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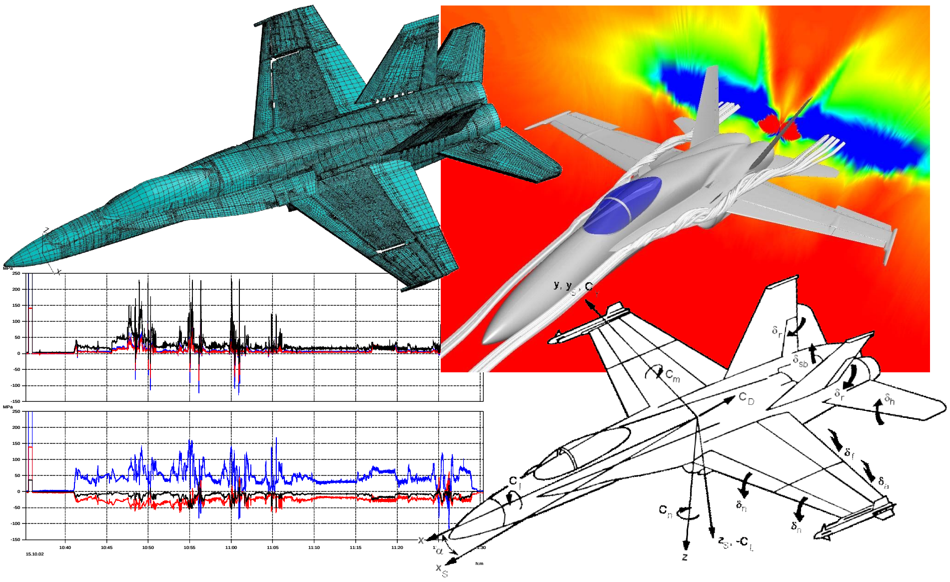

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A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND DURING THE PERIOD APRIL 2003 TO APRIL 2005

Presented at the 29th Conference of the International Committee on Aeronautical Fatigue (ICAF), Hamburg, Germany, 6-10 June 2005

Customer:	Finnish Air Force Headquarters Aircraft and Weapon Systems Division

Edited by
Aslak Siljander

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Title

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Summary

This document was prepared for the delivery to the 29th Conference and 23rd Symposium of the International Committee on Aeronautical Fatigue scheduled to be held in Hamburg, Germany on 6 -10 June 2005.

A review is given of the aircraft fatigue research and associated activities which form part of the programs within the Finnish Air Force Headquarters (FiAF HQ), the Finnish Air Force Air Materiel Command (FiAF AMC), Patria Aviation Oy Aircraft Business Unit (PFA), the Technical Research Centre of Finland (VTT), Helsinki University of Technology's (TKK) Laboratory of Lightweight Structures (TKK/KRT), Laboratory of Applied Thermodynamics (TKK/LAT) and Laboratory of Aerodynamics (TKK/LAD), Finflo Ltd. and Emmecon Ltd.

The review summarizes fatigue related research programs and investigations on specific military fixed wing aircraft since the previous Finnish National Review (presented in the 28th Conference, ICAF 2003, Luzerne, Switzerland) up to April 2005.

Date Espoo 31 May, 2005

Harri Soininen	Aslak Siljander	Keijo Koski
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Espoo, 30 April 2005

Editor

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1 Introduction

The year 2005 marks the 87th anniversary of the Finnish Air Force (FiAF). Currently there are 62 F-18C/D fighters, 50 Mk.51/51A Hawk jet trainers and 28 Valmet Vinka primary trainers within the FiAF. During the writing of this report, approximately 50000 FH have been flown with the Hornets, 200000 FH with the Hawks and 120000 FH with the Vinkas. No FiAF aircraft of these type designations have been lost due to structural issues.

Although this national review will concentrate on the Hawk and Hornet structural activities only, it is worthwhile to mention that the Vinka's Life Extension Program (LEP), as briefly described in [ICAF 2001; Chapter 3], has been implemented fleet wide by Patria Aviation by the end of 2004.

The severity of the Finnish usage in view of structural fatigue with the two jet aircraft types of noteworthy maneuvering capability can be seen in ***Fig. 1*** (Hornet) and ***Fig. 2*** (Hawk). Figs 1 and 2 clearly demonstrate the need to further develop concrete and systematic efforts on a national level to cope with the structural deterioration effects of these two aircraft types. These efforts are briefly described in this national review.

This Finnish review of current aeronautical fatigue investigations up to April 2005 comprises inputs from the organizations listed below.

FiAF HQ	The Finnish Air Force Headquarters, Aircraft and Weapon Systems Division, P.O. Box 30, FIN-41161 Tikkakoski; Finland
FiAF AMC	The Finnish Air Force, Air Materiel Command, P.O. Box 210, FIN-33101 Tampere; Finland
PFA	Patria Aviation Oy, Aircraft Business Unit, FIN-35600 Halli; Finland
TKK/KRT	Helsinki University of Technology, Laboratory of Lightweight Structures; P.O. Box 4300, FIN-02015 HUT; Finland
TKK/LAT	Helsinki University of Technology, Laboratory of Applied Thermodynamics, P.O. Box 4400, 02015 HUT; Finland
TKK/LAD	Helsinki University of Technology, Laboratory of Aerodynamics, P.O. Box 4400, 02015 TKK; Finland
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VTT	VTT Industrial Systems, Product Performance, Aircraft Structures, P.O. Box 1705 (Otakaari 7 B), FIN-02044 VTT; Finland VTT Industrial Systems, Product Performance, Maritime Operations and the Environment, P.O. Box 1705 (Otakaari 7 B), FIN-02044 VTT; Finland VTT Industrial Systems, Materials and Structural Integrity, NDE of Materials and Structures, P.O. Box 1704 (Kemistintie 3), FIN-02044 VTT; Finland VTT Processes, Materials and Chemicals, P.O. Box 1607 (Sinitaival 6), FIN-33101 Tampere; Finland

2 FiAF fatigue management policy and the ASIMP

The fatigue management policies used in the FiAF fleet management were outlined in the previous Finnish national reviews [ICAF 2001; ICAF 2003]. Since these policies, framework documents in which more rigorous damage tolerance based principles into the fleet fatigue management have been developed and formalized within the FiAF. The damage tolerance principles are in the form of formal Aircraft Structural Integrity Management Plans (ASIMP) [PAK I 1:15 2005 & PAK I 2:11 2004]. The objective of the new ASIMP philosophy is to formalize the existing procedures to be able to better direct the programs according to e.g. the FiAF fleet management principles. The first version of the FiAF F-18 ASIMP will be published during 2005.

3 Hawk Mk.51 and Hawk Mk.51A

3.1 Repair methods embodiments

The structural repair and inspection method development for the known structural damage scenarios [ICAF 2003; Chapter 3.1], developed by Patria and the FiAF, have been implemented in the Hawk fleet [Raunio & Tikka 2003]. The fleet-wide implementation, or the completion of it, will be manifested in the roll-out of the last FiAF Hawk on June 8, 2005.

The following chapters summarize some of the associated efforts.

3.2 Operator specific fatigue life analysis using virtual fatigue test

The fatigue life of one critical structural detail in the wing of the FiAF BAe Hawk Mk 51 was examined with analytical methods. Calculated results were compared with component test results. Traditional fatigue life calculation approach, which relies on finite element models and aerodynamic results from a Navier–Stokes flow solver, gave in this case unsatisfactory results. The used load spectrum was based on flight test measurements. In order to get more accurate fatigue analysis results, a virtual fatigue test approach was used. The load distribution and load history of the manufacturer's full scale fatigue tests were reproduced by using an FE model. The peak-through histories of the stresses in the critical structural location were determined, and predicted fatigue lives according to the test were calculated. A fatigue life calibration coefficient based on the ratio of virtual fatigue test estimates versus observed results in the test was calculated. By correcting the results of the traditional fatigue life analyses with the calibration coefficients, more accurate fatigue life estimates in operator usage could be given. Those were validated with component level tests. The realized costs of the approach used do reveal the economical benefit of the virtual fatigue test. A more detailed description of the above will be published elsewhere [Tikka 2005a].

3.3 Wing teardown inspection

Patria Aviation has conducted a teardown inspection for one of the retired premod 999 standard wings. The reason for this study was the numerous incidents found during the manufacturer's Full Scale Fatigue Test (FSFT) as the concern for new, until this far unknown damage types.

Based on the FSFT findings, Patria has earlier analyzed the most critical locations of the wing. These analyses did show positive, but in some cases extremely small margins compared to the certified fatigue life [Tikka & Keinonen 2001; Tikka 2003]. In order to support these analyses and to investigate also the non-analyzed FSFT incident locations and possible unknown damage types, a teardown inspection was necessary.

