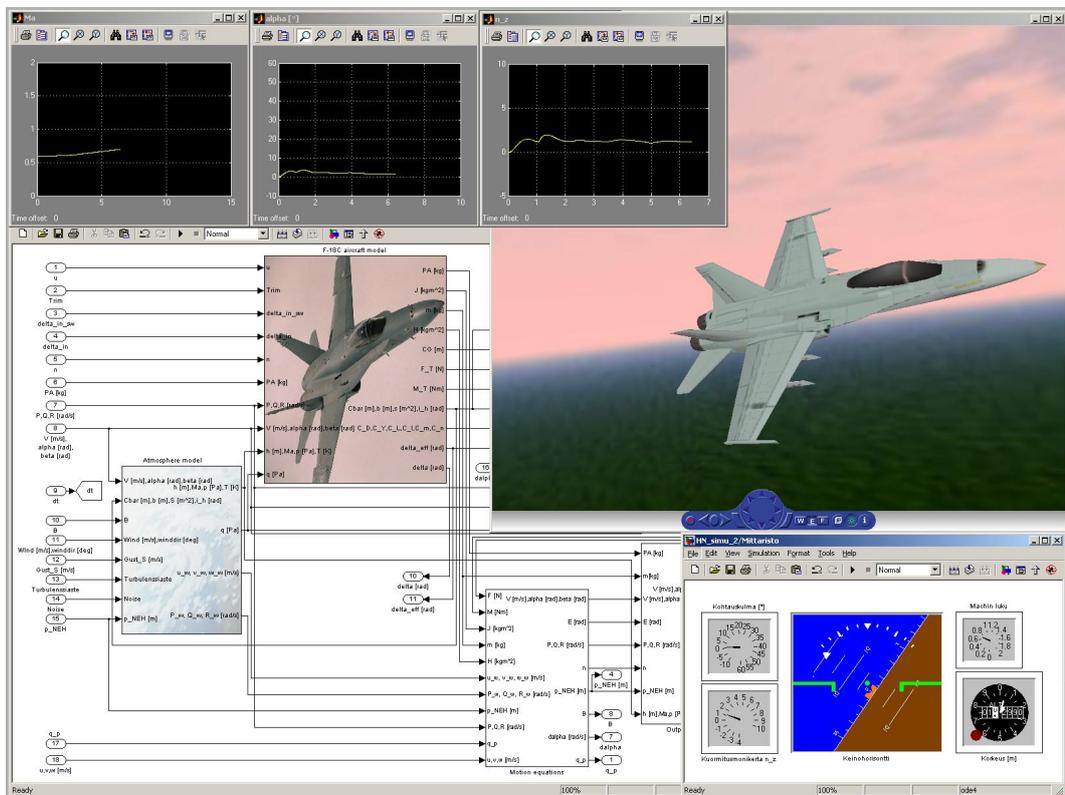
Figure 7:   *An overview of the HUFLY2 low-cost flight simulator tailored to the FINAF F-18C Hornet. Picture courtesy of VTT.*

13.2.1.3 Hornet FE modelling – update

Previous development phases of the global (coarse) Finite Element (FE) model of the FINAF F-18C Hornet have been outlined in [ICAF 2007 Chapter 13.5.1.1]. Since then, the dynamic behaviour (mode shapes and frequencies) of the FE model has been verified by comparisons with results obtained with an OEM FE model used for flutter analyses [Malmi & Liius 2007]. Also, the method and tools for transferring the aerodynamic loads from CFD analyses onto the global FE model have been updated, and the procedure for creating balanced load cases (by adjusting the aerodynamic loads) was automated [Malmi 2008]. Verification of the global FE model of the wing with full scale fatigue test measurement data, received from a foreign operator of the F/A-18 aircraft under the auspices of FISIF (F/A-18 International Structural Integrity Forum), has been completed.

The work with the FE detail modelling, which was started earlier [ICAF 2007 Chapter 13.5.1.1] based on the assessment of the fatigue critical structural locations of the FINAF Hornets, has been continued by preparation of some new detailed FE models *(Fig. 8):* Outer wing front spar region [Liius & Turkia 2007], outer wing fold region [Salonen 2007] and the engine bay door region near FS Y657.35 [Orpana & Liius 2008].

The fatigue life estimates for these locations have been determined by Patria in two ways: For locations for which applicable strain gauge data were available, the load spectra (strain gauge data) of a set of ten Mini-HOLM 1 test flights representing FINAF average usage were used. For location where applicable strain gauge data was not available, relative stress level comparisons (using FE detail models of different configurations, *Fig 8a*) between the cracked configuration (as per the OEM fatigue test) and the enhanced FINAF configuration were used. Due to the severe usage of the aircraft by the FINAF *(Fig. 4)*, the life estimates show the need not only for careful individual aircraft fatigue tracking (IAT) according to the real usage, but also for pre-emptive treatments for some locations.

The structural locations which have been found critical on the basis of the FINAF representative set of ten flights [ICAF 2007 Chapter 13.5.1.3.1], are being continuously monitored with the two Hornets equipped with the HOLM instrumentation suite (see Chapter 13.2.2.1). For most of these structural locations also flight parameter based neural network fatigue tracking methods have been developed (see Chapter 13.2.2.3). With these tools the FINAF F-18 tailnumber-specific fatigue life consumption can be analysed starting from the maiden flight, as the flight parameter data for all flights have been stored (MU data).
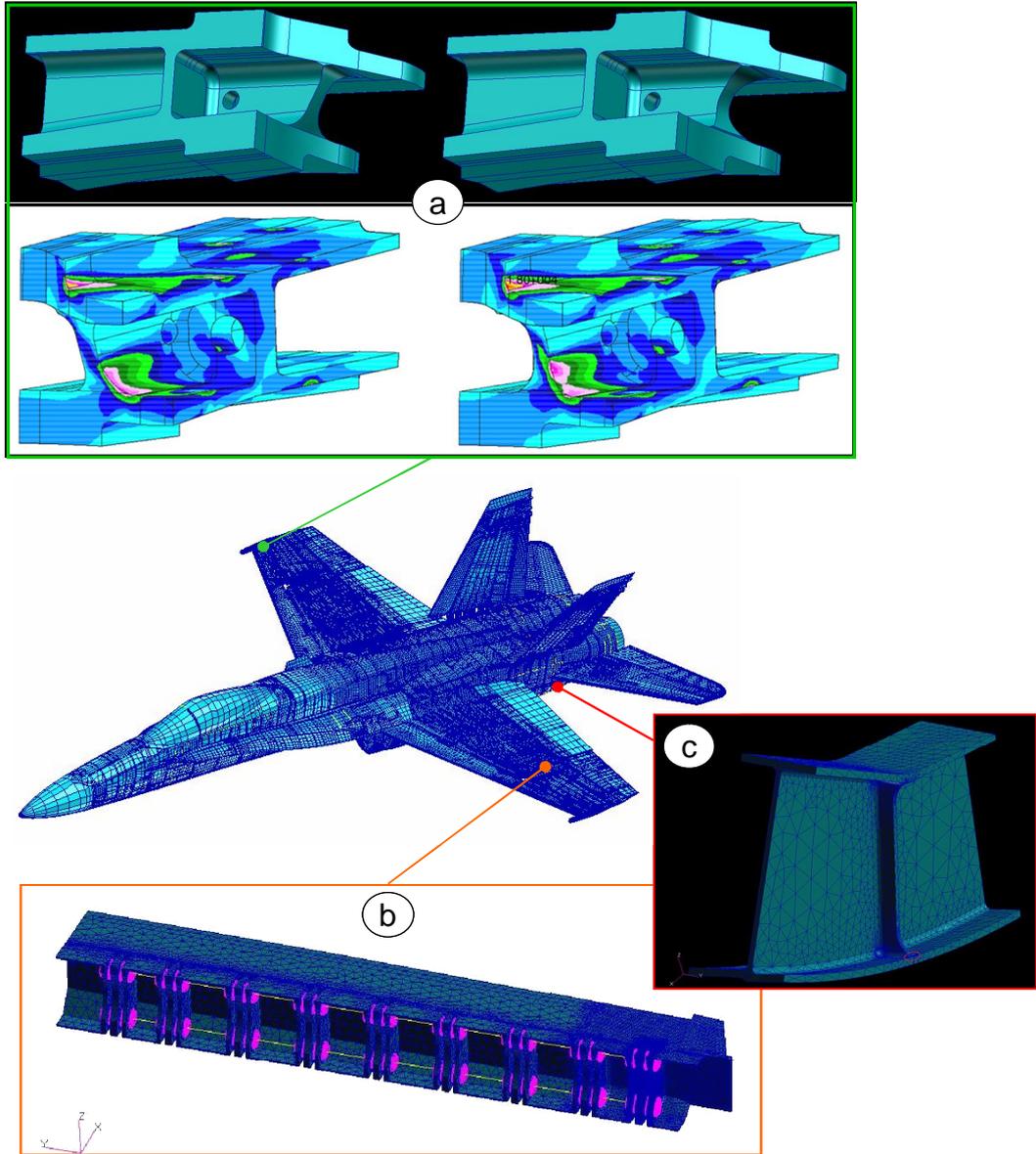
Figure 8: *Examples of the FINAF F-18 Hornet's most recent detailed FE models: **a**) Outer wing front spar region (note the different models for relative stress level comparisons of different configurations); **b**) Outer wing fold region; **c**) Engine bay door region near FS Y657.35. Courtesy of Patria Aviation Oy.*

13.2.2　Fatigue tracking systems

13.2.2.1　From HOLM flight tests to routine squadron service

Previous research activities of the two FINAF F-18 HOLM jets can be found in [ICAF 2007 Chapter 13.5.1.3.3]. The two aircraft were delivered to the FINAF as planned: HN-432 in September 2006 to the Lapland Air Command e.g. [Miettinen 2006; Laakso 2006] and HN-416 in April 2007 to the Satakunta Air Command e.g. [Miettinen 2007; Laakso 2007b]. Like the other Hornets the two HOLM jets will be rotated also in the Karelian Air Command according to the maintenance schedule.

The early "research" configuration flights (Mini-HOLM I) have been reported earlier [ICAF 2007 Chapter 13.5.1.3.1 – 13.5.1.3.2]. Since then, the "production" version of the two HOLM onboard systems have collected statistically reliable flight data from routine fleet usage of the FINAF for over 700 flights. The production flights have been and will be analysed and reported as the flight data is delivered from the FINAF squadrons to VTT:

  – To test and fine tune the ground system's analysis and reporting procedures [Laakso *et al* 2007; Laakso *et al* 2007b; Viitanen, Laakso, Janhunen, Merinen 2007], the first fistful of flights were analysed and reported in [Laakso 2007];
  – Up to 261 flights were analysed and reported in [Viitanen, Laakso, Merinen 2008] and the functionality of the ground analysis system was assessed [Laakso, Koski, Viitanen 2008];
  – Up to 435 flights were analysed and reported in [Viitanen, Laakso, Merinen 2009].
  – The remaining flights (up to the 700+ flights flown) are being analysed during the writing of this report.

Owing to the periodic calibration [Liukkonen 2007; Liukkonen 2007b; Liukkonen 2008; Liukkonen 2008b] and maintenance [Viitanen & Merinen 2008] activities the HOLM "production" system works very well i.e. the quality of the strain signals is good (no spikes found) and all the recordable strain data has been captured (minimal missing data). Thus, the HOLM data are used for various research purposes as described below.

13.2.2.2　Flight manoeuvre identification (FMI)

Research efforts related to Flight Manoeuvre Identification (FMI) have been many, which have been conducted in co-operation with (alphabetically) Patria Aviation, TUT/DSP and VTT. The objective of the project is to develop an ability to identify damaging events on flight and use the gathered information for structural integrity management. The information could be used in pilot training and mission planning e.g. [ICAF 2001 Chapter 2.2]. That would enable lower damage rates and therefore extend the life of structures.

An overview of the joint FMI activities between the FINAF, Patria, TUT/DSP and VTT are highlighted in *Fig. 9*. The base of the FMI activities is the available flight parameter data, especially the HOLM data. VTT verifies and analyses the HOLM data, and peruses the data to identify and visualise the most damaging flights and the manoeuvres therein. Patria contributes especially to the structure-related analyses of the flight parameter recordings (MU data). Patria examines the connection between damage caused by the manoeuvres and the flight parameters, i.e., the reasons behind the damage. TUT/DSP develops signal processing and data mining methods for the flight parameter analysis to find similar manoeuvres in an automatic manner from the bulk of the HOLM data. These methods aid in utilising the extensive flight recordings database. With joined efforts, the parties can rise to the challenge of this multidisciplinary research. More details of the FMI activities are provided below and in ICAF 2009 oral presentation *"Towards automated flight-maneuver-specific fatigue life analysis"* [Jylhä, Ruotsalainen, Salonen, Janhunen, Viitanen, Vihonen, Visa 2009].
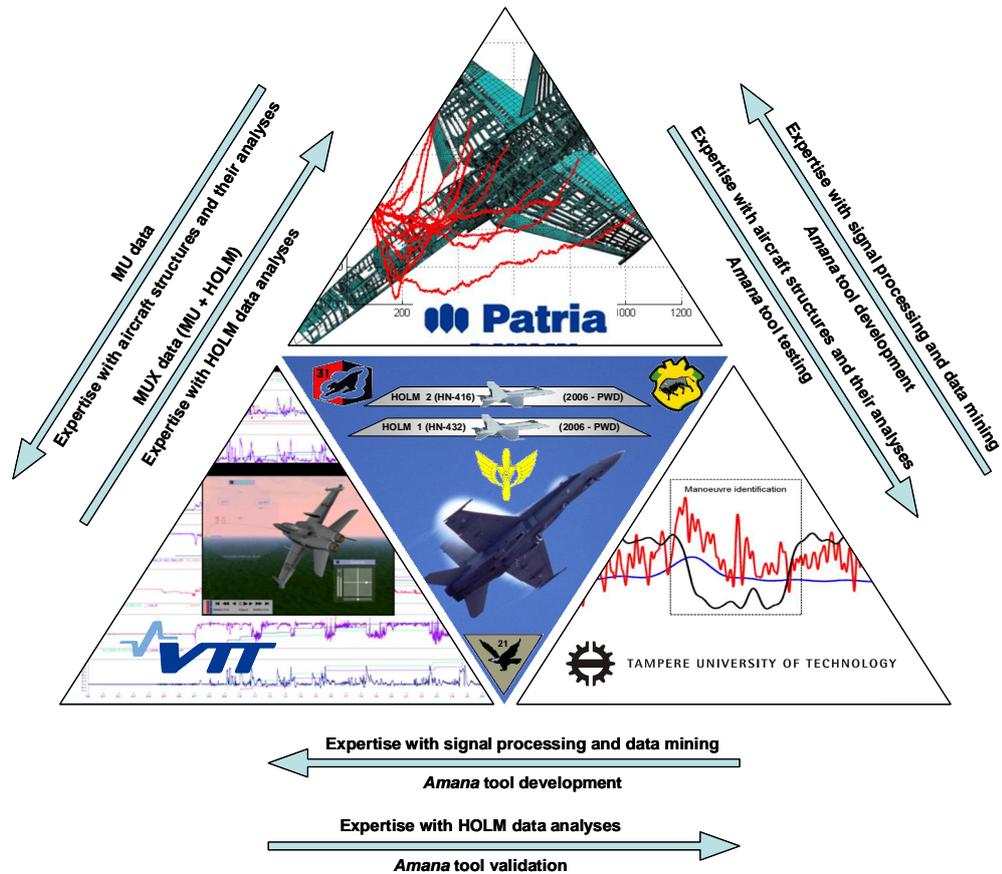
Figure 9:   *An overview of joint Flight Manoeuvre Identification (FMI) research efforts between the FINAF, Patria Aviation Oy, TUT/DSP and VTT.* Amana *is a Matlab tool for flight manoeuvre detection, developed by TUT/DSP. Picture courtesy of VTT / Patria / TUT/DSP.*

13.2.2.2.1   Flight segmenting and model building for damaging flight manoeuvres

Model based FMI requires models of the damaging manoeuvres. To expand the earlier work by TUT/DSP on structural vibration modelling for automated aircraft fatigue monitoring [ICAF 2007 Chapter 13.6.3.1.2] and by Patria on parameter based fatigue life analysis of F-18 aircraft [ICAF 2007 Chapter 13.6.3.1], TUT/DSP proposed an automated FMI procedure based on the flight parameters.