The teardown inspection was started with all normal structural inspections applicable to FiAF Hawk Mk 51's. This was done in order to allow the evaluation of standard inspection procedures in case those damages were detected in later stages of the study. The next step was the removal of control surfaces, practically all brackets, linkages etc. parts. Assemblies were subjected to further inspections including cut-outs and dismantle where necessary (***Fig . 3a***). Paint was removed from smaller parts (***Fig. 3b***) and a 100% penetrant (PT) or magnetic particle (MT) inspection was conducted (***Fig. 3c & 3d***). The last step in the study was the removal of leading the edge skins, inspection hole cutting to the integral torsion box and the removal of a noticeable amount of fasteners (***Fig. 3e & 3f***). This allowed a detailed eddy current (ET) and ultrasonic (UT) inspection on areas and fastener holes otherwise unreachable.

In the inspections until this far two new damage types have been discovered in sheet metal parts and one in machined parts. One damage has been discovered in a honeycomb structure. In the areas with most critical known damage types (based on FSFT findings) no cracking is found until now. Also the areas, where the FSFT loading was known to be non representative have been clean.

The teardown has produced a good amount of new, mostly positive, information about the structural integrity of the premod 999 wing. The information is in line with the fatigue life analysis made earlier, and with the experience of known damage types. Some new anomalies are found and the investigation of those is still going on. A similar teardown inspection is also planned for a retired tailplane in the near future.

3.4 The OLM programme

The Operational Loads Measurement (OLM) programme, in which the in-flight strain and associated flight parameter data are continuously being captured from two FiAF Mk.51/51A Hawk jet trainers, has been running since 1998. The first short term objective of the Operational Loads Measurement (OLM) programme was to collect usage data to be used to validate the design of the indigenous structural repair and rework efforts of the Finnish Hawk, which have been undertaken to protect and extend the life of the aircraft's structure. The OLM programme is intended to be a rolling programme continuing until the retirement of the Hawk from the FiAF service. Therefore the verified analysis tools and environment should be easy to use, more efficient, faster and more focused to the needs than those the OLM programme was started with. Previous OLM activities have been reported in [ICAF 2001 Chapter 4.4; ICAF 2003 Chapters 3.4, 3.5]. Subsequent activities deal with the further development of the ground analysis environment and a review of the onboard system. ***Fig. 4*** and the following summarize these efforts.

3.4.1 Complete restructuring of the ground analysis environment

3.4.1.1 Activities with the original analysis software

The original analysis software were debugged for error correction purposes, the various stages of the analysis chain were optimized and streamlined e.g. such that "auto features" (scripts) were added to replace routine analysis stages, some analysis modules (e.g. the undercarriage analyses) of the original OLM system were skipped from further analysis, the data archiving and bookkeeping were rationalized and all analyses were rerun [Liukkonen, Viitanen, Laakso, Siljander, Teittinen, Bäckström, Savolainen, Ovaska 2004; Laakso, Viitanen, Koski, Bäckström, Savolainen, Ovaska, Merinen 2004]. These analyses consisted of 924 OLM flights (425 flights with HW-348 and 499 flights with HW-319) and they consist of a wide spectrum of mission types or SPCs (Sortie Profile Codes) currently in use within the FiAF.

At this point, a decision was made to switch to VTT's standard analysis environment for all subsequent and additional analyses, including all new OLM flights, as well as all analysis tool development efforts.

3.4.1.2 Overview of VTT's analysis environment

To gain insight of which manoeuvring types really consume the life of a given structural detail (e.g. comparison of different flights within a given SPC in view of structural life consumption) with the continuously increasing amount of OLM data, an OLM database was developed as a first step towards this goal. Using the OLM database it is possible, in a flexible manner, to sort data flight-by-flight, by mission type (SPC) and to come up with life expenditure values for the flight training syllabi. The features, aspects and application examples of this application, in which the data of the 924 flights are stored, are highlighted elsewhere in the ICAF 2005 [Viitanen, Bäckström, Koski, Voutilainen, Lahtinen, Siljander 2005].

An OLM data repository was created by VTT to the changing needs of the national network. The data repository contains OLM flights data basic processed, e.g. Rainflow counting results for raw and filtered data, maxima and minima per channel and per flight as well as the associated background information.

In addition to the OLM database and the data repository, the streamlining activities of the analysis environment consisted e.g. of the acquisition of a commercially available software environment to serve as the basis for all development efforts, as well as in-house development and implementation of function libraries / own functions for various analyses (e.g. raw data conversion into proper format, rainflow analysis, damage analyses {εN, SN, da/dN}, aircraft parameter analyses) and a report generator, with which the routine analysis results can be printed in a "press-a-button" manner [Teittinen 2004; Bäckström, Liukkonen, Laakso, Viitanen, Koski, Teittinen 2005].

It is worthwhile to note that the new analysis environment has been and will be built on previous experience and needs faced with the flight data analysis efforts of the FiAF F-18 Hornet and vice versa [Liukkonen & Bäckström 2004]. Therefore, all development efforts have been such designed that the analysis capability includes (but is not limited to) both Hawk and Hornet data.

The fracture mechanics approach (the "da/dN" above) to predict residual life for complex crack geometries under spectrum loading was developed, verified and integrated in the new analysis environment [Koski & Bäckström 2003; Koski & Bäckström 2004]. With the da/dN module, many crack cases (e.g. all the Hawk details previously investigated by VTT, see [ICAF 2001; ICAF 2003]) can be run (analyzed) simultaneously in an automatic and batch manner, using user-defined load spectra (e.g. the OLM data). The approach allows rapid analyses depending on a particular need, e.g. the effects of varying mission mix (SPC distribution and its changes), individual SPCs or individual flights on the damage (residual life).

The full life approach (the "SN" above) was developed and integrated in the new analysis environment as well [Bäckström, Liukkonen, Laakso, Viitanen, Koski and Teittinen 2005]. The verification efforts (e.g. against known fleet cracking observations) of the SN approach are underway in close co-operation between the FiAF, Patria Aviation and VTT.

Similar efforts (development, verification and integration in the new analysis environment) of the local strain approach (the "εN" above) are underway.

3.4.2 Review of the onboard system

As the goal is to modify the OLM system to better suit the future needs of the FiAF, changes have been made to the onboard system as well. Patria and VTT carried out the aircraft embodiments. For the HW-348, annual onboard system calibration has been done [Bäckström & Liukkonen 2004] and five strain channels were removed, three new ones were installed and the whole system was calibrated [Tikka & Heletoja 2003; Kettunen 2003; Bäckström, Liukkonen, Viitanen, and Merinen 2004a]. For the HW-319, annual onboard system calibration has been done [Liukkonen 2003; Bäckström 2004] and five strain channels were replaced with five new ones and the system was calibrated [Bäckström, Liukkonen, Viitanen, and Merinen 2004b].

Although the current onboard system has fulfilled the need to get statistically representative amount of data, the overall percentage of OLM flights not found on tapes has been over 10 %. More recent experience shows these numbers are on the rise. Therefore, to further improve the data capture ratio, the current onboard data storage unit (data tape) will be replaced in near future with a more reliable one (e.g. a solid state recorder).

3.4.3 Examples of the analyses using the OLM data

The two OLM jets have different versions of the wing. Investigations done thus far using the OLM data, e.g. [Kettunen 2004a; Kettunen 2004b; Kettunen 2004c; Koski 2004; Viitanen, Bäckström, Koski, Voutilainen, Lahtinen, Siljander 2005] indicate that there would be a difference in the way these wing versions affect to the loading of the aft fuselage regions. Efforts to further study these differences are underway (e.g. dedicated test flights in as identical manner as possible with the two OLM aircraft).

Other studies to find reasons for some service fatigue crack observations on the basis of recorded in-flight structural responses have also been made [Bäckström, Koski, Siljander, Liukkonen, Tikka, Marquis 2004].

An example of the use of the new analysis environment [Bäckström, Liukkonen, Laakso, Viitanen, Koski, Teittinen 2005] with the bulk of the OLM data is provided in ***Fig. 5***. A particularly damaging flight (or a flight of a particular interest) for a given structural detail was first screened using the OLM database [Viitanen, Bäckström, Koski, Voutilainen, Lahtinen, Siljander 2005]. The structural responses (strain time histories) together with those of the aircraft parameters were plotted together with the calculated time history of the damage. The example highlights advantages compared to the original analysis environment: The high dynamic content (buffeting) of the data can now be evaluated on the basis of generalized SN curves, a feature which is not often included in the OEM full scale fatigue tests. Also, the calculated damage evolution, on a cycle-by-cycle (or reversal-by-reversal) is obtained together with aircraft parameter data, which will help gaining understanding of e.g. what individual maneuvers cause the damage. This understanding is a step e.g. towards the adjustment of the content of the training syllabi so that flying in severely damaging flight conditions is minimized without compromizing training objectives.

3.5 Hawk 2003-2007 structural plan

In line with the ASIMP plan (see Chapter 2) and the Hawk structural activities described above, as well as the other requirements of the FiAF concerning the future use of the Finnish Hawk inventory, efforts within the national network are underway to define the remaining activities necessary to cope with the post-midlife structural issues. It is foreseen that the FiAF Hawk -related key research and development efforts have been completed and most research efforts will be aimed at other aircraft types (e.g. FiAF F-18C/D Hornet).

4 F-18C/D Hornet

4.1 The HOLM programme

The Hornet Operational Loads Measurement (HOLM) programme has progressed according to the plans, ***Fig. 6.*** The HOLM is a research programme tightly combined to a development of a new fatigue tracking system. The programme is divided in three main phases: Research, Prototype and Series Installation. The research phase is ongoing and the prototype phase was launched in 2004 by a feasibility phase of the prototype design.

The goal in the programme is to get to a position in which there is the necessary in-country capability to analyze how Finnish flying consumes the structural life of the F-18 Hornet. The goal is planned to be achieved by combining the information from only a few HOLM aircraft equipped with the onboard fatigue tracking system, and by combining these data with those obtained from other projects, the structural life consumption of the whole FiAF F-18 fleet could be evaluated with adequate reliability.

4.2 Hornet Global FE model

The development of the global (coarse) Finite Element (FE) model of FiAF F18C Hornet began in spring 2000 [Chapter 5.2 in ICAF 2001 & Chapter 4.2.3 in ICAF 2003]. The FE models of all the port (L/H) side sections of the aircraft are now completed. These include the following fixed sections [Miettinen 2003a]:

- Nose Barrel (NB)
- Forward Fuselage (FF)
- Center Fuselage (CF)
- Aft Fuselage (AF)
- Leading Edge Extension (LEX)
- Inner Wing (IW)
- Vertical Tail (VT)

and the following *movable* sections:

- Outer Wing (OW)
- Inner Leading Edge Flap (ILEF)
- Outer Leading Edge Flap (OLEF)
- Trailing Edge Flap (TEF) and TEF Shroud
- Aileron (AIL) and AIL Shroud
- Horizontal Tail (HT)
- Rudder.

The starboard (R/H) side is produced by mirroring. The model of the whole aircraft contains 280k nodes, 310k elements, 1.5M DOF’s and 6100 element property definitions. An overview of the global model is provided in ***Fig. 7.***

The sections are used as External Superelements with PARTs method in MSC/Nastran [Malmi 2003]. The reduced matrices of the sections are assembled together in the Residual Structure analysis with movable sections rotated into user defined deflections. Tools have been developed for bookkeeping of the load/configuration data and generating the MSC/Nastran input files for the Matrix Reduction, Residual Structure Assembly and Data Recovery runs, and also, command scripts for running the analysis runs automatically. The Residual Structure has been constructed. It includes the interfaces between the fixed sections, the WF & LEF Transmissions and Hinges, TEF & AIL & HT & Rudder Actuators and Hinges, and, TEF & AIL Shroud Hinges and Drive Arms/Rollers. Tools for automated transfer and storage of the aerodynamic loads from CFD analyses have been completed [Tikka 2005b] and some aerodynamic load cases transferred [Malmi 2005]. The same outer surface model is used for both the CFD and FE models (surface geometry conformity) to enable automated load transfer between the models.

The acquisition activities of data sources for final verification of the FE model and CFD results are ongoing. Some in-country data are being acquired in the Mini-HOLM I ground & flight test program (ongoing, see Chapter 4.6). International co-operation from other F/A-18 users, under the auspices of FISIF (F/A-18 International Structural Integrity Forum), is respectfully acknowledged for e.g. full scale test data to aid in the final verification process.

4.3 Hornet Fuel Tank 2 & 3 Floor Analyses

The preliminary analysis (using published material data, without flight or load measurements) of the FiAF F-18 fuel tanks 2 & 3 were conducted. First linear static analyses were made with the global forward fuselage + center fuselage FE model for Arrested Landing, Catapult Launch, 7.5 G Symmetric Pull-Up and 3.5 psi tank pressure. Then nonlinear analyses were run with a refined FE model of the fuel floor area using the displacements from the linear analyses as boundary conditions and fuel pressure loads acting on the floors. The highest stresses were obtained at 7.5 G Pull-Up beside the floor stiffener at Y431.

Simple fatigue analyses were performed using the stress results of the FE analyses and material data from [Bruhn 1967] and [ASM Fatigue Data Book 1995]. A linear dependence was assumed between Nz and the stresses of the floor, with the (nonlinear) maximum stress at 7.5G Pull-Up as reference value. The FiAF Wing Root Bending Moment spectrum was used as the spectrum for Nz. The lowest calculated Safe Life results were 2178 FH – 2929 FH, depending on the material data source used. Catapult launches, arrested landings and flying at high altitude (high fuel overpressure) do not seem to have significant effect in the fatigue of the floor. However, shuttle release loads at the end of the catapult cycle were not included. Different repair options for the floors were considered and recommendations given for the FiAF to start the inspections of the floors at latest at 2000 FH and repair or replace floors not later than 2700 FH / 0.52 FLE [Kettunen, Orpana, Keinonen 2004].

4.4 The new CFD model of the FiAF F-18C

Previous activities on the computational fluid dynamics of the FiAF F-18 aircraft can be found e.g. in [ICAF 2003, Chapter 4.2.2]. The new CFD model of the FiAF F-18 Hornet has been completed [Salminen 2003; Salminen 2004]. The computational grid size of the model (one half of the aircraft) is 16 million cells. All control surfaces, which have been modelled using the Chimera technique, can be moved (i.e. adjusted to an anticipated position for the analysis). A selection of external stores (e.g. external fuel tank, AIM-9 Sidewinder, AIM-120 AMRAAM) and the associated underwing launchers can be included in the analyses. The CFD analyses can now be run for a selection of aircraft configurations.

An overview of the new FiAF F-18 Hornet CFD model is provided in ***Figs. 8 & 9***. The pull-up is simulated using a quasi-steady assumption, where the aircraft is in a circular motion (see ***Fig. 9a***). The same technique is used in a case of a rolling motion. The basic methods are descried in [Siikonen 2000]. Turbulence is taken into account using k-ω–SST model. The engine nozzle and the air intake are modeled with a sufficient accuracy. An example of the calculated results is given in ***Figs. 9b & 9c,*** where a pressure distribution is shown in a case of a pull-up. The distribution is used as an input for the structural analyses.

4.5 Inverse Flight Simulation for a Fatigue Life Management System

Previous activities concerning the flight control system have been reported e.g. in [ICAF 2003; Chapter 4.1]. As an update, the current study concentrates on developing an inverse simulation based on a low-cost PC-based six-degree-of-freedom flight simulation of the F-18 Hornet aircraft [Öström 2004a; Öström 2004b; Öström 2004c]. The goal is to complete the stored memory unit data before feeding it into a neural network that produces the stress time histories of chosen structural details (***Fig. 11***). This is done by determining the control surface deflections which would produce the flight path. An integration-based method [Hess, Gao, Wang 1990] was chosen for the inverse simulation. The algorithm was coded in Matlab code which runs the Simulink simulation model externally as an iteration loop. The model includes Flight Control System (FCS) and engine models and a full-flight-envelope non-linear aerodynamic model.

The basic idea of an inverse simulation is to solve a time-dependent control vector in such a manner that the error between a desired output vector and a simulation output is minimized. The fundamental controllability requirements state that the numbers of controls and output parameters must be equal. For example, if load factor and airspeed are to be controlled, elevator deflection and throttle setting are suitable controls. Modern fighter aircraft use complicated Flight Control Systems and hydraulic servo-actuators that add delay. To minimize the effect of delay and to speed up the inverse simulation, the FCS model must be simplified. Due to the FCS simplifications, the inverse simulation does not solve the pilot stick commands but just the control surface deflections. This is adequate for the purpose.

The inverse simulation results agree very well with the simulation output although the memory unit flight incident recorder data has to be coupled with the fatigue tracking data before using it in the inverse simulation. The study showed that the method proposed in [Hess, Gao, Wang 1990] can successfully be applied to this kind of a simulation that includes an aircraft model with a complex FCS.

4.6 Mini-HOLM activities

Previous "proof-of-concept" activities on the onboard/ground based fatigue tracking system development have been reported earlier [Chapter 4.2.6.1 of ICAF 2003]. These experiments were a part of the HOLM Prototype design efforts [Miettinen 2003b].