The FMI process developed by TUT/DSP comprises three steps: choosing, modelling and identifying manoeuvres. As the first step of the process, a representative manoeuvre is chosen from the flight parameter recordings by an experienced analyst. Next comes the modelling: For every manoeuvre to be identified, a model is built based on the chosen representative manoeuvres. The chosen flight parameters are quantised to three levels to enable a consistent treatment of different parameters. Thus, the quantised, chosen flight parameters within the representative manoeuvre form the model to be used in the comparison i.e. the similarity of the model to patterns that exist in the data is measured (so-called model based pattern recognition). The last step of the process is fully automatic FMI: In this step, an identification algorithm based on the built models is used to detect manoeuvres from the un-analysed flight parameter recordings.

To cope with the reality – the same manoeuvres can be performed in slightly different ways and their duration can vary – the Dynamic Time Warping (DTW) algorithm to handle the temporal variations is used. A DTW matrix is calculated between the modelled representative manoeuvre and the whole flight using the quantised flight parameters that were chosen at the modelling step. Manoeuvres' starts and stops are detected from the DTW matrix which provides a similarity values for the patterns. Good applicability to different manoeuvres has been verified by comparing

the results of the automated FMI procedure with those identified manually by an experienced analyst with pilot background. Further details of the automated FMI procedure can be found in the article [Ruotsalainen, Jylhä, Vihonen, Visa 2009] and in the ICAF 2009 presentation *"Towards automated flight-maneuver-specific fatigue life analysis"* [Jylhä, Ruotsalainen, Salonen, Janhunen, Viitanen, Vihonen, Visa 2009].

13.2.2.2.2   Identification and interpretation of damaging manoeuvres

Patria has worked with pattern recognition using amounts of the memory unit (MU) data and the HOLM data from FINAF F-18's to analyse the reasons for the fatigue damage accumulation. Patria has developed a corresponding method to the FMI procedure. In the research, flights are divided into damaging segments according to strain level and high vibrations in strain gauge signal. That yields hundreds of interesting segments. A clustering method was tested to classify the patterns and grouping similar manoeuvres into the same group. Several clusters are obtained and their centres can be used as templates of the damaging manoeuvres [Salonen 2008].

Patria also tested the FMI method for the detection of flight manoeuvres causing damage to the vertical tail and wing fold. The models were manually created and they were pure manoeuvres e.g. split-s. With good accuracy, the FMI method was able to detect the manoeuvres causing similar damage to the structure. To understand reasons for the structural damage, the identified manoeuvres were inspected. As expected, the typical hard flying causes major part of the damage. On the other hand it was found that small changes in flying could have significant impact in damage. For example, lowering the angle of attack (AoA) rate and the time spent in the high AoA regime would substantially reduce vertical tail damage [Salonen 2008].

Up to now the feasibility of the FMI for comprehensive structural management has been demonstrated. This research branch is still to be continued i.e. further studies in this research are needed to get full benefits.

13.2.2.2.3   Search of similarity between "similar" flight manoeuvres

Using the bulk of collected and analysed HOLM data (Chapter 13.2.2.1), VTT's FMI efforts are focused on finding the most damaging manoeuvres for a given structural detail on the basis of the most damaging sorties and flights identified. Having identified the most damaging flight for a given structural detail, the time segment producing the highest calculated damage is located. Using the Flight Analyzer [ICAF 2007 Chapter 13.4.4.2] tool, the manoeuvre producing the highest calculated damage is visualised. Next, the most significant flight parameters (and their envelope i.e. their min and max values together with their synchronised time histories) representing the "image" or "pattern" of the manoeuvre in question are identified. With the "pattern" obtained, similar "patterns" (flight manoeuvres similar to the most damaging one) are searched automatically (using the method developed by TUT/DSP described above) from the bulk of the analysed HOLM data. As an example, the automatic "pattern" search for an approximately 300 flights took less than one hour wall clock time.

Although the scatter in calculated damage for the "similar" manoeuvres is noteworthy, the method is being used in the search of the most damaging manoeuvres. The work performed thus far provides a solid starting point to further investigate the reasons (the connection between flight parameters' temporal behaviour and damage) why nominally similar manoeuvres provide significant scatter in the calculated damage.

13.2.2.3 Flight parameter based fatigue life analysis of aircraft structures

Previous research efforts on the flight parameter based fatigue life analysis of aircraft structures, aimed at enhanced individual aircraft fatigue life tracking (IAT) of the FINAF F-18's using flight parameters, have been summarised in [ICAF 2007 Chapter 13.6.3.1; ICAF 2005 Chapter 5.3]. In-depth description of the program can be found from [Tikka & Salonen 2007; Jylhä, Vihonen, Ala-Kleemola, Kerminen, Tikka, Visa, 2007].

The project is reaching the end of the developing phase. Methods and tools for individual aircraft fatigue life tracking of the FINAF F-18 aircraft *(Fig.10)* have been developed and implemented in the project.
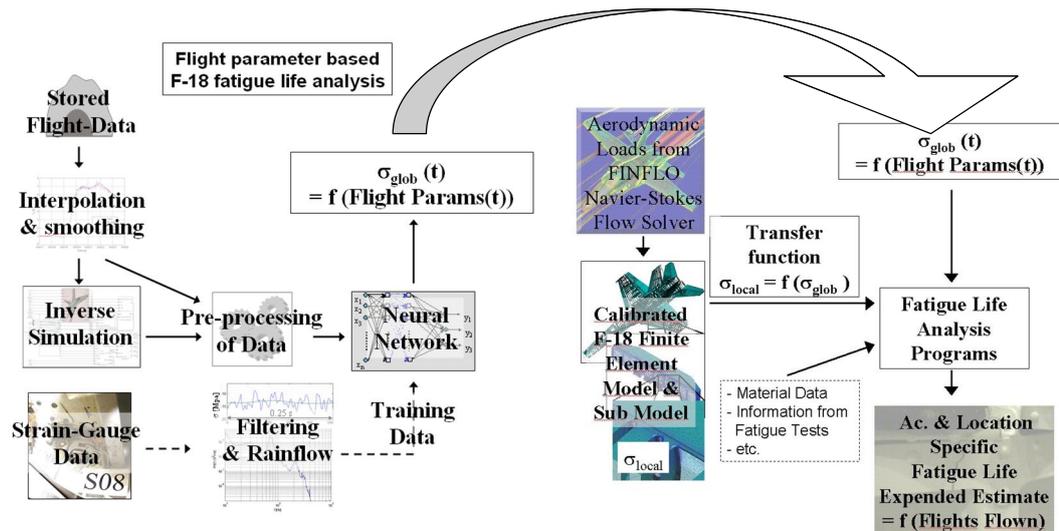
Figure 10:   *An overview of the analysis chain of the flight parameter based fatigue life analysis. Courtesy of Patria Aviation Oy.*

The most recent actions related to Parameter Based Fatigue Life Analysis are: The training of new neural networks (NNs), validation of results by using amounts of HOLM data and adding new structural details into the analysis. The analysis should be in routine use and tens of thousands of flights analysed by the end of 2009. The following provides an overview of the most recent achievements.

13.2.2.4 Analysis validation and NN training by using hundreds of HOLM flights' data

Two FINAF F-18 HOLM aircraft have gathered a lot of strain gauge data to exploit on analysis development work. Therefore, neural network (NN) training data selection and utilisation procedures have been developed to cope with that. The training data has been selected to cover the entire flight envelope, including flight parameter extremes as well as whole strain response area.

The analysis has been developed to fulfil the essential requirements of the DEF STAN 00-970. The standard presumes that the data used in the development phase is stored and the whole process is well documented. The HOLM data from the two aircraft enable proper validation and calculation of performance metrics. In addition to an extensive set of training data flights, there are hundreds of distinct flights to be used as an independent validation set.

All flights during 2002-2007 for 5 aircraft have been analysed in order to confirm the proper function of analysis environment. No major problems were encountered in the analysis.

13.2.2.5 Extending analysis capability by new structural details

In addition to the initial 10 structural details, 5 more will be added to the analysis by Patria. Of these, the Upper Outboard Longeron and Dorsal Longeron are already implemented, *Fig. 11*. The remaining three details will be chosen by the end of 2009.
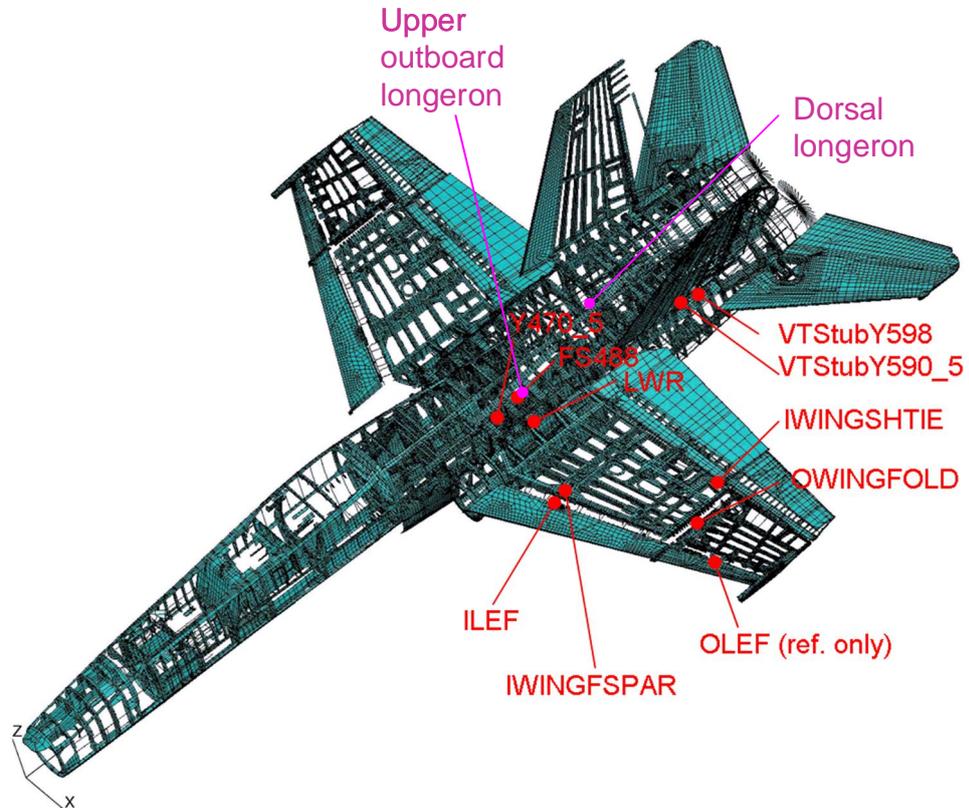
Figure 11: *Structural details being included into the production level analysis environment. The two new details (upper outboard longeron and dorsal longeron) are highlighted using violet colour. In addition, three more will be added by the end of 2009. Courtesy of Patria Aviation Oy.*

13.2.2.5.1 From instrumented to new (un-instrumented) structural locations

The number of the structural details of interest in view of fatigue tracking exceeds that provided by the onboard HOLM instrumentation suite [ICAF 2007 Chapter 13.5.1.3.3]. Therefore, additional locations have been obtained with the use of Patria's FE models e.g. [Malmi, Liius, Orpana 2007]. Patria has prepared the sub-models and associated transfer functions from the strain gauge locations to selected non-instrumented locations of interest.

These data were provided by Patria to VTT, where the data have been integrated into the HOLM ground analysis environment [Laakso & Koski 2007; Laakso & Koski 2008]. In summary, with the above additions the HOLM ground analysis environment now has the capability to analyse 22 non-instrumented locations in addition to those with strain gauges.

To complement the above, there will be further additions to the structural locations to be monitored: Transfer functions up to eight (8) new structural locations will be prepared by Patria, while slight adjustments (e.g. some mirroring of locations from port to starboard side and/or vice versa) are being prepared and implemented at VTT [Laakso, Koski, Viitanen, 2009].

13.2.2.6 The Hawk OLM program

Previous activities related to the Operational Loads Monitoring (OLM) program of the FINAF Hawks is highlighted in previous ICAF reviews e.g. [ICAF 2007 Chapter 13.4.3].

13.2.2.6.1 On the future of the Hawk OLM rolling program

All OLM flights until the end of 2006 (total of 1 300+ flights) were analysed and reported using the ground station developed entirely by VTT [Viitanen, Laakso, Bäckström, Janhunen, Merinen, Ovaska 2007]. Using the fatigue analysis database, the analyses included the FI consumption[2] (on the basis of g counts), the fatigue damage rate and life estimates (in FH) as well as the most damaging flights for the structural assemblies (fuselage, wing, tailplane, vertical tail) on the basis of the collected strain gauge data [Viitanen, Laakso, Janhunen, Merinen, Ovaska 2007].

Since then, the changes as outlined in Chapter 13.1.2 have compromised the continuity of the individual aircraft tracking (IAT) part of the HW OLM program which was intended to be a rolling program until the planned withdrawal of the entire FINAF Hawk fleet *(Fig. 12)*: The routine OLM data analyses have ceased as the two OLM aircraft (HW-319 and HW-348) are out of service. The FINAF decisions regarding the future of the OLM are pending.
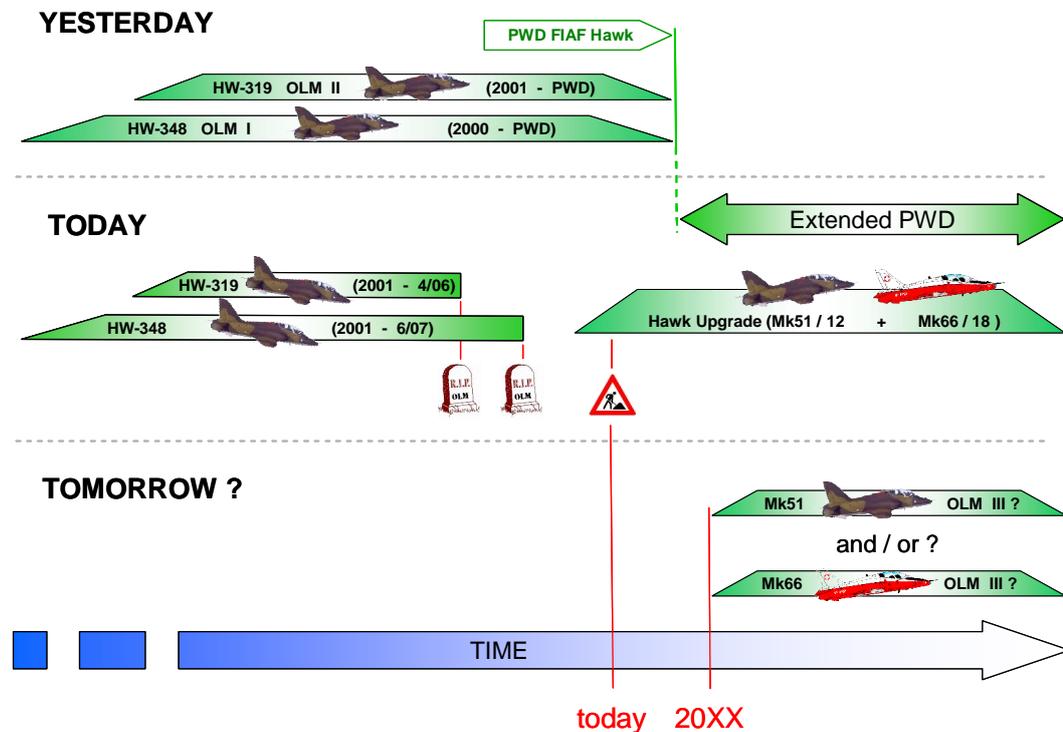
Figure 12: *The two HW OLM jets have ceased collecting the OLM data, HW-319 in April 2006 and HW-348 in June 2007. Selected FINAF Hawks are being upgraded at Patria Aviation Oy. The future of the Hawk OLM is pending. Picture courtesy of VTT.*

The need for the OLM embodiment is obvious, as the jet trainers are still being used in Kauhava: Currently the only means to estimate the sudden increase in the structural fatigue life consumption *(Fig. 3)* could be done on the basis of the flight reports (LSI) i.e. the recorded OLM data representing Kauhava usage is rare.