In view of the future needs of the FiAF and the definition of requirement process e.g. [Liukkonen & Teittinen 2004; Gustafsson, Koivu, Alanko, Lahtinen 2004], a decision was made to replace the onboard system used in the "proof-of-concept" activities (based on the ALBUS flight test recording system) with a more flexible and modern COTS system. This guarantees e.g. better aircraft availability, as the number of the aircraft equipped with the ALBUS is limited and they are needed in other flight testing purposes. The new onboard system will provide experience prior to making the "design freeze" decisions concerning the HOLM prototype. The HOLM prototype design work is scheduled to be completed by fall 2005, after which installations in a small number of aircraft will commence. The following summarizes developments thus far:

The instrumentation design activities [Miettinen 2005a; Liukkonen & Teittinen 2004] and the strain gage instrumentation of one FiAF F-18 jet were completed by end of 2004 [Miettinen 2005a; Liukkonen & Teittinen 2005a]. A total of 55 channels of strain gage data from global net sections (39 channels) as well as from local structural details (16 channels) will be collected. The international co-operation under the auspices of FISIF (F/A-18 International Structural Integrity Forum) proved vital in guiding the selection of the local measurands [Viitanen, Liukkonen, Siljander 2004]. Together with the strain gage data, over 100 flight parameters are being captured for later analyses.

The ground calibration activities were completed in February 2005 [Miettinen 2005b; Miettinen 2005c; Liukkonen & Teittinen 2005b]. A total of 15 ground calibration load cases, each of which containing up to approximately 20 individual loading stages, were performed. An overview of the ground calibration activities is provided in ***Fig. 10***.

The test flights are underway. Approximately 25 flights with a dedicated flight program, utilizing the experience of the FiAF and Patria Aviation of the FiAF F-18 usage, will be flown by June 2005 [Orpana 2005].

4.7 Assessment of fatigue critical structural locations

As a part of the ongoing Hornet Operational Loads Measurement (HOLM) program, the assessment of the F/A-18C/D structure's fatigue critical structural locations is underway at the FiAF, Patria and VTT. The purpose of the work is to establish a stand-alone fatigue cracks database about the locations, which have been identified as critical in the fatigue tests of the Original Equipment Manufacturer (OEM). The results, if possible, will be compared to the FiAF usage and modification level. Previous database updating efforts have been reported in [ICAF 2003, Chapter 4.2.5].

The database is being updated for the fifth time (version 3.0) using the information contained in [SLB008], data obtained under the auspices of the FISIF (F/A-18 International Structural Integrity Forum) as well as some fleet findings of the FiAF [Viitanen 2005].

5 Related activities

5.1 Aircraft structural fatigue training package

The first version of a training package of aircraft structural fatigue has been created. The purpose of the training package is to tailor the contents of the course to various "target groups" e.g. pilots, ground crew (service & maintenance), industry (engineering) and research institutes and academia. The package is made of modules, and by combining different modules the "target group" specific contents can be constructed. The package was designed and created as a joint effort between the FiAF, Patria Aviation, HUT and VTT.

5.2 Structural health monitoring activities

5.2.1 WEAG RTP 3.20 ("AHMOS")

The joint European Research and Technology Program (RTP 103.015 "AHMOS"; **A**dvanced Structural **H**ealth **Mo**nitoring **S**ystems) under the auspices of Western European Armament Group (WEAG) was successfully completed. In the AHMOS project, a number of sensing techniques were evaluated in laboratory environment. The joint achievements have been reported in [SHM 2003]. In view of the Finnish activities, the overall goals can be found in [ICAF 2001 Chapter 6.1.1] and results obtained in [ICAF 2003 Chapter 5.5] and [Hedman, Siljander, Tikka 2003; Tikka, Hedman, Siljander 2003].

5.2.2 WEAG ERG 103.015 ("AHMOS II")

The follow-on project to the "AHMOS" project, the joint European Research and Technology Program (ERG 103.015: Prototype Demonstration of Modular Structural Health Monitoring System for Military Platforms; AHMOS II) within the framework of European Understandings for Research Organisation, Programmes and Activities Memorandum of Understanding (EUROPA MOU), and European Research Grouping Arrangement No 1 (ERG No 1) was launched in 2004. The participants from seven European countries in the three-year project are: EADS and WIWEB (Germany; the former is the single leading industrial entity), BAE Systems, QinetiQ and Smart Fibres (England), Alenia and CIRA (Italy), EADS-CASA-DSS, INTA, UPM and Airbus-España (Spain), DEMEX and Risoe (Denmark), Fokker Services and NLR (the Netherlands), Patria Aviation Oy, Emmecon Oy and VTT (Finland).

Some of the sensing techniques within the AHMOS project were discarded from potential monitoring solutions. A reduced number of sensing techniques were selected as technologically mature enough for performing the next major step necessary to increase the technological readiness level: An operational prototype system implementation for a demonstration on flying test beds ("flight test path") together with parallel technological development activities ("technology development path").

Finland's research activities within the AHMOS II project concentrate on the "flying test path". These activities are briefly described in the following.

5.2.2.1 Flying test laboratory

As a part of AHMOS II project structural health monitoring systems (SHMS) will be tested in actual military aviation environment. This is partly to get experience of the operation of the SHMSs and partly to get first feedback from the ground crews who will operate the systems in the future.

Patria’s role in AHMOS II is to design a flying test laboratory which will be installed to the wingtip weapon station of F-18 Hornet of the Finnish Air Force (FiAF). Together with the FiAF, Patria will organize the flight test program.

The test laboratory, called the F-18 AHMOS pod, is a look-alike of an AIM-9M Sidewinder air-to-air missile. The outside geometry, mass, centre of gravity and moments of inertia of the AHMOS pod will be identical to the actual missile. However, no wings or fins will be installed to it. The space inside the pod is used for test purposes. The test setup consists of fatigue test specimens, constant amplitude loading system and tested SHMSs. In the F-18 tests, strain gage and ultrasonic systems will be used.

The preliminary design of the pod, fatigue test specimens and the system to load the specimens will be completed in May and the design in December 2005. The test program will start in August 2006. According to the project plan, the AHMOS pod will fly about 100 hours operational flying in the FiAF.

5.2.2.2 Monitoring system

The damage detection software employed in the "AHMOS" project has been transferred by Emmecon to a new, Ethernet based, environment to support Patria's test equipment use. Significant changes to software were made to improve its reliability and to fit the software to a new microcontroller type. The first trials of the monitoring system's "proof-of-concept" are underway.

The new "AHMOS II" strain gage electronics, which combines sensor interface, signal processing and Ethernet communication, is under construction and a prototype of it will be tested during 2005. The custom design enclosure has been designed to withstand the environmental loads of the F-18 pod: It will be 'semi-hermetic' and shock and vibration resistant. These properties will be achieved with enclosure design in which electronics and connectors fit to the enclosure and with proper potting with heat conducting silicon. MIL-DTL-83513 connectors have been chosen to the latest design to reach high signal count in small area with a MIL specified connector.

Emmecon has, together with Lappeenranta University of Technology (LUT), been testing DCDC converters' compliance aspects in view of MIL-STD-461-E.

Emmecon has realized, together with BAE Systems and other AHMOS II partners, the system schematic diagrams for the other flying test bed, i.e. the Hawk pod.

5.3 Flight parameter based fatigue life analysis of aircraft structures

5.3.1 Background

In the construction of a military aircraft loading spectrum, typically normal acceleration has been used. Or alternatively, a strain gage such located which is sensitive to wing bending moment and in that way to normal acceleration. The use of these kind of loading spectra allow reasonably accurate fatigue life analyses for inner wing and center fuselage areas. In the aircraft perimeter areas, however, they do not correlate with applying loads, forcing fatigue analysis be based on loads monitoring. This applies especially to control surfaces and their mountings.

The strain gage installation requires an expensive flight measurement system and data analysis needs still a lot of human work. For these reasons the number and sampling frequency of permanently installed strain gages is very limited in modern aircraft designs. For example, the standard instrumentation of the FiAF F-18 jets includes seven strain gages, which are sampled at a frequency which omits practically all buffet loads. Data from these strain gages are used in subsequent analysis (called SAFE) to produce information for aircraft fatigue management. The enhanced usability of the information gathered from standard instrumentation is among the goals with the more extensive instrumentation of the HOLM (Hornet Operational Loads Measurement) aircraft. The purpose of these aircraft will be to produce strain gage data from normal operation service during several years.

In addition to the strain gage data, aircraft equipped with a modern flight control system typically store some flight parameter data, like airspeed and altitude. Until this far this information has not been used to the best extent in fatigue life analysis. It has not been linked directly to the strain gauge data or to the stress state in the critical locations. In a research program led by Patria Aviation this link will be developed. The aim is to model the stress state in structure's fatigue critical locations based on the flight parameter data stored by the aircraft standard instrumentation. This data can be used in aircraft specific fatigue life analysis [Tikka 2004].

5.3.2 Path from flight parameter data to stress state in FiAF F-18 case

To determine the stress state for a structural detail loaded by other than purely normal acceleration, information of flight condition including control surface deflections are needed. All necessary parameters are not stored to the F-18's Memory Unit (MU). Not at least in sufficiently high frequency and resolution. On the other hand the MU data is the only stored source of information from each aircraft and flight, which sets the fatigue analyst to a challenging position. The modern flight control system still complicates the situation, because the control surface deflections are a function of pilot commands and flight conditions. The procedure used to solve the stress state is presented in ***Fig. 11a***.

The first step in the MU data processing is the identification and removal of data outliers. After that a smooth continuous fit can be done for each parameter. By using turning points of the fits, flight conditions which are significant for fatigue life can be selected. Due to the computer time needed for further steps, the stress state is solved only for these points.

The selected turning points of the available flight parameters are fed to an inverse simulation algorithm developed by HUT Laboratory of Aerodynamics (see Chapter 4.5). The simulation solves control surface deflections, which are able produce the flight condition used as input signal. Simulation takes into account the control laws of flight control system as well as the kinematic constraints.

An efficient pre-processing of the data produced by inverse simulation is essential for precise modeling of the stress state. The significant load components relating to the analyzed detail, like for example the hinge moment should be as visible as possible after data pre-processing. The relationships between input and output parameters should be as smooth as possible. This concerns especially transonic flight regime. To limit the modeled problem, dependent inputs should be combined by using e.g. the principal component analysis.

If the fatigue life analysis should be done for a non-instrumented aircraft type, or for a type under development, one can only rely on calculated values. In the case of FiAF F-18, Patria Aviation and VTT have, under the HOLM contract from the FiAF HQ, instrumented one aircraft with strain gages (the Mini-HOLM I; see Chapter 4.6). The strain gage data can be used as the result according to the input of the neural network data pre-processing. As the number of strain gage channels of the Mini-HOLM I instrumentation is limited, all fatigue critical locations are not instrumented. For this reason, the majority of the strain gages measure global stresses, which have to be converted to the local stresses later on.

The stress measured from the structure of a highly aeroelastic aircraft operating at high angle of attack is not a constant value depending only on the flight condition. Typically there exists significant amount of random vibration superimposed to the deterministic component. In certain flight regimes the vibration component can be responsible of the majority of the fatigue life consumption. The neural network used to model the stress according to the flight condition, can anyway produce only one deterministic value or vector. To model this vector from measured strain gage data, frequency analysis and filtering have to be used. The modeled frequency response has to be further compressed in order to keep the problem size reasonable. This area is under study in a project conducted by Tampere University of Technology, Institute of Signal processing.

In the point where both input and output vectors for interesting flight conditions are determined, all available human knowledge of the problem is hopefully used effectively. In this research, multi-layer feed forward type neural networks are used for the problem modeling. Assuming that there indeed exists reasonable amount of representative sample data, the link between stored MU data and the related stress state can be created. According to the tests done by Patria Aviation and Emmecon Oy, one central problem is the balance between the precision of the model needed and the generalization ability required. Also the choice between one neural network which can handle all flight configurations and external storage case or several specialized nets is still under study. In some cases the response to be modeled can have significant delays, like in the areas where load from leading edge extension (LEX) vortex is dominant. To identify this kind of special cases self organizing maps (SOM), tested by VTT (see Chapter 5.4) can maybe bring additional information. The test environment shown in ***Fig. 11b*** helps problem source recognition, while ***Fig. 11c*** shows the achieved modeling capability in one test case.

5.4 Using SOM in OLM data analyses

The structural integrity of ageing aircrafts can mainly be managed either by estimating structural life using analytical methods or by observing the growth of structural damage. Parallel to these methods, research efforts towards embedded structural intelligence are increasing (e.g. neural network applications).

Among the neural network application efforts (within the context of aircraft structural integrity) currently under work is the Self-Organizing Map (SOM), an unsupervised neural network approach and a highly visual Data Mining (DM) tool, which offers new possibilities to the flight data analysis. The DM tools become particularly interesting the more data there exists. The FiAF Hawk OLM programme offers a convenient test and development environment of the SOM tools. These research activities will be highlighted elsewhere within the ICAF 2005 [Laakso, Siljander, Tikka, Bäckström 2005].

5.5 Progressive damage models for composite materials

The failure of composite structures divides into three stages; damage initiation, damage progression and final failure. A typical mechanism of damage initiation is matrix cracking in some layer of the laminate. Consequently, damage initiation is often referred to as the first ply failure (FPF). Damage progresses with several mechanisms that often occur interactively. Most important of these are additional matrix cracking and crack propagation, debonding of fibres and the matrix, and delamination of layers. The final failure typically takes place when the ultimate load carrying capability of the fibres is reached in some layer.

Since multidirectional laminates can carry considerable loads after the FPF, failure models extending the analysis beyond the initial failure are needed. A common approach is to model a degrading laminate with layerwise failure criteria and degradation rules. Such models are called progressive failure models. According to ***Fig. 12a****,* the laminate stress state is computed by applying the classical laminate theory (CLT) and an applicable failure criterion. If failure occurs, the material properties of the damaged layers are then revised according to the degradation rules. The process is continued to the final failure of the laminate. A progressive failure model can thus estimate the ultimate failure load of a laminate. It can also be used with finite element analysis to estimate the damage progression and strength of entire structure. An example of the analysis of a notched laminate with ±45^o lay-up is presented in ***Fig. 12b****.*

The analysis tool is developed using the commercial finite element software ABAQUS. The progressive failure has been added to the model with the use of a user subroutine and material dependencies. In addition, a commercially available progressive analysis method software GENOA is used. At first the damage simulation tool is developed for static load cases and the results are verified with own static tests. In future, the fatigue degradation models are investigated and the tool is extended to analyze also fatigue loading [Skyttä 2004a; Skyttä 2004b; Skyttä 2004c; Skyttä, Saarela, Wallin 2004; Wallin 2004; Skyttä, Saarela, Wallin 2006].

5.6 Developments on composite moisture content measurements

The FiAF capabilities for composite moisture content measurements during drying period were developed.

In the first phase, composite parts were vacuum bagged and the vacuum line air moisture content was measured with Vaisala DM70 and checked with an indicator. The composite parts used in the testing were moisturized in a humidity cabinet and in outdoor conditions. The weight increase was measured during conditioning period and compared to theoretical estimates. The dew point, relative humidity and absolute moisture content threshold values for sufficiently dry composite material were established with USN indicator color changes. The threshold values for dew point, relative humidity and absolute moisture content were -9°C, 12% and 10000 ppmv respectively.

The meter requires one hour transient time after heating ramp before accurate drying measurements. Lost of vacuum, leaks or temperature changes complicate the measurements, but can be detected from the histogram. With the drying histogram the part drying below threshold values can be traced. Estimates of remaining drying times can be made with theoretical studies [Aakkula & Paukkeri 2004].

In the second phase of the investigation, the effects of change in drying temperature and vacuum pressure to the moisture values were measured with Vaisala DM79 and dewpoint were determined. The monitored values were dewpoint temperature, relative humidity and absolute humidity. The loss of the vacuum pressure was indicated with a sharp change in the absolute moisture value. The changes in the other values were moderate. The changes in the drying temperature changed the moisture diffusion rate. The effects were seen clearly in all monitored values. The changes in the ambient conditions in the drying room had an effect to the monitored values as the drying time became longer. This phenomenon is probably due the increasing leaks in the vacuum bag or vacuum line as the sealant tape is drying. The leaks through the actual composite part are also possible. The relative humidity in the drying room should be as low as possible. With theoretical calculations the order of magnitude for remaining drying time can be estimated. The USN moisture indicator threshold values varied when compared to the measured values. A draft of a manual for moisture measurements was written. Additional second moisture measurement probe was provided for monitoring the ambient conditions in the drying room [Aakkula 2005].

5.7 Carbon fiber heat blank developments

In the investigation, a carbon fiber blanket was tested for bonded repairs. The blanket operates in protective voltage area from 16 to 23 volts and is flexible.

The temperature distributions produced by the carbon fiber blanket were compared to the distributions produced by a standard metal wire blanket. The carbon blanket was operated with 16 and 20 volts when heating a composite part, while 16, 20 and 23 volts were used when heating an aluminum table with heat sinks. Three types of vacuum bags were tested: SRM vacuum bag with a copper sheet, copper sheet replaced with a dry carbon fabric and without the copper sheet.

The copper sheet can be omitted when repairing a composite part. Both blankets produced acceptable temperature distribution in the repair are. Dry carbon blanket replacing the copper sheet inside the vacuum bag was not beneficial.

Copper sheet is beneficial when heating aluminum table with heat sinks. However, none of the vacuum bags produced acceptable temperatures for the whole repair area. Tailored heat blanket and multiple control thermocouples should be used.

Carbon fiber blanket provided more uniform temperatures to the blanket edges. Carbon blanket is flexible and could be bended round composite panel edge. The temperature distribution was acceptable in all tested edge repair scenarios.