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[2] The average FI consumption results calculated at VTT using the OLM data (FI_{HW-319} = 13,8; FI_{HW-348} = 15,7) were well in agreement with the results calculated by the FINAF and shown in *Fig. 3*.

13.2.2.6.2   Hawk OLM's current activities (onboard configuration and ground analysis system)

Activities towards replacing the onboard data storage unit (data tape) with a more reliable solid state recorder have started [Liukkonen & Teittinen 2008]. Embodiments to the onboard OLM instrumentation suite are likely to be implemented in near future, as there may be strain data channels of little use and the remaining FINAF Hawks will not have the original[3] (pre-mod 999) wing.

The use of GPS data to support structural life estimation has been investigated [Sailaranta 2008; Sailaranta 2008b; Laakso 2009], but due to the on-going Hawk upgrade (glass cockpit) this option is no longer deemed necessary.

The ground analysis environment [ICAF 2007 Chapter 13.4.3.2] has been further developed, as the same analysis environment is used for the FINAF Hawks as well as Hornets. The analysis tools within the ground station now include the local strain (εN) approach [Bäckström, Liukkonen, Laakso, Viitanen, Koski, Teittinen 2007] to support the previously integrated methods ("stress life" i.e. SN and "fracture mechanics" i.e. da/dN). It should be noted that the current ground analysis configuration is continuously developed to further improve the life prediction accuracy [Bäckström, Liukkonen, Laakso, Viitanen, Koski, Teittinen 2009].

Flight report (LSI) data will be used to estimate the structural fatigue life consumption of the Kauhava-based Hawks and to compare the FI consumption results with those obtained prior to Kauhava-based flying. Efforts to define structural-specific life consumption metrics to those structural assemblies subjected to buffet-induced severe dynamic loading (e.g. aft fuselage, tailplane, fin) are underway.

The FMI activities are continuing by flight simulations and by investigating proper selection criteria in order to identify the most damaging flight manoeuvres e.g. [Janhunen 2007]. One goal is to create flight visualisation routines such that the most damaging flights could be visualised to facilitate the *"conference with the aircrew to try and avoid flying in severely damaging flight conditions unless specific training or operational reasons dictate otherwise"* [ICAF 2001 Chapter 2.2].

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[3] Research efforts concerning the structural integrity of the recently retired original (pre mod 999) wings of the FINAF Mk51 Hawks have been reported e.g. in [Koski *et al* 2007; Koski *et al* 2009.]

13.2.3 Structural integrity of composite materials

13.2.3.1 Thermographic studies – update

Previous research efforts on the thermographic investigation based on phase transition of water at 0 °C to find structural flaws due to moisture ingress were highlighted in [ICAF 2007 Chapter 13.6.4.5]. Thermographic research has continued in cooperation with the FINAF and VTT to find a reliable routine to inspect multiple flight control surfaces in a reliable manner (rudder, trailing edge flap and horizontal stabilizer). The investigation has concentrated on the inspection method where the whole structure is first cooled below the freezing point of water before warming the structure in room temperature; the inspections are done during the warm-up period.

Thermographic inspection based on the phase transition of water has already proved earlier to be very sensitive to moisture: Artificial defected areas had showed that very small amounts (less than 1 g) of water in the laminate honeycomb (carbon fibre/epoxide composite with aluminium honeycomb core) interface can be detected by exploiting the phase transition of water, *Fig. 13*.
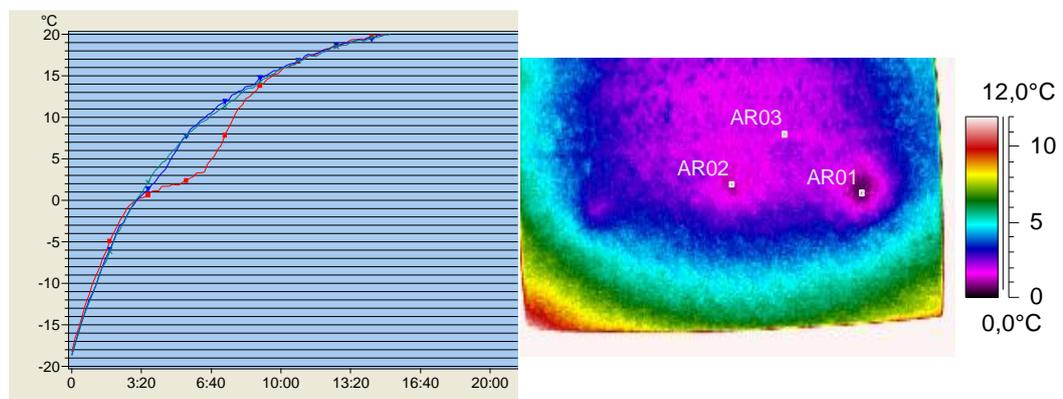
Figure 13:   *Penetrated water (in laminate/honeycomb interface) detected with thermographic inspection based on phase transition of water. AR01 refers to red line (0.7 g water), AR02 refers to blue line (0.1 g water) and AR03 is a reference of dry area (green). Picture courtesy of VTT.*

Critical areas of the rudder are assumed to be around the hinges due to the possible leakage in the sealing of the grounding grooves. Thus, the main effort of seeking moisture from the structure was concentrated to these areas.

Optimal Inspection Frame (OIF) time research with real rudder structure displayed some abnormal warming-up behaviour around the upper hinge of the rudder, *Fig. 14*.
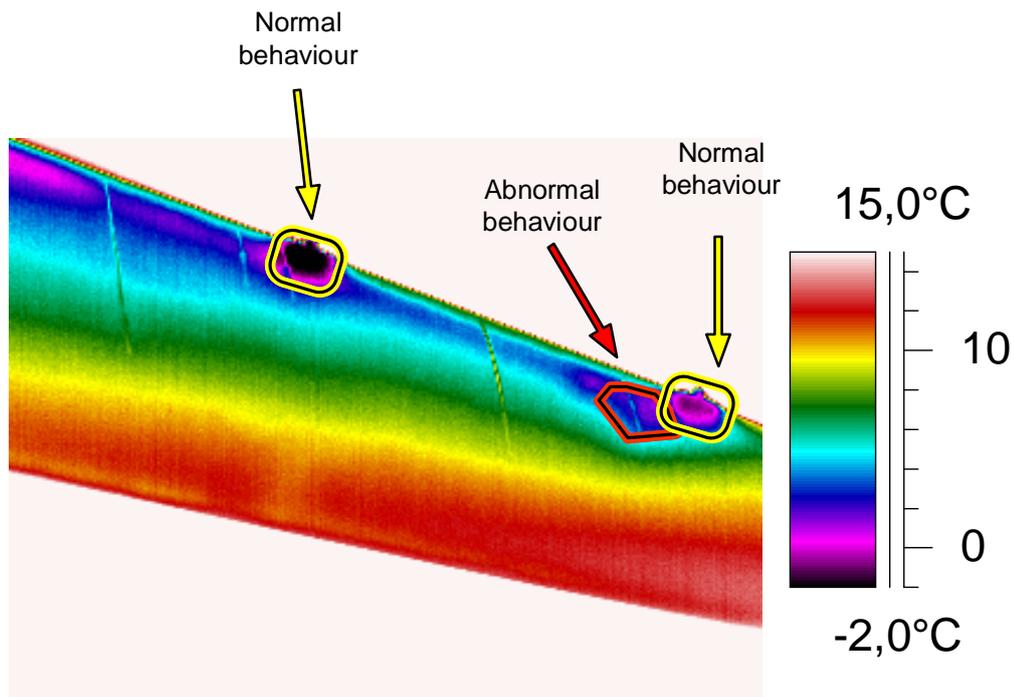
Figure 14: *Moisture detected under the upper hinge of the rudder test sample. Normal and abnormal warming-up behaviour shown. Picture courtesy of VTT.*

Individual images do not explain reliably the reason for the abnormal behaviour, but they show clearly the area of interest to be further inspected as a sequence of thermographic images (e.g. temperature curves from pulse thermography or thermography exploiting phase transition of water) or with other NDT methods sensitive to moisture penetration. Warming-up curve of different surface points of the rudder showed very small plateau at the curve, which referred to the moisture inside the rudder, *Fig. 15*.
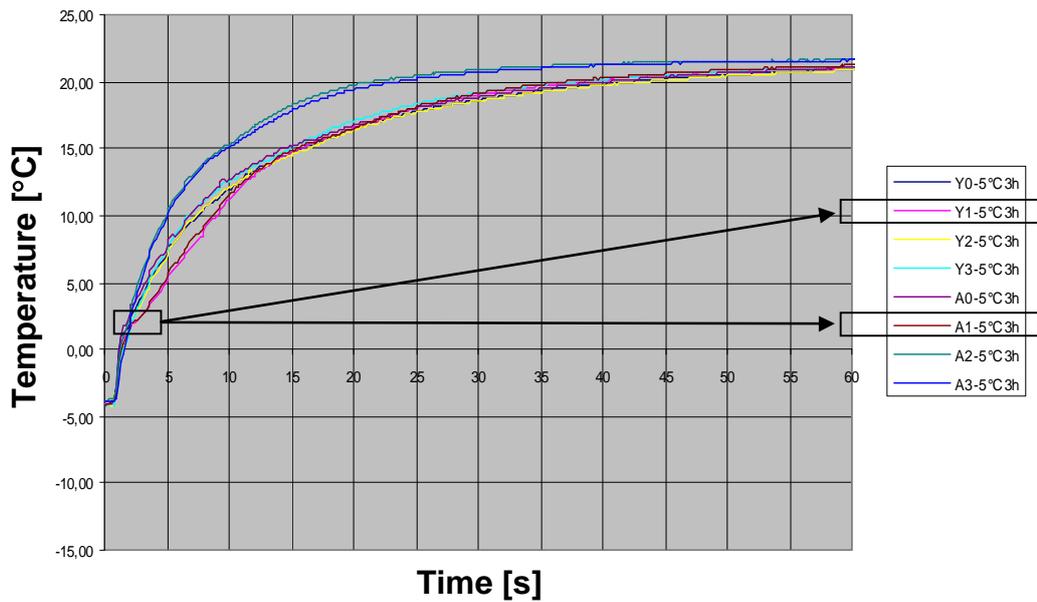
Figure 15: *Comparison of the temperature evolution of all measurement points of the rudder. Initial temperature 5 °C, cooling time 3 hours. The plateau (slight deviation from expected) observed for Y1 and A1 curves near 0°C refers to moisture inside the rudder. Picture courtesy of VTT.*

Thermographic research with real aircraft structures showed the complicity of the inspection, due to the additional (metallic) supporting structures and/or changes in material thicknesses inside the structure. Sufficient amount of reference data (inspected non-defected structures) was found to be a very practical way of defining warming-up behaviour of non-defected structures. Speed of the warming-up of the real rudder structure was inspected in order to find proper optimal inspection frame (OIF) time for finding the penetrated water from each structure. An example of the OIF time of different surface areas of the rudder structure can be seen (as a green colour) in **Fig. 16**.
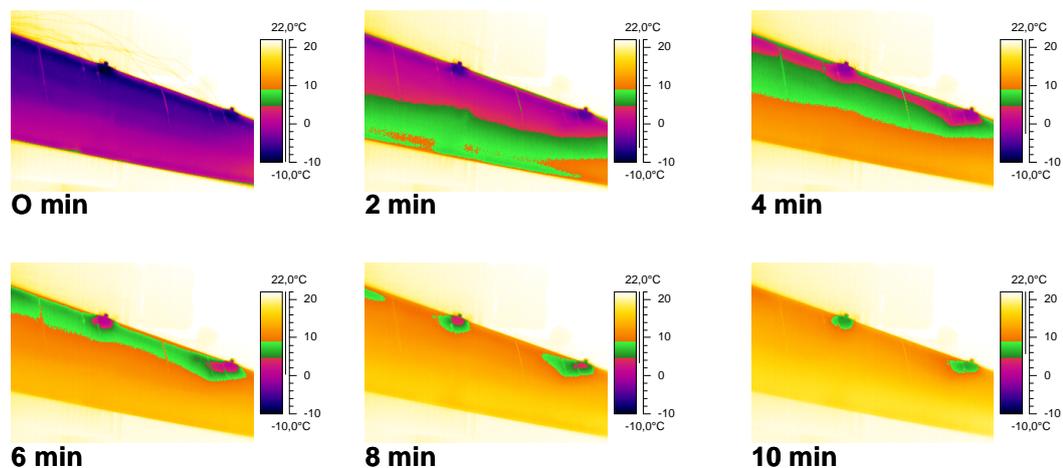
Figure 16: *Optimal inspection frame time for different areas of the rudder surface (green area in the images). 0-time refers the temperature where the first area reaches 5 °C. Picture courtesy of VTT.*

The warming-up behaviour of other structures was also investigated and the optimal inspection times for interesting areas (inspection points) were determinated. Inspection of the other structures is reported in [Saarimäki 2008; Saarimäki 2008b; QIRT2008].

The effects of environmental conditions were investigated to ensure reliable inspection conditions for the inspected structure. Different cooling temperatures and times were investigated to ensure that the whole structure is frozen before the warming phase. Different defrosting conditions showed however that weather and cooling conditions affected strongly to the results. To prevent the condensation of moisture and hence formation of rime layer on the surfaces is a critical factor, which can be significantly reduced and even eliminated by cooling the whole aircraft or composite structure in a hangar with proper ventilation.

13.2.3.2 Phased array ultrasonics of aircraft parts made of composites

Ultrasonic NDI techniques applicable to the examination of aircraft parts made of either single or multi layer composite materials have been studied at VTT [Lahdenperä & Leskelä 2009] in cooperation with the FINAF, Patria Aviation and TKK. Ultrasonic phased array technique and single transducer technique were applied (pulse echo mode). Suitable equipment (ultrasonic transducers and equipment as well as a manual scanner) were used in the study. The examined parts consisted of test samples containing artificial defects (crushed core, potted core, debonding, delamination, flat bottom holes), as well as a F/A-18 horizontal stabilator of a foreign origin retired from service after nearly 6000 FH, from which selected areas were chosen for the examinations. The examination surfaces of the test samples were painted. The horizontal stabilator was painted "as is". The examination volume included the surface laminate and the interface (adhesive layer) between the surface laminate and the honeycomb core.

The recorded ultrasonic data was used to generate B and C scans from the examined areas for the purposes of data interpretation and reporting. The use of the B and C scans is helpful to gain understanding of the internal structure and defects therein, as long as there is a commonality between artificial (test samples) and true (flown aircraft parts) structural features and internal flaw characteristics. The B and C scans can also be applied to compare the results of consecutive examinations.