Thermographic investigations were performed from carbon fiber and metal wire blankets. The joints of the carbon blanket were damaged prior the shooting, which resulted compromised temperatures for the carbon blanket. The conclusions are that carbon fabric blanket has better characteristics to aircraft repairs than the metal wire blanket.

In the next phase a carbon fiber blanket to produce more heat to the edges and to function as a combined heat/vacuum bag should be constructed. However, the joints have to be manufactured more durable and reliable [Aakkula 2004].

5.8 NDI research activities

5.8.1 Ultrasonic transducer development for the F-18

Research to replace periodic NDI by the use of permanently installed systems (i.e. aircraft structural health monitoring systems - SHMS) has been conducted at Patria Aviation. The objective of the research, which was carried out as an MSc thesis, was to find a permanently installed SHMS to replace the trailing edge hinge NDI of the F-18. The thesis contains the following aspects: A basic study of structural materials, suitable structural parts and assemblies for the SHM and the associated typical defect types in metal and composite structures as well as the measurement methods and sensors employed. Significant subjects that should be considered in the design, implementation and utilization of a permanently installed SHMS are highlighted. Theory and practical examples are used to give a better understanding of the SHMS design and measurement methods related subjects. The measurement methods suitable for the structural defects and their principle of operation are presented with measurement related factors. The F-18 trailing edge lug related studies with the above subjects, and especially the comparison of the properties of measurement methods are included. The result of the thesis is a study on the permanently installed SHMS and integrated eddy current sensor for the F-18 trailing edge lug [Ylitalo 2005].

5.8.2 Thermographic studies

Thermography is investigated as an NDI method due to its potential to be used without removing aircraft composite parts from the aircraft. The goal is to create a reliable inspection method for finding penetrated water and other defects. The benefits of the method are also that large areas can be investigated simultaneously, it is a non-contact inspection method and it can be used prior or during the service operation without disturbing the aircraft maintenance. Two different thermographic methods have been investigated - pulse thermography and thermography based on phase transition of water at 0 °C [Saarimäki 2002; Mäkinen, Syrjälä, Saarimäki 2003].

Pulse thermography is a fast method to find the water and simultaneously other defects under the composite skin of the aircraft but it needs additional external flash heating system to heat the surface of the structure (***Fig. 13a***). The surface of the sample was heated with two xenon flash lamps and the temperature evolution of the same surface was recorded. Three artificially made different types of defects could be seen during the same inspection (***Figs. 13b & 13c***). If the structure of the sample is known, also the depth of the samples can be calculated from the moment that defect comes visible. Indications from defects caused by impact have been also detected from artificial and real structures.

Thermography based on phase transition exploits the phase transition energy that is needed for the water defrosting. Method based on phase transition exploits the long period of arctic weather conditions in Finland. Whole aircraft or separated parts of the aircraft need to be in frozen conditions for few hours. Moisture or penetrated water can be detected due to the much larger need of specific heat of water during defrosting compared to the warming up of the surrounding structure. Aircraft can be either inspected right after the flight or it can be left outside in freezing conditions during the night and inspected when it has been brought to the maintenance hall to warm conditions. Multiple tests with different specimen and different amounts of water showed that penetrated water can be detected for several minutes as a colder area in the structure (***Fig. 13d***). The time and the developed temperature difference when the defect can be seen is strongly dependent of the amount of water and the environmental conditions during the inspection.

Research in close cooperation between VTT and the FiAF is continuing to create a reliable inspection routine for the thermographic inspection exploiting phase transition of water. The aim is to find defect indications from many different aircraft parts at the same inspection. Found indications would then be further inspected with traditional NDI methods e.g. ultrasound.

5.8.3 Leaky Rayleigh wave experiments

Surface waves, Rayleigh waves and leaky Rayleigh waves are widely used in acoustic microscopy to characterize different materials and thin surface films and coatings. Much less is reported in the open literature about the application of the same wave types in the low-frequency range. However, the same theoretical background and principles, on which the high-frequency acoustic lenses are based, can be utilized in low-frequency immersion and contact transducers. Experiments concerning the application of low-frequency (4 - 12 MHz) transducers used for creating the leaky Rayleigh waves have been conducted at VTT.

The main goal of the ultrasonic activities is to check the applicability of the "immersed Rayleigh" method on realistic aircraft parts in which there would be flaws due to flight and/or laboratory loads. The current detectable crack threshold is one of the most significant obstacles to improvements in Aircraft Structural Integrity. The research is directed at reducing this threshold. The overall and long-term goal is at developing and demonstrating NDI method(s) able to characterize sub-millimetre flaws in production aircraft parts, F/A-18 in particular. As the availability of Finnish F-18 aircraft parts with adequate flight hours was limited due to a new fleet, samples from other F/A-18 users could be made available under the auspices of FISIF (F/A-18 International Structural Integrity Forum). Parts obtained from Canada and Australia were used in the technology validation studies. The results of these studies will be published later [Jeskanen, Siljander, Kauppinen 2005].

5.9 On the risk based approaches

A risk-informed fatigue analysis framework to support the management of a fleet of aircraft is being developed at VTT. One of the challenges faced by a fleet manager is to organize and manage the fleet such that operational and training objectives are met while at the same time constraints related to a safety of flight, fleet availability, maintenance actions and maintenance costs, and planned Out of Service Date are complied with. In the risk-informed fleet management, it is desirable to get estimates and predictions of the fatigue damages (fatigue lives) of the structures comprising the fleet. These are used in evaluating the feasibility of flight task mixes with respect to the objectives / constraints given for the operative management.

The fatigue analysis framework supports risk-informed fleet management by providing means to do *‘what-if’* risk analyses and probabilistic evaluations of flight task mixes with uncertain consequences on multiple, partly conflicting, objectives. For every type of flight task, the amount of fatigue load and damage on a structure will vary due to variability in pilot performance and external conditions. Therefore, the fatigue damage incurred by a flight task is uncertain. The uncertainty related to the fatigue damage of a structure can be assessed by collecting data in the form of {flight task code, fatigue damage measurement value(s)} and making probabilistic inference on the underlying (hidden) fatigue damage parameters in the data model. An inferential procedure that links different types of evidence (measurements) is provided by Bayesian statistical theory. The fatigue analysis framework is therefore based on the Bayesian approach. The "top down" framework will be presented elsewhere [Rosqvist, Koski, Siljander 2005].

6 Summary

The aircraft structural integrity activities are orchestrated and funded by the FiAF and conducted by the national network. These activities, which are briefly described in this review covering the past two years, logically follow the need further strengthen the concrete and systematic efforts on a national level to cope with the structural deterioration effects of the most important aircraft types of the FiAF. While it is foreseen that the FiAF Hawk -related key research and development efforts have been completed, these experiences have formed a sound basis to build similar capabilities aimed at other aircraft types (e.g. FiAF F-18C/D Hornet).

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- pp. 820-827 (McGugan, M. *et al:* Improving the structural testing of wind turbine blades by monitoring acoustic emission);
- pp. 828-835 (Martin, T. *et al:* Automated notification of structural damage for structural health management using acoustic emission detection);
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8 Figures

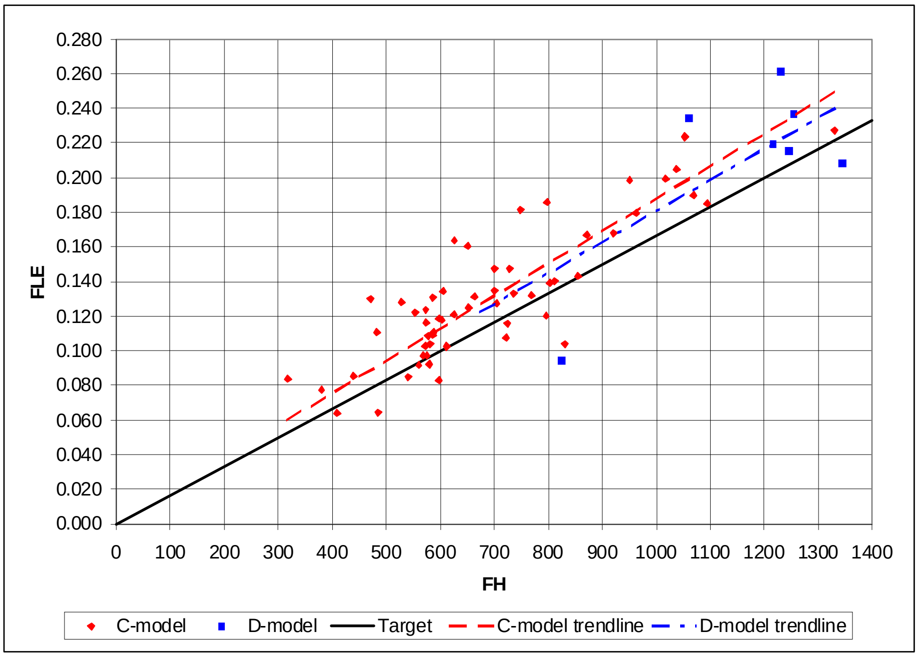


Figure 1. *Summary of the wing root fatigue life expended (FLE) of the FiAF F-18 fleet (data from all 64 aircraft included) as ranked according to the data obtained from the current onboard strain recording system. Courtesy of the FiAF.*

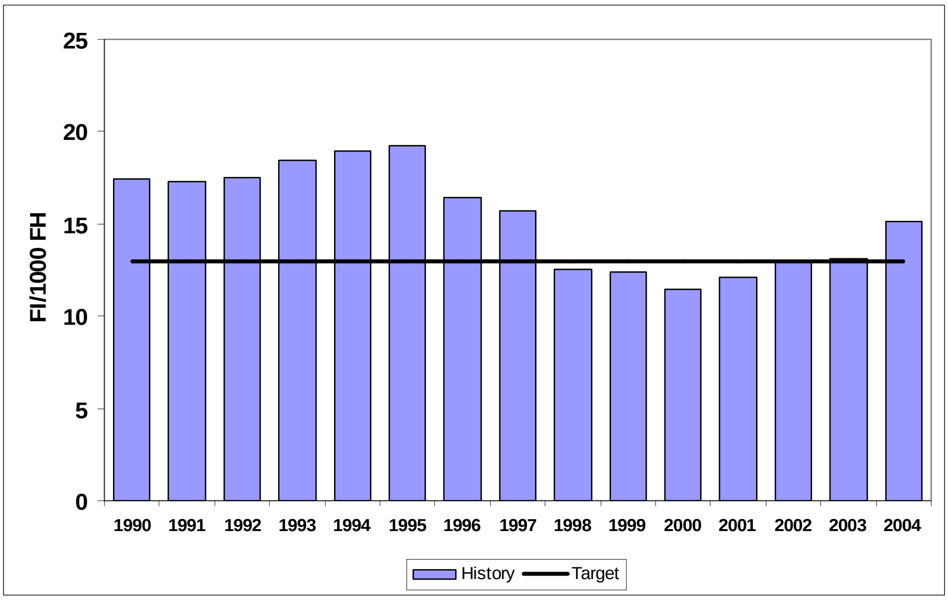


Figure 2. *Fatigue Index (FI) development of the FiAF Hawks (fleet average; data from all 57 aircraft included). Courtesy of the FiAF.*

Figure 3. *An overview of the FiAF Mk.51 Hawk premod 999 wing teardown inspection:* ***a)*** *an aileron cut for the inspections;* ***b)*** *examples of removed and inspected parts. Courtesy of Patria Aviation.*

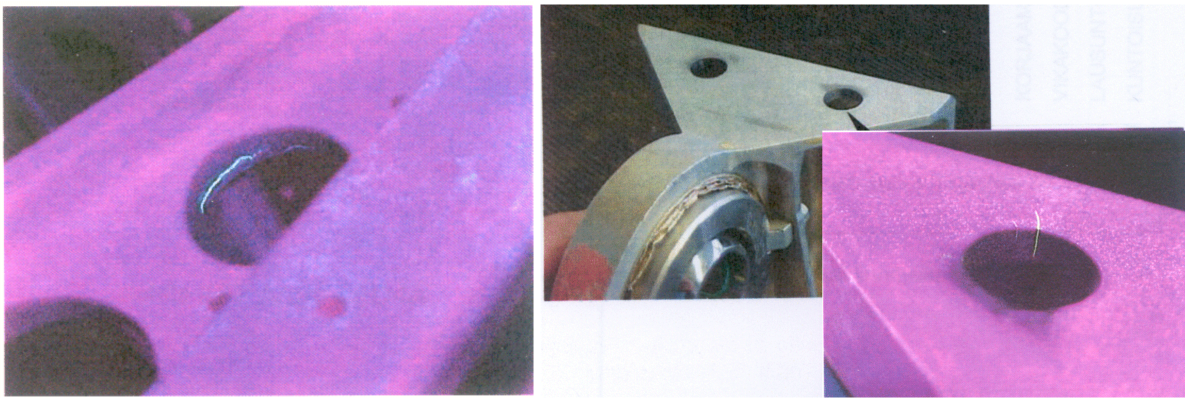


Figure 3 (cont'd). *An overview of the FiAF Mk.51 Hawk premod 999 wing teardown inspection:* ***c)*** *&* ***d)*** *examples of found anomalies. Courtesy of Patria Aviation.*

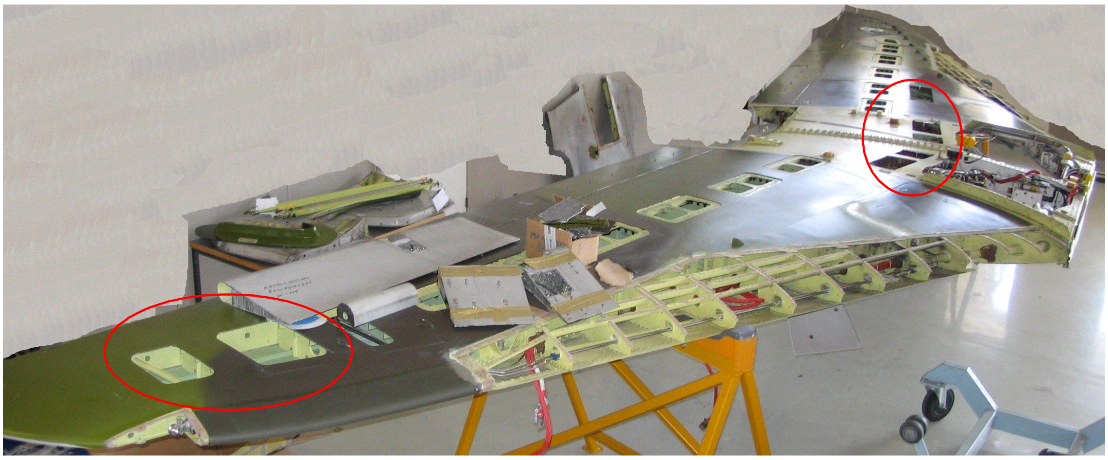


Figure 3 (cont'd). *An overview of the FiAF Mk.51 Hawk premod 999 wing teardown inspection:* ***e)*** *Overview on the wing's top surface. Note holes cut to the upper torsion box skins. Courtesy of Patria Aviation.*

Figure 3 (cont'd). *An overview of the FiAF Mk.51 Hawk premod 999 wing teardown inspection:* ***f)*** *Example of holes cut to the lower surface of the wing. Note removed fasteners. Courtesy of Patria Aviation.*