13.2.3.2.1 Test samples with artificial flaws

All flaws within the surface laminate of the test samples were detected with conventional and phased array ultrasonics. The artificial flaws within the interface between the surface laminate and the adhesive layer were detected. The artificial debond between the adhesive layer and the honeycomb core was not detected (the core was cut out manually with a sharp thin blade knife without damaging the adhesive layer). An example of the results is provided in *Fig. 17*.
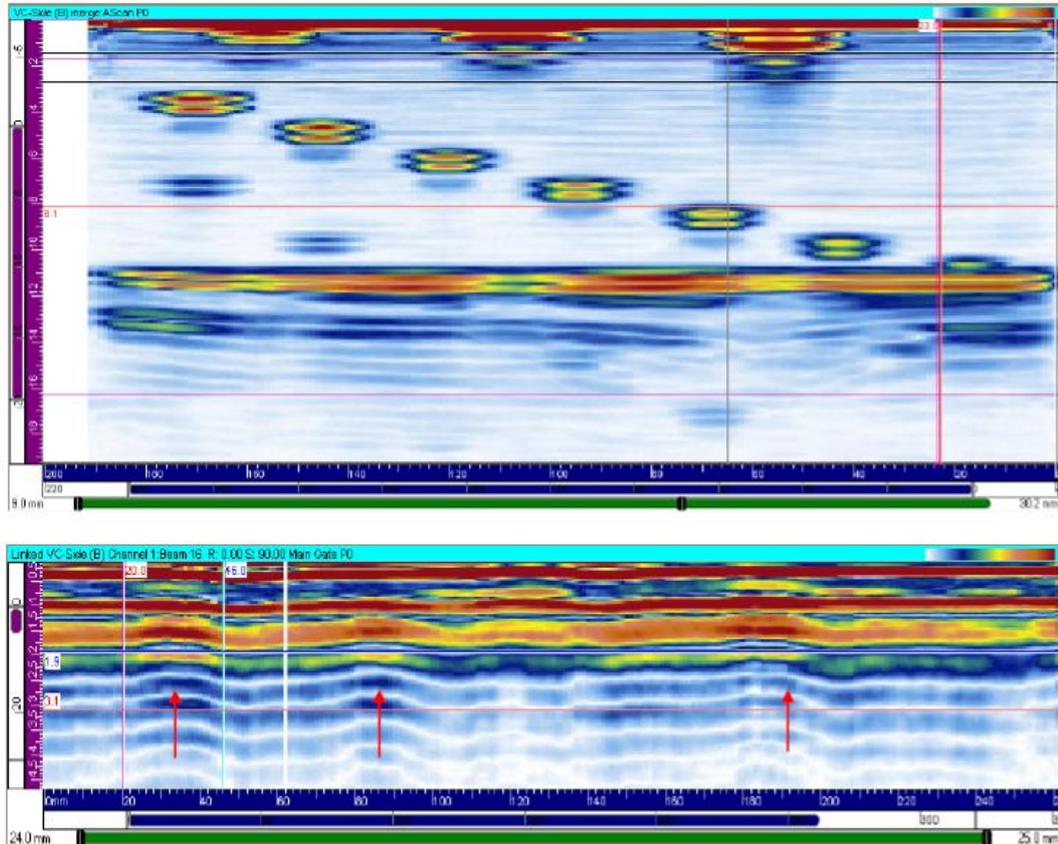
Figure 17:   *Examples of B scans from test samples. **Above:** Artificial defects (7 drilled flat bottom holes of different depth). All holes were well detected. Each hole is giving rise to a double indication, due to the shape of the ultrasonic pulse. **Below:** Artificial defects (unbond within the adhesive layer between the surface laminate and the honeycomb core). Three of the four flaws can be seen (marked with red arrows). Picture courtesy of VTT.*

13.2.3.2.2   Horizontal stabilator

The achieved examination sensitivity was found to depend on the surface curvature (aerodynamic shape) of the horizontal stabilator skin and the geometric dimensions of the ultrasonic transducers used.

On the basis of the results, recommendations regarding proper equipment and procedures to be applied in the examination of aircraft structural components fabricated of composite materials were made.

13.2.3.3   Developments in metal bonding

The difficulties in developing durable and robust surface preparation techniques have limited the use of bonded joints in highly loaded metal to metal and metal to composite structural joints in aircraft applications. The PAA and γ-GPS silane based techniques have matured to an acceptable level with aluminium. Some difficulties are still experienced with γ-GPS silane on titanium. However, no acceptable method has been available for structural steel bonding.

In the DIARC process the metal part is plasma treated in a vacuum chamber at room temperature. Ions with enough kinetic energy form a thin (from nanometers to microns) well adherent

amorphous and dense nanostructure when they hit the surface. The process is environmentally safe and economical. The surface is dense, hard, corrosion resistant, has very low coefficient of friction, and is also bondable to epoxy. In addition to epoxy bonding, the DIARC process can be used for coating tools, sliding parts and molds for lower friction and wear resistance, and for replacing other environmentally hazardous corrosion protection coatings on metals (e.g. epoxy primers containing chromates or cadmium often used with high strength steels). For epoxy bonding the treated metal part does not need any additional primer. It also stays stable and is robust to the bonding process. The DIARC pre-treatment thus decreases the workload in the final bonding and also decreases the requirements for the surface treatment stage of the process.

Testing has been performed with the AC-130 Sol-Gel and DIARC plasma coating surface treatment methods for metal bonding applications. Bare and clad 7075 aluminium, TiAl-4V titanium, AISI 304 and AISI 4130N steels were bonded with the 120°C curable FM300-2 epoxy adhesive. Wedge test specimens were tested at hot/wet (60°C/98%RH) environment and in neutral and salt hot (60°C) water immersion. The γ-GPS silane based AC-130 Sol-Gel treatment provided acceptable results at hot/wet conditions with bare and clad aluminium even without primer when grit blast or suitable mechanical abrasion techniques were used. The crack growth was gradual and the failure mode was over 95% cohesive. With titanium the BR 6747-1 primer improved the durability of AC-130 Sol-Gel treatment to an acceptable level. AC-130 Sol-Gel with the AISI 301 steel provided a reasonable crack growth but unacceptable failure mode at hot/wet conditions.

The testing of the DIARC plasma coating with the 301 steel and titanium in epoxy bonding provided very good results at hot/wet environment. The crack growth measured in the wedge test was less than 5 mm in two days and the failure mode was 100% cohesive. The results were as good as the best wedge test results achieved in aluminium bonding. The DIARC plasma treatment increases the durability of bonded steel joints to the same level as composite to composite joints, which opens a wholly new option to design light bonded metal/composite joints and structures for space, air, naval, land, construction and industry applications.

Immersion tests in neutral tap water and in salt water (North Baltic Sea water with 0,5% salt content) have been accomplished. Results showed that DIARC coating provides good results with aluminium, steel and titanium also in immersion. With high strength steel also the edges have to be coated for preventing corrosion between base material an the coating. AC-130 Sol-Gel treatment provided inconsistent results in hot water immersion tests. A more detailed description of the above metal bonding activities can be found in the ICAF 2009 poster presentation [Aakkula, Lumppio, Saarela 2009].

13.2.3.4 Progressive failure analysis of composite laminates – update

Research activities to come up with an analysis tool (ABAQUS & GENOA) of progressive failure analysis of composite laminates subjected to static loading were highlighted in [ICAF 2007 Chapter 13.6.4.3]. Recent research activities at TKK are highlighted below.

The analysis of laminate strength after the First Ply Failure (FPF) has been studied for decades. Traditional strength based failure criteria and damage models based on stiffness reductions of partially failed plies were investigated in a worldwide failure exercise [Soden, Hinton, Kaddour, 1998]. Some contestants argued that the strength data provided for unidirectional (UD) ply was not adequate to predict laminate failure. The transverse *in-situ* strength of an embedded ply in a laminate is greater than the transverse strength of a UD laminate. FE analysis is nowadays a common practice when large structures are analysed. The calculated strengths for structures including stress concentrations are mesh dependant because small elements close to the stress concentrations predict high stresses. This study addresses these two problems and presents analysis results for notched glass fibre laminates using a traditional progressive failure model and an energy based damage model. The results are calculated with various mesh sizes and the in-situ strength effects are taken into account. Ply data and reference data for two laminates were measured.

Tests were performed on glass fibre prepreg laminates. Six specimens were used for each test performed. The damage progression in the laminate was simulated using two different damage models; ply discount method and an energy based damage model. Additionally to the tested laminates, a notched UD laminate was analysed in transverse tension loading. The failure loads

were calculated with three different mesh sizes. A close-up of the meshes is shown in *Fig. 18* and the failure loads in respect to the element size are shown in *Fig. 19*, in which the measured failure loads with the standard deviation are shown as a horizontal grey area. The software used in the analysis was ABAQUS.
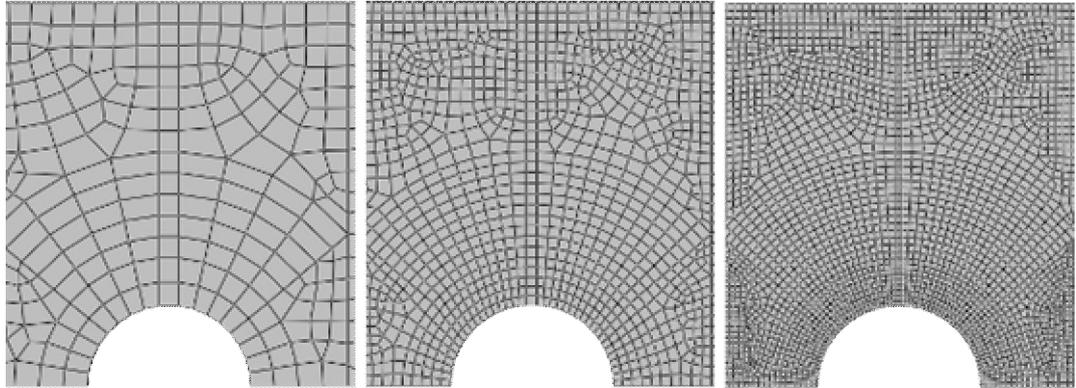
Figure 18:   *Meshes with 0.8 mm (left), 0.4 mm (middle) and 0.2 mm (right) elements used in the study. Courtesy of TKK.*
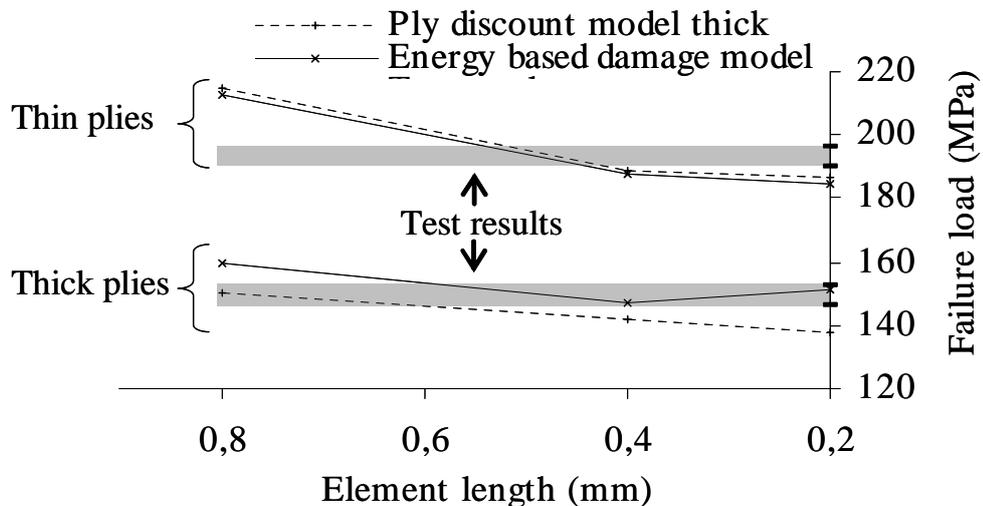
Figure 19:   *Failure loads vs. Element size using two damage models. The measured failure loads with the standard deviation are shown as a grey colour. Courtesy of TKK.*

For UD laminates the energy based damage model gave good results irrespective of the element size but for multidirectional laminates the results were mesh dependant with both methods. The dependence on mesh size was greater for the laminate with thin plies than or the laminate with thick plies. More work needs to be done to determine the effect of laminate layup and material properties on the mesh dependency. As expected, the laminates with thin plies carried higher loads than the laminates with thick plies. This indicates that the strength of an embedded ply, i.e. the *in-situ* strength, is a function of the layer thickness. The equations proposed by Camanho [Camanho

et al 2006] worked well to model this phenomenon. The results for the final failure load agreed well with the test results [Skyttä, Saarela, Wallin 2008].

13.2.3.5 Fracture mechanics based studies on composite structures – update

The fracture mechanics based methods (Virtual Crack Closure Technique – VCCT and Discrete Cohesive Zone Modelling – DCZM), as mentioned in [ICAF 2007 Chaper 13.6.4.3] have been furter studied at TKK.

The use of advanced numerical analysis methods for progressive failure of composite laminates requires that the fracture mechanic behaviour of composites must be well understood. The use of fracture mechanics based methods was investigated in two master's thesis projects. The first thesis concentrated on numerical analysis methods and the second on testing fracture mechanic properties for composite laminates.

13.2.3.5.1 Numerical analysis methods

In the first study at TKK the numerical analysis methods developed for analysis of single delaminations are reviewed based on literature survey [Jokinen 2009]. The main focus in the thesis was the virtual crack closure technique (VCCT). The main principle of the method is presented in *Fig. 20*.
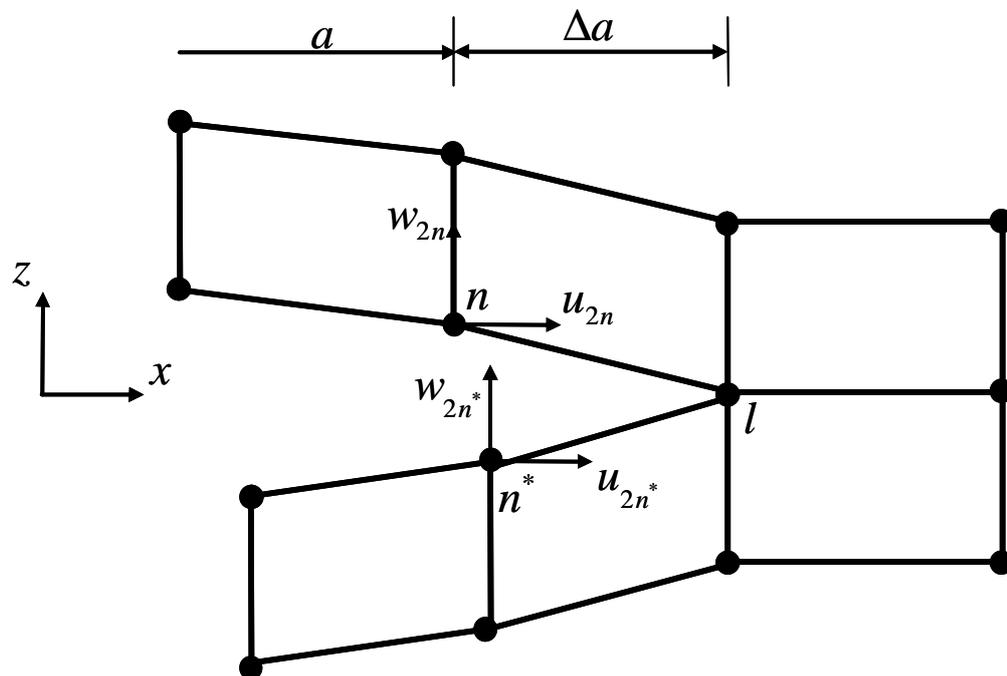
Figure 20:   *Basic principle of the VCCT analysis method [Jokinen 2009]. Courtesy of TKK.*

The basic theory of the method is presented and examples found from literature are reviewed. Own analyses (using ABAQUS) included 2D and 3D analyses on the same cases as found in the literature survey. In addition, the method was applied to study a tensile test specimen including out-of-plane stress state. On the basis of work performed, a solid base for further analyses of composite structures was obtained and it can be concluded the method is a powerful tool for the analysis of single delaminations in laminates.

13.2.3.5.2   Fracture mechanics properties of composite laminates

The second thesis study at TKK concentrated on testing fracture mechanics parameters for composite laminates [Hintikka 2009]. The existing test methods and standards were reviewed including pure mode I, II and III test methods and various mixed mode test methods. In addition, the challenges in actual testing as well as interpretation of test results were reviewed. The test facilities were designed including test fixtures and measurement arrangements, *Fig. 21*.
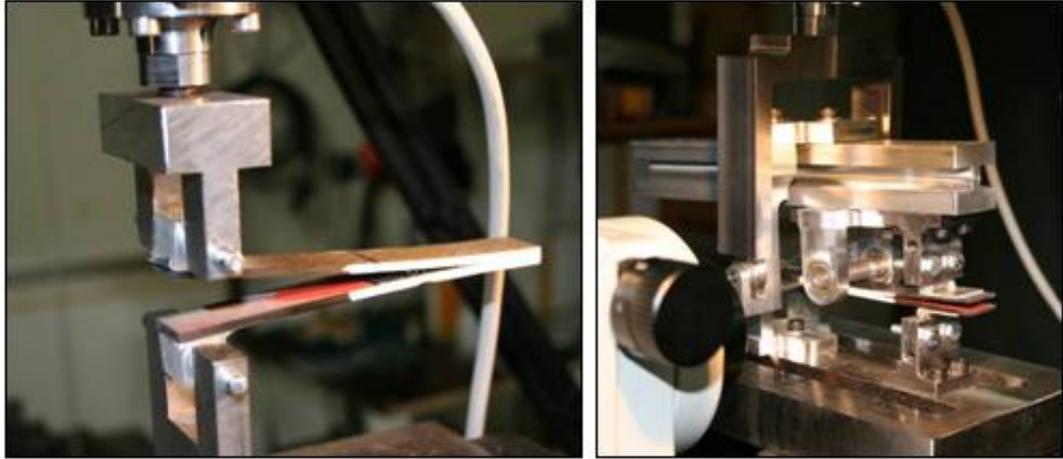
Figure 21:   *Left: Testing the mode I properties for laminate using standard DCB test method (DCB – Double Cantilever Beam). Right: Testing the mixed mode I/II properties for a laminate using the MMB test method (MMB – Mixed Mode Bending). Courtesy of TKK.*

The basic properties in mode I, II and mixed mode I/II were measured for AS4/3501-6 prepreg material. The test parameters included the effect of the lay-up, environmental exposure and the use of hybrid metal/composite test specimens. Based on the work the capability to make fracture mechanic testing was obtained and basic properties for the AS4/3501-6 were measured that can later be used as a reference data.

13.2.4 Structural integrity of metallic materials

Various surface renewal activities take place on fleet aircraft to remove incipient cracks arising at structural critical locations in order to make the structure crack-free and more fatigue resistant. Of particular interest in these surface renewal activities are those carried out in regions containing etched surfaces, which – for the FINAF F-18C/D aircraft – are due to e.g. pre-IVD processes during the parts' OEM manufacturing. The highlights of the associated research projects are provided below.

13.2.4.1 Effect of chromic and phosphoric acid anodizing on the fatigue life of 7075-T76

The effect of anodizing on the fatigue life of 1,8 mm sheet aluminium alloy 7075-T76 were studied by Patria and TKK. The test series included 56 specimens: 20 clad, 20 chromic acid anodized and 16 phosphoric acid anodized specimens. The stress ratio was R = -0,3. For all surface preparation methods four specimens were tested at each studied stress level. The fatigue tests were performed by TKK. The main conclusions were [Linna 2007b]:

- If the fatigue stress level is over 200 MPa, the effect of surface preparation is minimal.
- If the fatigue stress level is under 200 MPa, phosphoric and chromic acid anodized specimens were better than clad specimens based on average test results. The margin is even more significant if the stress level is low enough (≤175 MPa).
- In every stress level the scattering of the results was clearly lowest for clad specimens.

13.2.4.2 Effect of surface working methods on the fatigue life of 7050-T7451 (R = -0,3)

The effect of various surface working methods (shot peening, polishing and etching) on fatigue life of laboratory specimens made of two common 7000 series (7050-T7451 and 7175-T7351) subjected to completely reversed cycling (R = -1) were highlighted in [ICAF 2007 Chapter 13.6.6.1]. These experiments were extended by Patria and TKK to obtain data for also R = -0,3 loading as described below.

The effect of surface etching, polishing and shot peening on fatigue life of laboratory specimens made of 7050-T7451 aluminium alloy were investigated. Thickness of the specimens was 6,35 mm, the stock material thickness being 100 mm. All specimens were manufactured in L rolling direction. The total number of specimens was 48 including 12 basic (as machined), 12 etched, 12 polished and 12 shot peened specimens. The tests were made using three different constant amplitude stress levels.

Shot peening with Almen intensity of 0,14 mmA was made by using ceramic beads. The surface roughness of the polished specimen was 0,4 μm $\leq$ R$_a$ $\leq$ 0,6 μm. Etching was similar to the production pre-IVD coating process. The fatigue tests were performed by TKK. The following main test results and LIF's (Life Improvement Factors) were obtained [Linna 2007]:

- if the maximum stress level is higher than 0,5 · σ_y (σ_y = yield stress) polishing is more efficient than shot peening resulting $LIF_{polishing}$ = 2…3,5.
- $LIF_{polishing}$ is always higher than 2.
- Shot peening also improves the fatigue life of the structure, but the benefit is not substantial, if the stress level is relatively high ($\geq$ 0,5 · σ_y).
- Lower stress levels equal better shot peening effects.
- At low stress levels ($\leq$ 0,45 · σ_y), $LIF_{shot\_peening}$ can be more than 5.
- The influence of etching (and IVD coating) is significant, $LIF_{etching}$ can be 0,5 or less

13.2.4.3 Effect of hole preparation methods on the fatigue life of mechanical joints

The effect of hole preparation methods were tested by Patria and TKK using two different test sections. The first set of specimens were made of 3 mm thick Al 7050-T74 plate (stock thickness 100 mm) and 1,8 mm thick Al 7075-T6 sheet. The test series consisted of single lap shear joints. Hole tolerances were Clearance Fit (C/F) and Interference Fit (I/F). The number of fasteners was six in all specimens. 4x12 = 48 specimens were tested using 4 specimens for each S-N –curve point. The fatigue tests were performed by TKK. The main results were [Linna 2007c]:

- For 1,8 mm thick single lap shear specimens, the I/F hole tolerance did not produce fatigue life improvement when comparing to the C/F hole tolerance in all tested stress levels.
- For 3 mm thick single lap shear specimens, the effect of hole tolerance (I/F or C/F) was minimal, but small life improvement factor can be achieved.
- I/F is probably not suitable for single lap shear joints when using relatively thin sheets.
- More test series are needed.

The second series of tests were made of 4 mm thick Al 7075-T76 sheet. The test series consisted of single and double lap shear joints. Hole tolerances were again C/F and I/F. The series included also Cold Worked (C/W) specimens. In the future also Force Mate (F/M) bushed specimens will be tested. The number of specimens for each S-N –curve point was as in the earlier test section totalling 6x12 = 72 specimens. The number of fasteners per specimen was six. The main results were [Linna 2009]:

- For the single lap shear joint, $LIF_{I/F} =1,3$ when comparing to the C/F joint.
- For the single lap shear joint, $LIF_{C/W} =2$ when comparing to the C/F joint.
- For the double lap shear joint $LIF_{I/F} =2$ when comparing to the C/F joint.
- For the double lap shear joint $LIF_{C/W} =3$ or more when comparing to the C/F joint.

13.2.4.4 FISIF Surface Renewal Joint Coupon Program (SRJCP)

The F/A-18 users' FISIF consortium – alphabetically from Australia, Canada (project lead), Finland, Switzerland and the USA – are conducting materials tests to complement the existing data regarding the LIF due to surface renewal operations to help further substantiating the selected potentially simple and cost-effective solutions for fatigue critical areas. The background and motivation of these materials tests were provided in [ICAF 2007 Chapter 13.6.6.2].

Of the hundreds of specimens within the joint project, Finland's share included the constant amplitude fatigue testing of approximately 60 coupon specimens (by VTT) of selected surface finishes:

- Machined, no surface renewal, cycled to failure
- Pre IVD etched, no pre-cycles / surface renewal, cycled to failure
- Pre IVD etched, various amounts of pre-cycles followed by surface renewal, then cycled to failure
- Anodized, no pre-cycles / surface renewal, cycled to failure
- Anodized, various amounts of pre-cycles followed by surface renewal, then cycled to failure

As the test program is underway, the time is not ripe for a more detailed appreciation of the experimental results.

13.2.4.5 Fatigue management policies of the FINAF and the ASIMP

The fatigue management policies of the FINAF have been outlined in previous national reviews [ICAF 2001; ICAF 2003; ICAF 2005; ICAF 2007]. The tools and instructions for the ASIMP documentation for the fatigue life cycle management of the Hawks (meeting the requirements for the remaining post-midlife structural integrity issues) and Hornets (structural lifing policy and damage tolerance aspects) will be developed by Patria for the FINAF Hornet and Hawk aircraft. The first version of the FINAF Aircraft Structural Integrity Management Plan has been delivered for review to the FINAF. The ASIMP methodology follows MIL-STD-1530C guidelines.

13.2.4.6 Reflected (leaky) Rayleigh wave experiments on Canadian parts

The ultrasonic non-destructive testing method, Rayleigh wave technique, was applied in the testing of a selection of CF aircraft samples provided by Canada (the CF and L-3 MAS) under the auspices of FISIF – F/A-18 International Structural Integrity Forum. The samples consisted of laboratory test coupons of the CF-18 web taper section (Y453 bulkhead) and actual parts from the CF-188727 aircraft retired from service. The purpose of the proof-of-concept tests was to check the applicability of the Rayleigh wave technique to detect minute surface cracks from parts known to have been subjected to either laboratory test loads (coupons) or flight-induced loads (aircraft 188727 parts). It was assumed that there would be minute surface cracks resulting from these cyclic loads. The detection of these cracks was the goal of this study.

The location of the UT indications detected from the web taper coupons agreed reasonably well with the reversed liquid penetrant inspection (RLPI) crack indications reported previously by QETE. Surface cracking indications were also detected in UT from the areas where QETE had not reported any indications. It was estimated that the cracks giving rise to the 0.5 mm RLPI indications were also detected in UT. The cracks with shorter RLPI indications could not be reliably detected. No clear crack indications were detected by VTT from the aircraft CF-188727 samples [Jeskanen, Lahdenperä, Siljander, Kauppinen 2009]. Examples of the experiments are shown in *Fig. 22*.
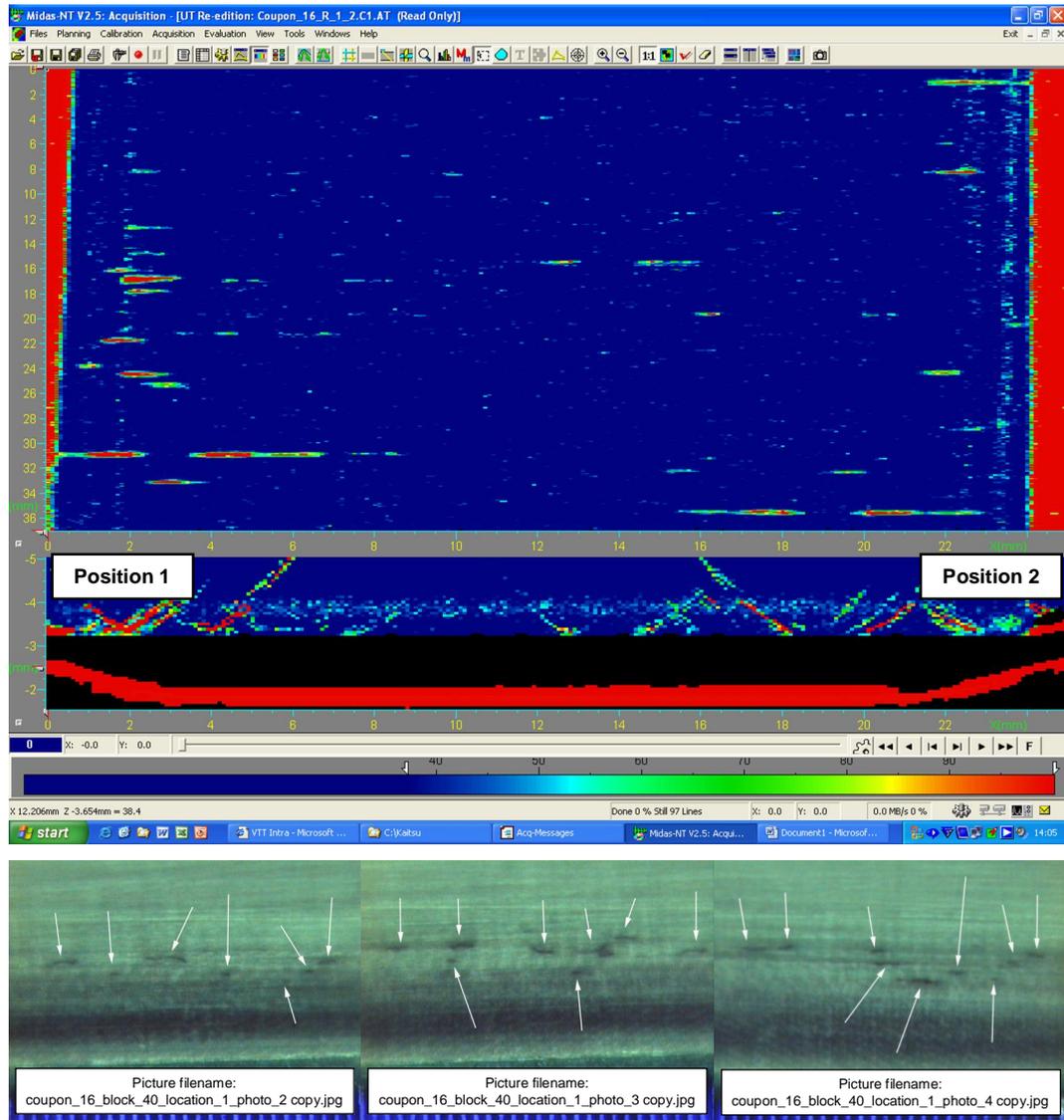
Figure 22a: **Above:** *An example of results obtained with the ultrasonic Rayleigh wave testing by VTT, topmost the C scan (X axis= scanning direction=longitudinal axis of the coupons), below the B scan.* **Below:** *Photographs of the coupon surface after the reversed liquid penetrant inspection (RLPI) by QETE. Multiple ultrasonic indications (VTT, above) well distinguished from the background noise can be seen on the C scan. Multiple indications can also be seen on the photographs from position 1 after RLPI by QETE, below). Note the UT indications between positions 1-2. This area is not included in the RLPI photographs. Picture courtesy of VTT (above) and the CF / L-3 MAS / QETE (below).*
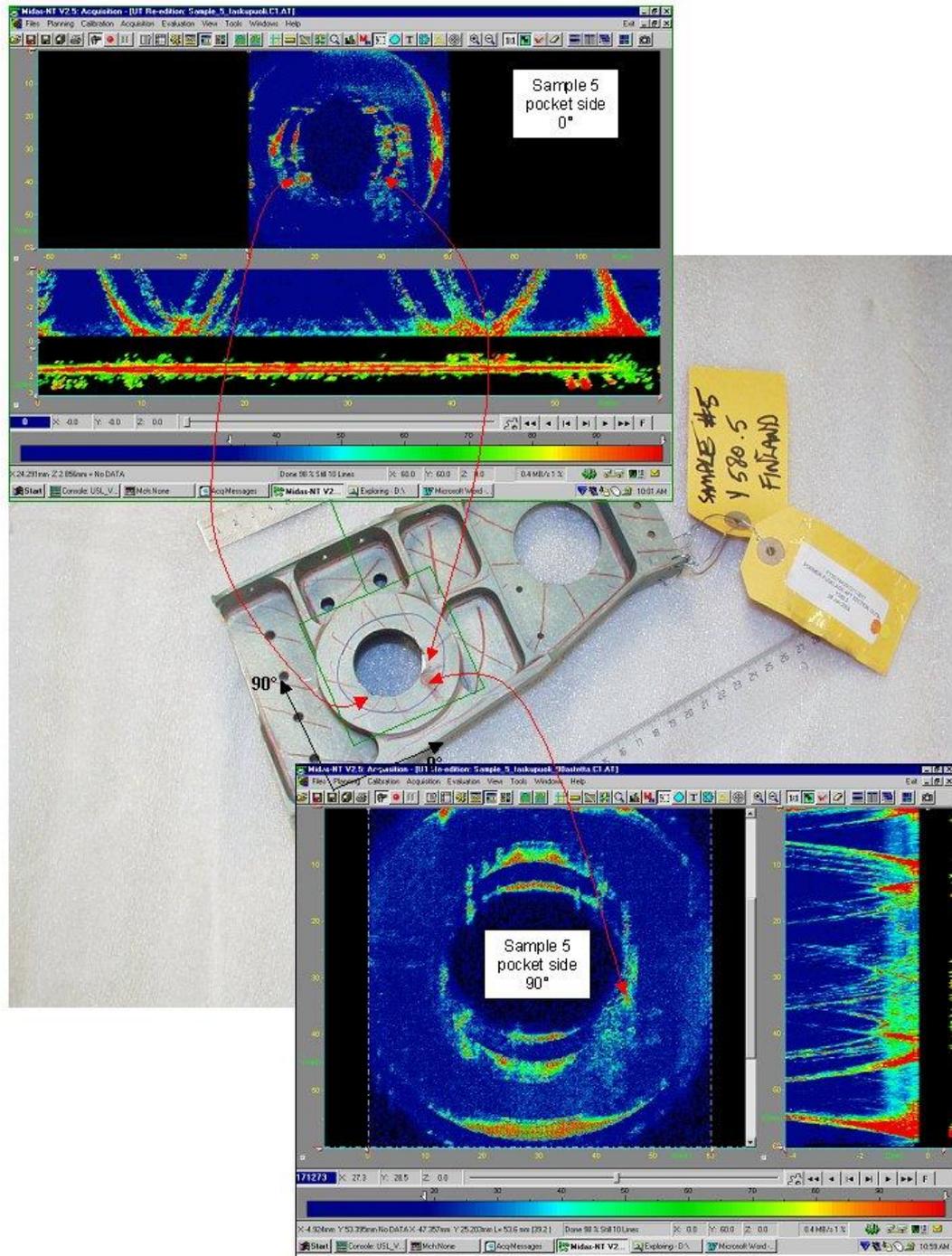
Figure 22b: *Aircraft CF-188727 sample #5, C and B scans of the loom hole area, pocket side. There are indications due to surface dents and scratches. In the upper C scan the angle between the Rayleigh wave and the scanning direction was 0˚. In the lower C scan the angle was 90˚. Picture courtesy of VTT.*

13.2.4.7 Analysis program for multiple fatigue crack initiation, coalescence and growth

The corrosion protection of the aluminium structures of the Hornets has been improved by the OEM during manufacturing of the aircraft by introducing an IVD coating. The process involves surface cleaning by etching (pre-IVD etch) prior to the IVD coating process. The etching process is believed to cause crack-like flaws (etch pits) on the metallic surfaces e.g. [Barter 2003] thus adding unanticipated crack initiation and growth potential.

To quantify the multiple crack initiation, coalescence and growth characteristics of fatigue cracks emanating from the etch pits, (alphabetically) FOI (the Swedish Defence Research Agency), Patria Aviation Oy and VTT teamed up to develop and validate a tool for reliable fatigue analysis. Both analytical and experimental methods were applied in a case study of a representative FINAF F-18 Hornet structural detail subjected to representative service loading.

In the analytical part of the study, developed by FOI, the bulkhead detail was assumed to contain randomly distributed crack-like flaws resulting from the OEM's pre-IVD etching process. A computational framework was developed with which stress intensity factors (SIFs) for multiple 3D cracks with various geometries and at arbitrary locations and in close range can be determined exactly and with control of the error in the computed Mode I, II and III SIFs. Aiming at a reliable probabilistic fatigue crack growth analysis tool with fast determination of the SIFs for multi-site crack patterns and crack shapes/sizes, a novel mathematical multi-scale technique, which utilises a hp-version of the FE method was used to achieve the computational requirements on accuracy, efficiency and generality.

A SIF database was created containing data for 1600 cracks of different sizes located at numerous different locations in the bulkhead detail. A module was developed for very fast and virtually exact calculation of SIF data for a multiple crack scenario consisting of arbitrary combinations of (non-overlapping) cracks in the database. Probabilistic fracture mechanics analysis was performed using Monte Carlo simulations. Crack sizes were calculated by cycle-by-cycle crack growth analysis. Proper accounts were taken for crack interaction, spectrum loading with load interaction, small crack growth and small load cycles for the actual material (Al7050-T7451). Validated fatigue crack growth data was used together with proper crack propagation laws. The numerical solution scheme was verified by extensive convergence test. Further details of the analytical model and the analysis program is provided in [Andersson *et al* 2009] and the ICAF National Review Sweden [Ansell 2009].

13.2.5 Repair technologies

13.2.5.1 Repair technologies for the FINAF F-18 metallic primary structures

The applicability of existing repair engineering technologies tailored to the FINAF F-18 Hornets has been investigated by Patria Aviation. The main emphasis has been on the metallic primary structures. The repair technologies include testing of interference fit and cold-working of fastener holes, development of proof-of-concept-level bonded Boron fibre composite reinforcement for aluminium structure and testing of various surface treatments such as polishing and sulphuric and chromic acid anodizing.

13.2.5.2 Spectrum fatigue tests of I-beams representing a bulkhead detail of F-18

The analytical fatigue life prediction method by FOI for multiple interacting 3D cracks (Chapter 13.2.4.7) will be validated using results from variable amplitude fatigue tests. The fatigue tests consisted of integral I-type beams of a geometry emulating a critical part of an F-18 Hornet fuselage bulkhead subjected to actual in-flight bending and tension loads in the critical section. The I-beams were designed by Patria Aviation. The fatigue tests and associated activities (NDI, fractography etc.) were done by VTT [Koski, Juntunen, Sarkimo, Merinen, Teittinen, Pitkänen 2009], *Fig. 23*.
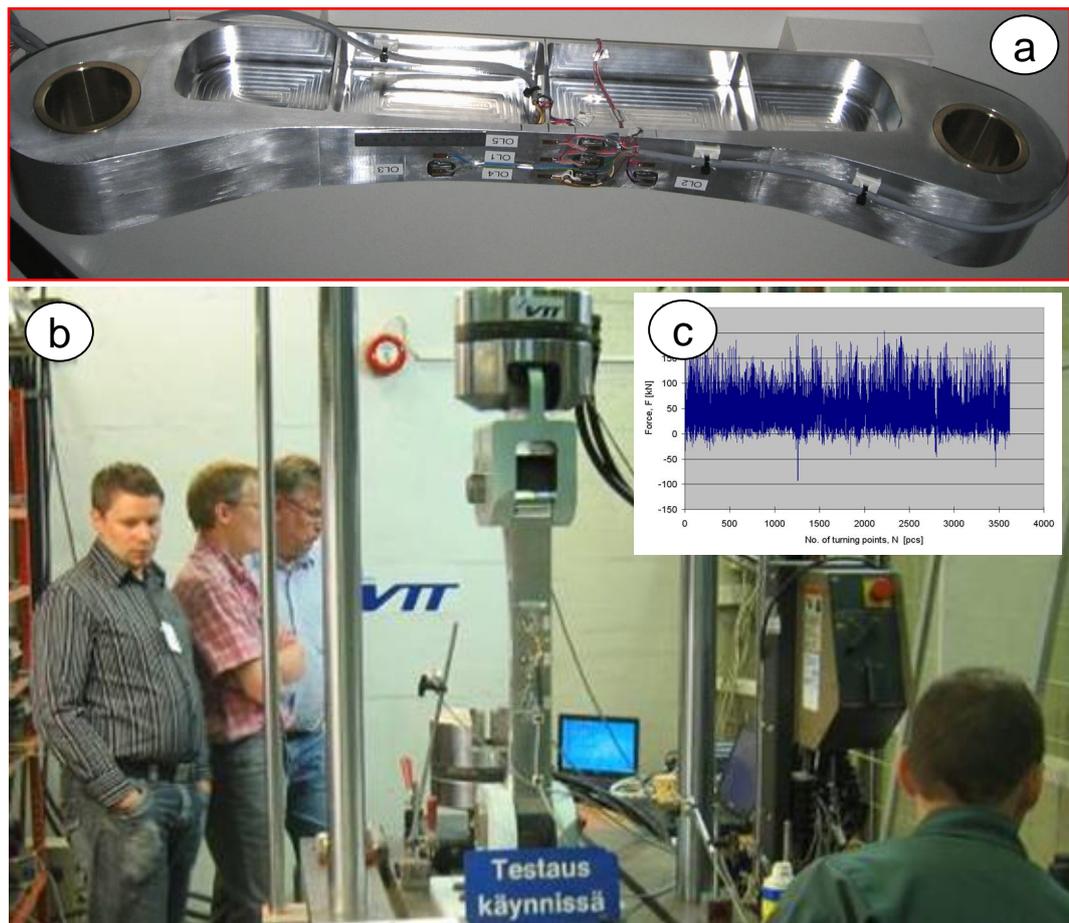
Figure 23: An overview of the experimental set-up of the I-beams: *a)* An I-beam instrumented with strain gauges; *b)* spectrum fatigue test set-up (the I-beam mounted vertically); *c)* load spectrum. Picture courtesy of VTT.

The applied fatigue tests were part of a test series in which a strengthening method (proactive repair patching) of a critical part of the bulkhead was validated. The test series included eight I-beam specimens. Two specimens (without the pre-IVD etching) were used for residual strength purposes. Six specimens (all surfaces pre-IVD etched) were fatigue tested. One residual strength and three fatigue specimens without any strengthening (proactive repair patching) served as reference specimens. These three reference fatigue specimens were utilised in the verification of FOI's analytical tool. The variable amplitude spectrum used in the fatigue tests was created using the HOLM flight data (Chapter 13.2.2.1).

Fractographic inspection, carried out after the fatigue testing was utilised in the validation process to quantify main crack features: point(s) of origin, local crack growth rates and directions; and associated secondary cracks adjacent to the main crack e.g. [Varis 2009]. Marker loads were included in the test spectrum in order to characterize conclusions made from the basis of the quantitative fractographic inspection. An example of the fractography activities is provided in *Fig. 24*.
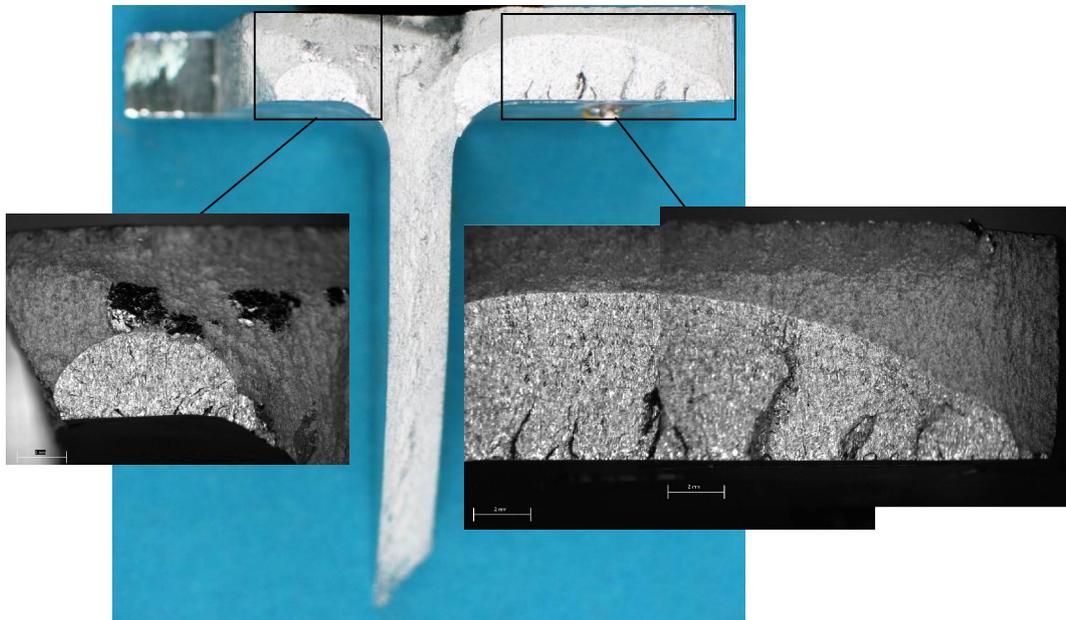
Figure 24: *Examples of the fractographic inspection results of an I-beam specimen tested to failure. **Top:** Fracture surface from one I-beam specimen. **Below:** Higher magnification pictures (stereo micrograph), from which multiple crack initiation features can clearly be seen. Picture courtesy of VTT.*

13.2.6 Structural health monitoring

The following activities, aimed at a permanently installed structural health monitoring system (SHMS) on a selected aircraft type to monitor the suspected fatigue critical location in an automatic manner and without the need to dismantle the aircraft for the inspections unless the SHMS indicates otherwise, summarise the highlights.

13.2.6.1 Integrated Eddy current inspection system – update

Previous research activities related to the development of low-cost ET sensors and related electronics were highlighted in [ICAF 2007 Chapter 13.6.2.2]. The goal at Patria Aviation Oy and Emmecon Oy is to develop a SHMS and associated integrated low-cost Eddy current (ET) sensors to be permanently installed in air vehicles.

A prototype of the microcontroller based inspection module was developed and tested. Sensor interface of the module was electrically multiplexed allowing sequential use of up to four sensors. The measurement parameters are individually programmable for each sensor. The trends of measuring responses for each sensor can be tracked and the damage initiation and/or growth can be interpreted from the trend. The performance of developed sensors and electronics in a real aircraft structure was evaluated in 2007 using a retired Hawk centre fuselage section subjected to fuel tank pressurisation cycling.

The integrated Eddy current (ET) inspection system consists of the following elements, *Fig. 25*:

– a laptop computer for overall system configuration and control as well as for measurement data analyses
– a microcontroller-based, networked and automated signal processing unit (SPU)
– a field multiplexer (FMUX)
– an interface (data bus) to the SPU
– low-cost ET sensors, installed in fatigue critical structural locations

FMUX (field multiplexer)

Interface (data bus) to SPU (Signal Processing Unit)

Cabling to sensor groups #2, #3 and #4

Sensor group #1 (4 sensors)
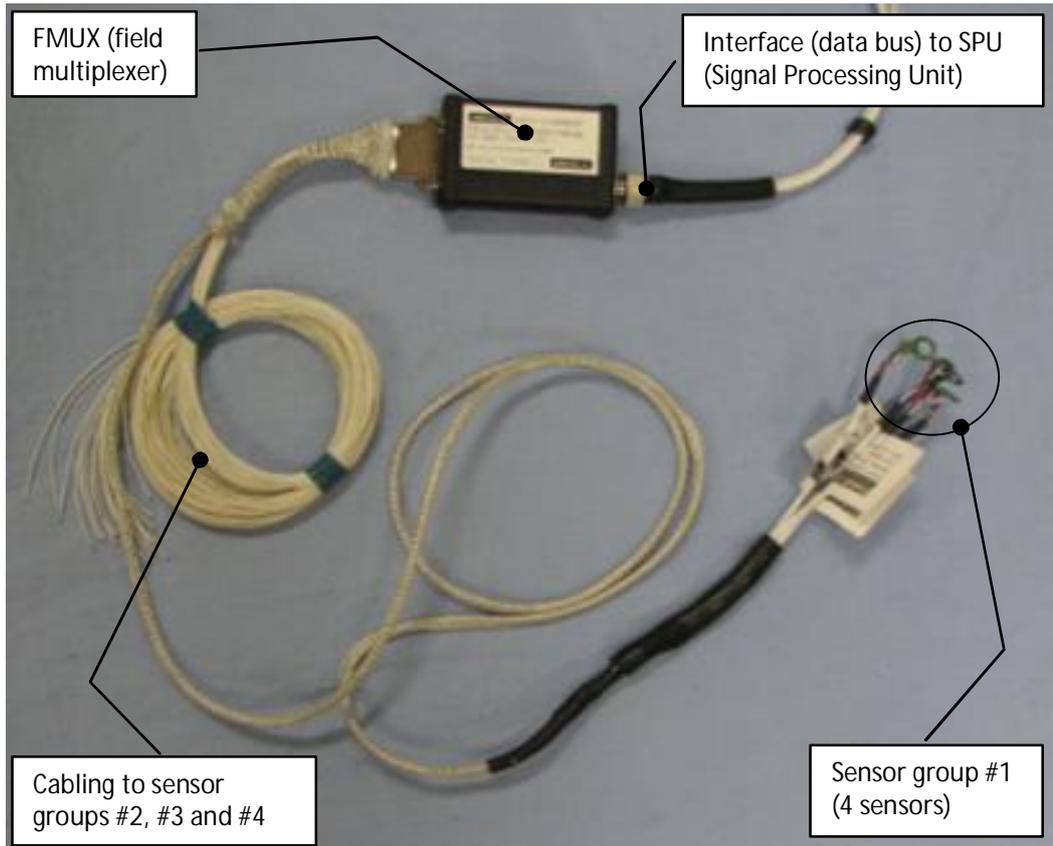
Figure 25a: *An overview of the integrated Eddy current (ET) inspection system which is permanently installed on-board the aircraft in question. Courtesy of Emmecon Oy.*
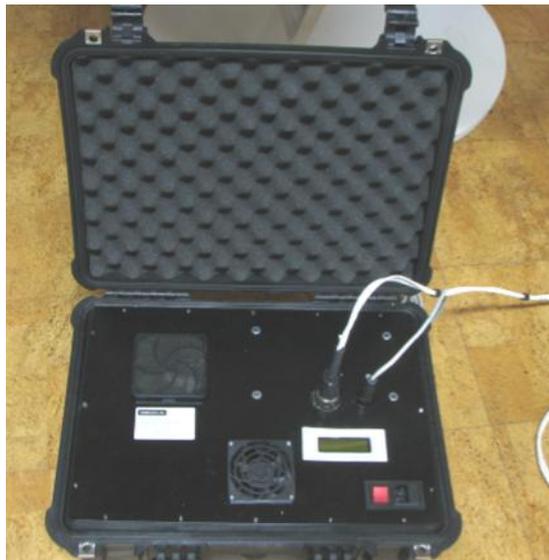
Figure 25b: *Mobile signal processing unit to be used by ground maintenance personnel. Courtesy of Emmecon Oy.*

There can be four sensor groups, maximum of four sensors in each group thus providing maximum of 16 ET sensors for each FMUX. Several FMUXs can be connected in parallel to the data bus.

The environmental tests in true aircraft conditions – in accordance with the MIL-STD-810E – will be realised in near future. It is worthwhile to note that special emphasis has been put in the elimination of temperature drift characteristics within the entire SHMS, including the on-board and ground system elements of the ET inspection system.

13.2.6.2 F-18 flying test bed (the AHMOS pod) – update

Previous highlights of the joint European research and technology program under the auspices of EDA, the project *"ERG 103.015: Prototype Demonstration of Modular Structural Health Monitoring (SHM) System for Military Platforms"* were provided in former reviews e.g. [ICAF 2007 Chapter 13.6.2.1].

Two of the many flying test laboratories of the AHMOS II project were related to research activities in Finland [Siljander & Hedman 2008]. The first flying test bench, designed and developed by Patria Aviation Oy, was subjected to the FINAF usage for a given FH. The other flying test laboratory, designed and developed by BAE Systems, was subjected to test flights with an aircraft arranged by BAE Systems.

As a part of AHMOS II project, SHM Systems were tested in actual military aviation environment. The goal was partly to get experience of the operation of the SHMSs and partly to get feedback from the ground crews who will operate the systems in the future.

Patria designed a flying test laboratory (the AHMOS pod) which was carried at the wingtip weapon station of F-18 Hornet of the FINAF. The pod was a look-alike of the AIM-9M Sidewinder air-to-air missile without wings and fins. The test setup consisted of fatigue test specimens, an electric motor with associated equipment to generate constant amplitude loading and the tested SHMSs. In the F-18 tests strain gauge (Emmecon Oy) and ultrasonic systems (KT-Systems GmbH) were used. The test equipment is shown in *Fig. 26*.
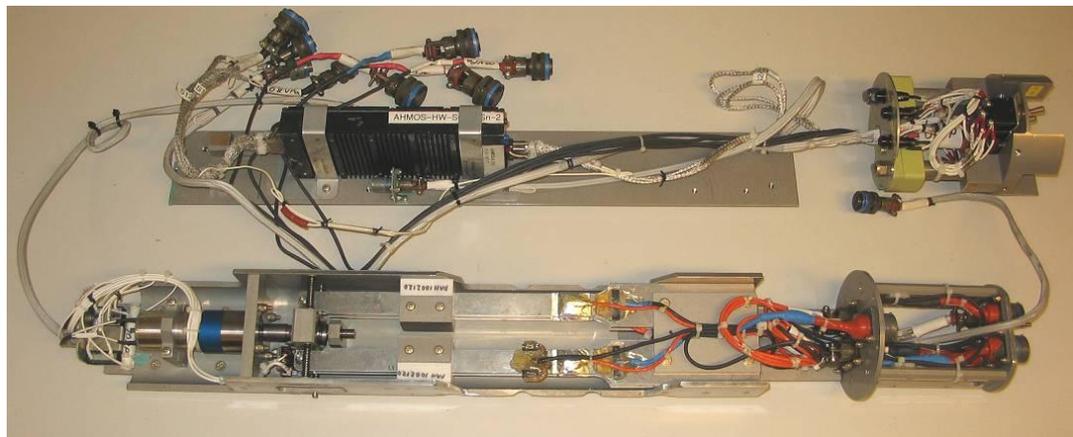
Figure 26:   *The test equipment inside the AHMOS pod. Courtesy of Patria Aviation Oy.*

By the end of the project the pod logged 17 flights and 11,5 flight hours, which was less than originally planned. The flight testing, carried out entirely by the Flight Test Centre of the FINAF, covered the whole V-n-envelope of the F-18. During the tests the lowest ground temperature was -26°C. In spite of the severe conditions the tested systems operated normally. During the flight tests, small cracks emerged to the test specimens as anticipated. The strain gauge system was able to indicate the emergence of cracking [Pirtola 2007].

13.2.7 Mechanical systems integrity

Research on the field of mechanical systems integrity is divided in two main areas, i.e. *Simulation and modelling* as well as *Condition control and monitoring*. To support the two main areas, research efforts are also focused into problem-oriented smaller scale research subjects. Below is an overview of the two research areas, which is carried out in co-operation between the FINAF and TUT/IHA.

13.2.7.1 Simulation and modelling

The main goal of the Simulation and modelling research is to improve understanding on the entire hydraulic system and its interconnections and interactions with other aircraft subsystems and structures. Another goal is the ability to simulate the functional characteristics of selected components and their modification alternatives from the viewpoint of the performance of the entire hydraulic system and ultimately the entire aircraft.

Hydraulic system modelling is done in two different levels of detail to enable studying both complete system and individual component levels with appropriate accuracy. Detailed analytical component models are developed for single component or partial system simulation for situations where point of interest lies in single component and high level of accuracy and detail is needed [Aaltonen *et al* 2007; Hietala 2008; Hämäläinen 2007]. The complete system model, which is connected to the flight simulation model (HUTFLY2) in an interactive manner, utilises simplified semi-empirical component models thus enabling model solving in real-time. HUTFLY2 is capable of producing simplified aerodynamic forces acting on flight control surfaces and also command values for hydraulic actuators. A simulation environment utilising distributed computing was developed to enable real-time solving of simulation models needed in hardware/pilot-in-the-loop (HIL/PIL). ***Fig. 27*** describes the basic structure of the simulation environment.
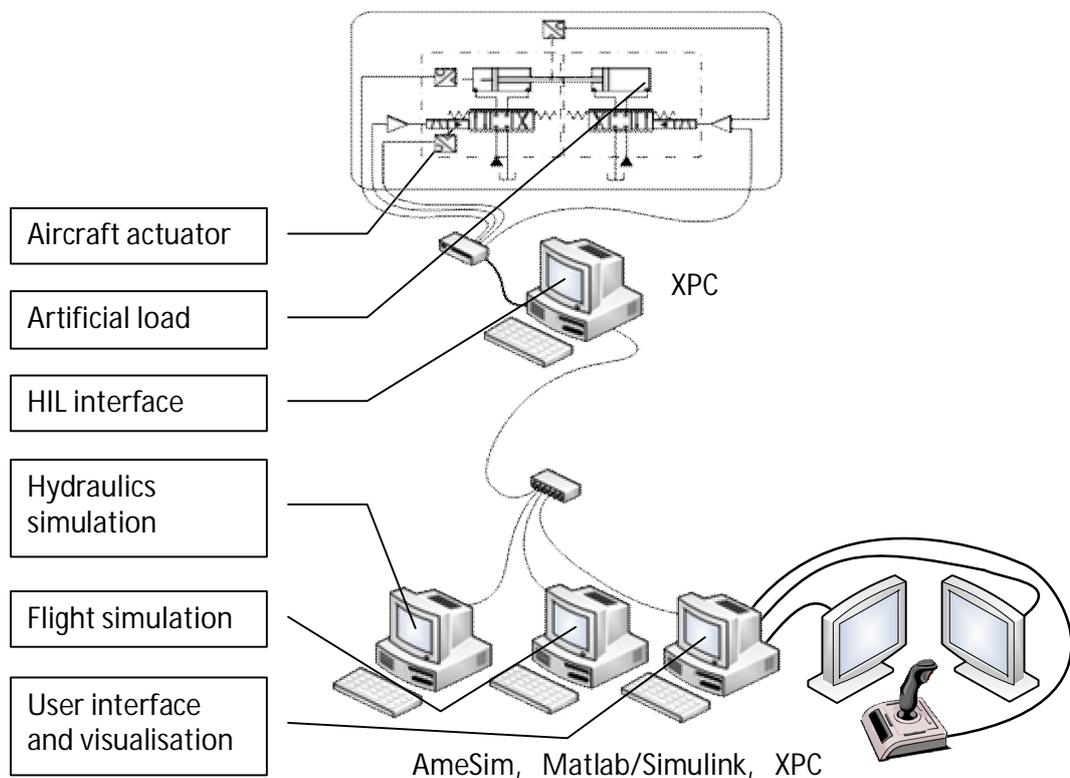
Figure 27: *Basic structure of the simulation environment. Courtesy of TUT / IHA.*

The hardware-in-the-loop (HIL) interface can be used for including real components into the simulated system. The HIL interface transforms command values (produced by the flight simulation) into real-life command signals for the component and calculated loads into real-life loading forces. The loading force is produced by hydraulic servo actuator counteracting the real-life component. Hydraulic system variables (such as available flow rate, system pressure etc.) can also be varied according to instantaneous operating conditions of the hydraulic system calculated by the hydraulic system simulation model. Output parameters of the real component are measured and the HIL interface transmits the output parameters to system and flight simulations. The user interface and visualisation give simplified possibilities for pilot-in-the-loop (PIL) simulations. Simulation can be controlled in realtime from a simple virtual cockpit. When finished the simulation environment and simulation models together form a virtual ironbird which gives a possibility to study hydraulic system operation in an arbitrary in-flight operation point.

13.2.7.2   Condition control and monitoring

Condition control and monitoring research is targeted into improving usability and reliability of aircraft hydraulic systems and also to lower maintenance costs involved. Research efforts in this field include:

- Monitoring the hydraulic fluid quality of the fleet and supporting equipment [Aaltonen *et al* 2007b] and developing practices to improve it;
- Testing hydraulic fluids to find variations in between different manufacturing brands and to find most suitable fluid;
- Developing an in-line hydraulic system condition monitoring unit.

The research of the in-line condition monitoring unit is targeted into developing a hydraulic system condition monitoring unit based on COTS condition monitoring sensor technology (chemical quality sensors and particle counters). The unit is developed to be installed in portable test stands where it monitors the quality of the fluid returning from the aircraft's system and also the fluid quality in the test stand itself. Thus the unit will have two main applications: It can be used for determining the condition of the hydraulic system for predictive maintenance purposes and it acts as contamination migration safe guard in between individual air vehicles by indicating contamination in the fluid of the test stand. Application of in-line particle counters for fault finding is also studied extensively.

13.2.8 Engine integrity

The FINAF, Patria Aviation Oy, TUT and VTT teamed up to improve the in-country capabilities related to jet engine integrity assessments in a proactive manner i.e. before the life limits related to certain FINAF F-18 engine components are reached. Special emphasis has been on experimental methods focused on certain turbine blades and the life extension possibilities therein.

VTT conducted fractographic examinations of selected turbine blades removed from service i.e. the condition of the base material and the coating has been studied by destructive metallography: Cracks located around the cooling holes and oriented in the longitudinal (axial) and perpendicular direction of the blades were typically observed, *Fig. 28*. A literature review on the failure mechanisms (fatigue, creep, oxidation) of selected turbine blades was conducted at VTT [Auerkari, Tuurna, Rantala 2008], for which TUT performed damage mapping scenarios [Sarlin 2008]. A test program to determine the crack growth rate was defined. The static crack growth experiments are being carried out, and creep-fatigue tests will be made in the next stage.

2 mm
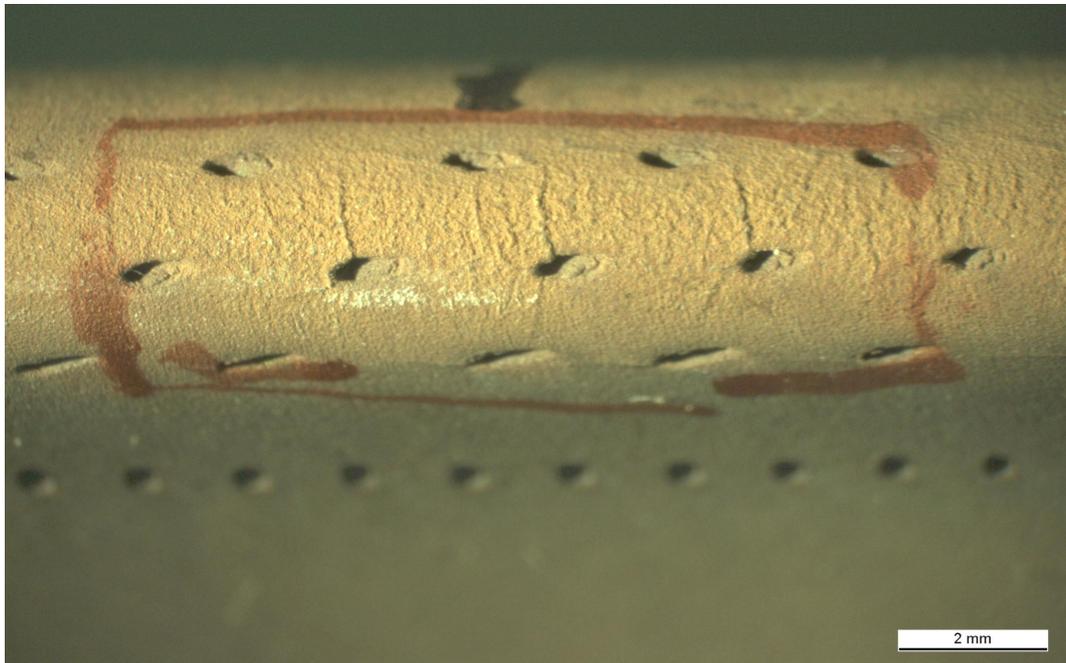
Figure 28:   *An example of cracks found around the cooling holes of the FINAF's F-18 engine's high pressure 1st stage turbine blade removed from service. Courtesy of the FINAF.*

13.2.9   Life cycle cost models

The overall goal is to improve the life cycle cost (LCC) analysis capabilities of the FINAF by developing a mathematical model for LCC calculations of avionic system components.

Based on the mathematical model created by VTT for the Mission Computer (MC) [Välisalo & Tuominen 2008], the model prototype was generalised for the life cycle cost analysis of other avionic system components, such as the oxygen generating system (OBOGS) and the air speed indicator [Välisalo 2008].

The features of the prototype model include the cost elements for corrective and preventive maintenance, as well as the options to estimate the failure (availability) expectancy for an individual component from within a population of similar components, including the spare (redundant) components. The generalised model has been tested using real life cycle cost data of the selected avionic components. The prototype model will be tailored to a production version by Insta DefSec Oy.

13.3   Related activities

13.3.1   From HN-413 (one-seater) to HN-468 (two-seater) F-18 Hornet

Two FINAF F-18C Hornets collided in mid air on a training mission at night in November 2001. One aircraft (HN-430) was destroyed (the pilot ejected and survived). The pilot of the other aircraft was able to return the severely damaged HN-413 jet to base with one engine.

On the FINAF initiative in 2002, Patria started investigating possibilities to modify the damaged one-seater into a two-seater knowing that suitable D models were not available. Having evaluated a suitable B model forward fuselage, the FINAF purchased the CF-920 from Canada in 2003. With funding provided by the Finnish Government, Patria started the challenging modification work in November 2005 in cooperation with the FINAF, the US Navy, Boeing and L-3 MAS.

In order to provide the combined airframe adequate fatigue life, extensive fatigue analysis was performed based both on ex-Canadian and future Finnish usage, and critical forward fuselage structural members such as upper longerons and skins were replaced by new parts. Several other structural modifications were performed to update the airframe into more recent building standard. The aircraft final assembly will be essentially completed in June 2009 and the aircraft is expected to be at delivery phase in the second half of 2009.

13.3.2   Runway deicing chemicals

The corrosion issues concerning the FINAF aircraft started emerging in late 1990's [Paajanen 2007]. It soon became evident that the corrosion issues were of a new type, affecting specifically to "long lead time" and expensive items such as landing gear components (shock absorbers and wheels), as well as various electrical connectors within the undercarriage areas, *Fig. 29*. There was a suspicion that the corrosion might be due to the "new" runway de-icers[4] replacing urea used to maintain safe winter operations by mitigating adverse effects of snow and ice on runway friction.
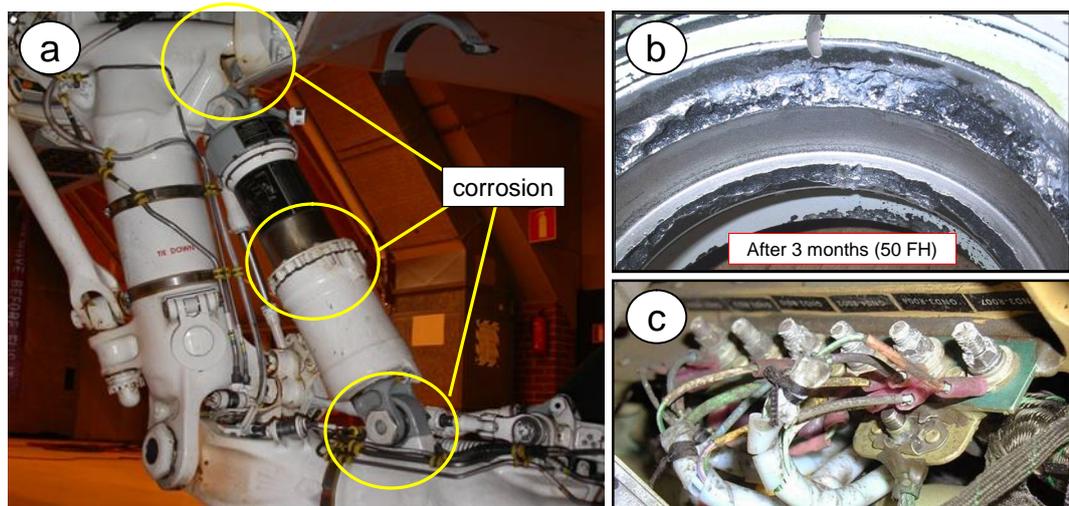

Figure 29:   *An example corrosion findings of the FINAF: a) Corrosion in the main landing gears of the F-18 Hornet; b) corrosion in the landing gears of Hawks; c) corrosion problems in various electrical connectors. Courtesy of the FINAF.*

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[4] The "new" de-icers are: Potassium acetate and formate, sodium acetate and formate, calcium magnesium acetate

The corrosion tests (cadmium plated high strength steel samples subjected to exposure tests for 28 days as per the Boeing method [Straus 2002]) carried out in 2003 by the FINAF and TUT lead to the following conclusions:

– there were no winners among "new" de-icers i.e. the acetates and formates dissolve cadmium plating although they have passed the AMS1435 tests: The cadmium corrosion test according to AMS 1435 does not predict the corrosion phenomena of the de-icers. Further, the use of corrosion inhibitors makes it possible to pass the tests required by aviation standards.
– The "new" de-icers cause heavy corrosion to parts made of magnesium alloys and when the de-icing chemicals dilute, corrosion effects increase. The "new" de-icers have good electrical conductivity (which is a feature not favoured), they are harmful to all sacrificial coatings and their use will possess high risk for galvanic corrosion.
– Cadmium is usually used to protect high strength steel from corrosion and cadmium corrosion can result to corrosion of high strength steel thus increasing the risk of hydrogen embrittlement (HE) or stress corrosion cracking (SCC).

In a follow-on research program in 2005, the FINAF and TUT investigated a new chemical called Betafrost (BF), developed by Finnish companies Fortum Oil and Gas Ltd and Danisco. The BF (fluid), which is based on a chemical called *betaine* (trimethyl glycine which is a by-product of sugar manufacturing process), was subjected to field tests in actual runway conditions and the following conclusions were drawn:

– BF, although 3-4 times more expensive than acetates, is better than urea but not as good as acetates or formates.
– BF's ice-melting capacity should be better: The condition of the runway must be monitored frequently (temperature, friction values) and BF can cause surprises (safety risks)
– The FINAF should have a solid de-icer as reserve: Urea is not a good alternative thus sodium formate or acetate grain are of interest

In the course of the above in-country activities [Kuokkala, Huttunen-Saarivirta, Kokkonen, Vivo 2006] it became evident that similar problems are faced world wide [ACRP 2008]. One of the main risks includes the risk of hidden corrosion (including the risk of HE and SCC) in high strength steel parts, such as landing gears. A more recent example of hidden corrosion is the collapse of the starboard side main landing gear (MLG) of SAS Dash 8 during landing [Dash 2009]. According to the accident investigation report [Dash 2009], the main reason for the MLG collapse was hidden, heavy corrosion in the MLG actuator rod end threads. Although the starboard side MLG collapsed, cracks 30 mm were found also from the same part from the port side MLG. Both actuators had been examined three months before the failure because of loose nuts.

Together with three other European nations, Finland will participate in a three-year (2009 – 2011) research program under the auspices of EDA (European Defence Agency). Finland's interest in the project *Environmentally Compliant Coatings* is to investigate SolGel coatings in the corrosion protection of cadmium plated high strength steel parts and parts made of magnesium alloys subjected to the environmental attack of the runway de-icer chemicals. Finland's project team consists of (alphabetically) the FINAF, Millidyne Oy, Patria Aviation Oy, TUT and VTT.

13.3.3 Landing simulations

The FINAF has been funding the development of a fully functional model of the F/A-18C/D Hornet landing gear in order to investigate reasons for landing gear failures (so-called Planing Link failures) that have caused several Hornet landing mishaps in Finland and elsewhere. The F/A-18C/D Hornet landing gear has been modelled using Adams simulation software by Patria Aviation. The model consists of the nose landing gear (NLG) and both main landing gears (MLG) thus providing asymmetric landing simulation capability. Adams-Simulink co-simulation is used to simulate the actual MLG function in touchdown e.g. [Öström 2008c].

To define realistic approach flight paths and to include aerodynamic effects for the landing simulations, Matlab/Simulink based HUTFLY2 flight simulation software with F-18C Hornet aircraft model has been used by VTT to provide the necessary data. The output files from each

simulated landing case were sent to Patria as input files for Adams-Simulink co-simulation which were used to simulate the actual MLG function in touchdown [Viitanen & Janhunen 2008]. HUTFLY2 is generic flight simulation software which includes an atmospheric model, non-linear six degree-of-freedom rigid-body flat-earth equations of motion, determination of forces and moments and other common routines required by the simulation. The F-18C Hornet aircraft model, describing the aerodynamic properties, Flight Control System (FCS), mass distribution and propulsion system, was incorporated into the simulation as a subsystem [Öström 2008a; Öström 2008b]. An example of the landing simulation is provided in *Fig. 30*. Further details of the landing simulations can be found in [Öström, Lähteenmäki, Viitanen 2008].
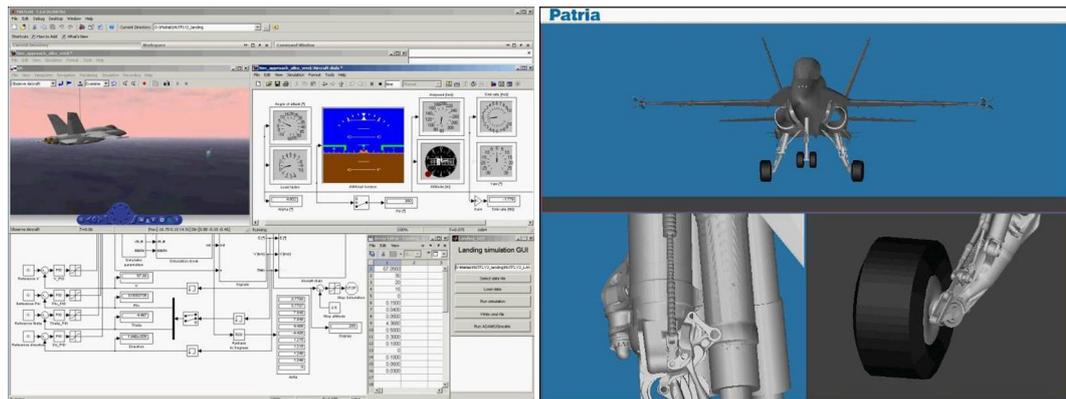

Figure 30:   *Left: An example landing approach simulation of F-18 in the HUTFLY2 flight simulator at VTT. Right: An example co-simulation of the F-18 landing by Patria Aviation. Courtesy of VTT (left) and Patria Aviation Oy (right).*

13.3.4   Process to revise the maintenance intervals of a fighter aircraft

A method of how to re-evaluate the maintenance intervals of the fighter aircraft JAS 39 Gripen, adapted to the work processes used at Saab, was presented in a Master's Thesis work at TKK [Peltoniemi 2009]. The areas of responsibility, Saab policies and co-operation were in the focus. The objective of the thesis was also to study the use of the current database for fault remarks and to find ways to utilise it more.

Knowledge of how the maintenance is originally planned is of significant importance when revising the preventive maintenance intervals. For this purpose, the theory part of the thesis included an overview of the MSG-3, F-FMEA and fault tree analysis techniques. General information was given on how the maintenance is planned for Gripen by the manufacturer Saab. The theory part also summarised how the fault remarks are collected and stored for the purposes of statistics. The factors affecting the statistics were briefly discussed. The thesis also included a short review to the earlier studies of the subject done at Saab. Another part of the thesis work was to study suitable presentations of the fault remarks from the common database. Co-operation and information flow in the company was studied through interviews and continuous discussions with the employees. As a result, a work process in the company to revise maintenance intervals was described.

The experimental part of the study included the testing of the process by re-evaluating a pair of maintenance intervals according to the method developed: One case example was included and another case study was reviewed. Actual data was used when studying the statistics.

The presentation of the fault remarks from the database worked as an additional basis when re-evaluating the current preventive maintenance intervals of a maintenance object. The work process

presented, involving employees from different departments, should be advantageous when re-evaluating the maintenance intervals in the future.

13.4   Intermediate summary: it pays to ASIMP

The applied research & development activities associated to the ASIMP (Aircraft Structural Integrity Management Plan) – orchestrated and funded nationally over the years by the FINAF and briefly reviewed herein – have not only markedly improved the in-country capabilities within the FINAF, national industry and academia, but also gained savings of the order of 600 million euros [PIA ILO 2008].

13.5   Future activities: ASIMP 2010 – 2012

In line with the fatigue management policy of the FINAF, outlined for the first time within the ICAF community [ICAF 2001 Chapter 2] and highlighted within the ICAF national reviews from [ICAF 2003; ICAF 2005; ICAF 2007] to this document, the FINAF have again defined a follow-on program to the aircraft structural research activities for the period 2010 – 2012. The follow-on-program, ASIMP 2010 – 2012, will be based on the elements briefly outlined in this review. The new ASIMP will be biased towards proactive life cycle support methodology developments to support the fatigue management principles set to protect the FINAF's fixed wing jets.

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Summary

This document was prepared for the delivery to the 31st Conference of the International Committee on Aeronautical Fatigue scheduled to be held in Rotterdam, the Netherlands on 25-26 May 2009.

A review is given of the aircraft structural fatigue research and associated activities which form part of the programs within the Finnish Air Force Command (FINAFCOM), the Finnish Air Force Air Materiel Command (FINAFAMC), Patria Aviation Oy, the Technical Research Centre of Finland (VTT), Helsinki University of Technology (TKK), Tampere University of Technology Institute of Signal Processing (TUT/ISP) and Department of Materials Science (TUT/DMS), Finflo Oy, Emmecon Oy and Insta DefSec Oy.

The review summarises fatigue related research programs and investigations on specific military fixed wing aircraft since the previous Finnish National Review (tabled in the 30th Conference, ICAF, Naples, Italy) up to April 2009.

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