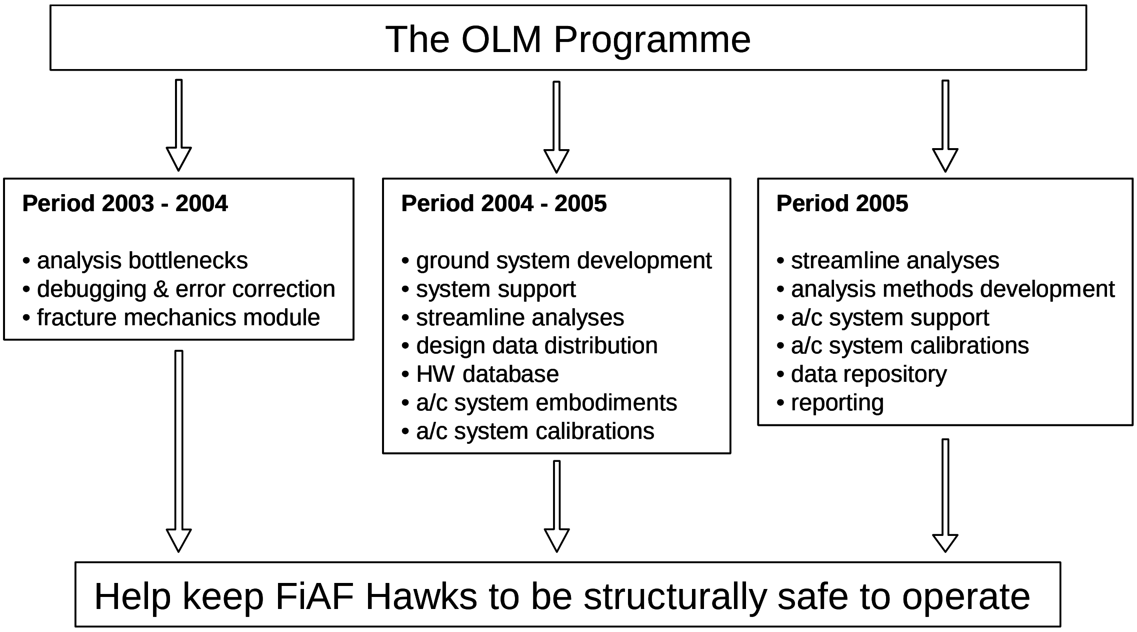
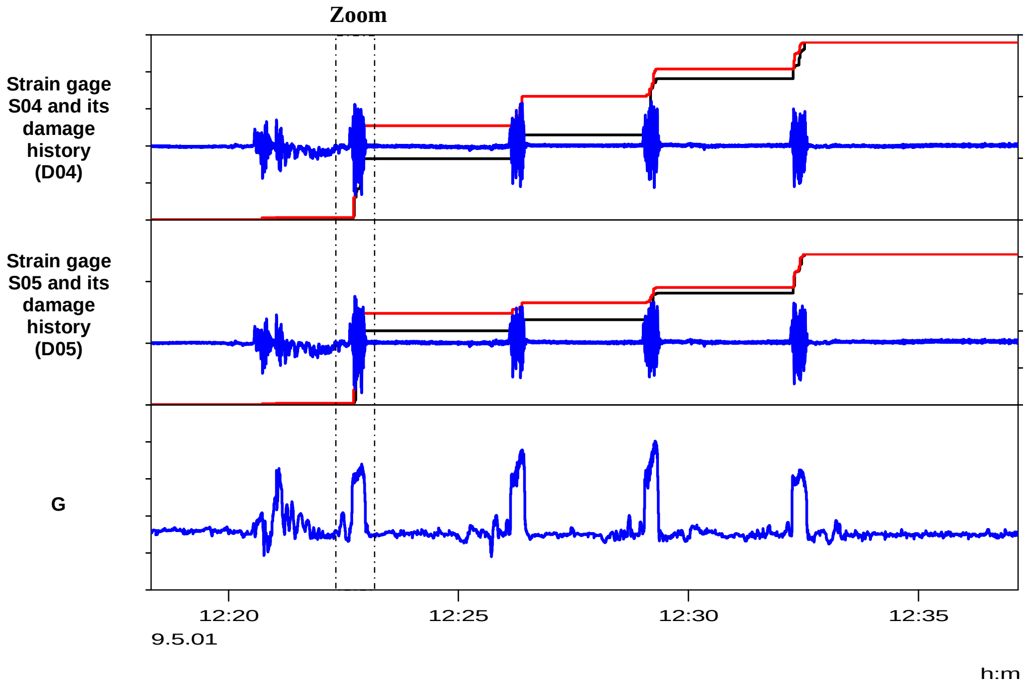
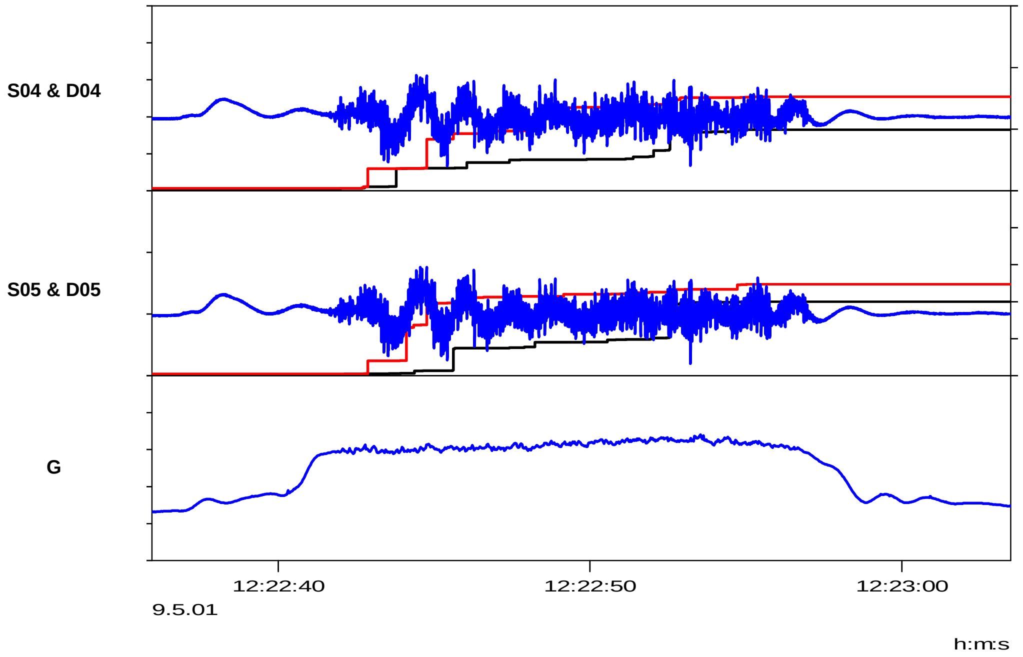


Figure 4. *An overview of the FiAF Hawk Mk.51/51A OLM programme (Operational Loads Measurement). Courtesy of VTT Aircraft Structures.*



Time histories (full flight).



A zoomed segment from the full flight's time history.

Figure 5. *An example of VTT's new analysis environment. A full flight is first analyzed and selected structural responses (e.g. S04 & S05) together with selected aircraft parameters (e.g. G) are printed together with the accumulated damage (SN approach). In the damage histories, the start (red) and end (black) of each damage value are shown. Courtesy of VTT Aircraft Structures.*

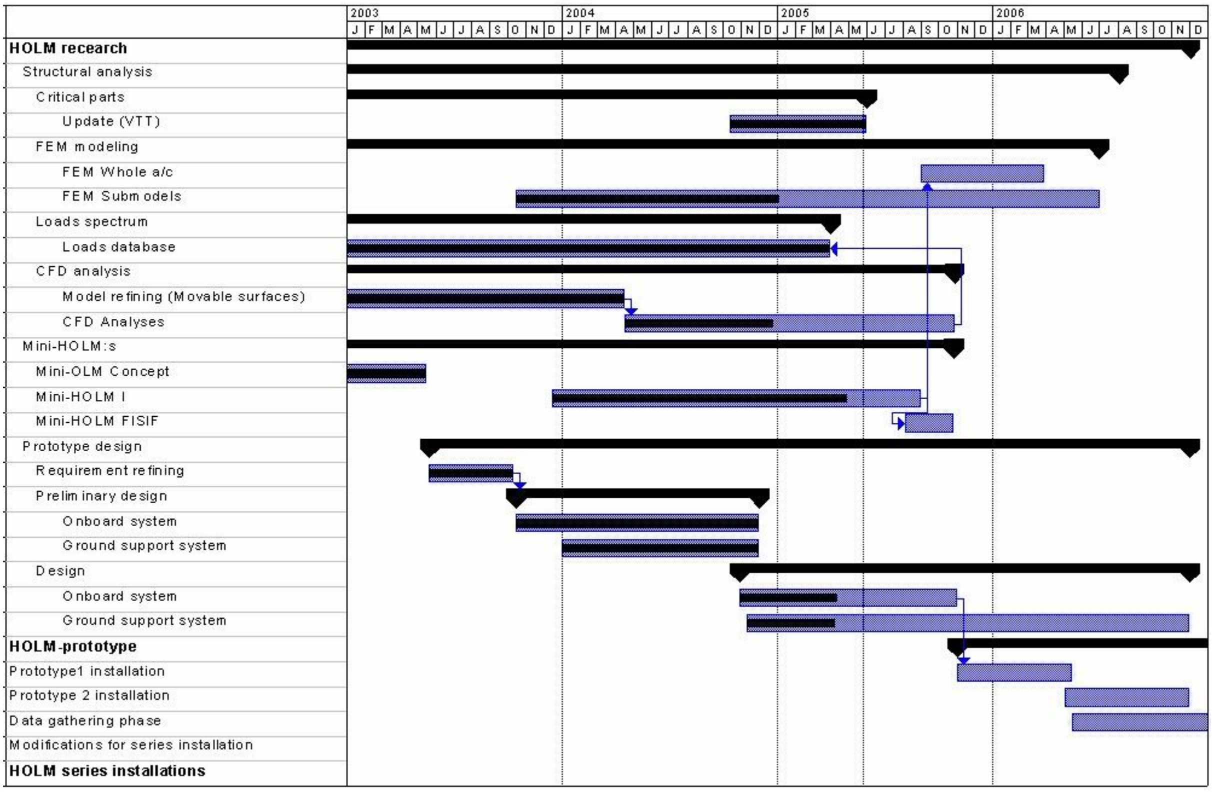


Figure 6. *A schematic of the Hornet Operational Loads Measurement (HOLM) Project. Courtesy of the FiAF.*

Figure 7. *An overview of the Hornet FE model; outer surface (above) and inner structure (below). Courtesy of Patria Aviation, Aircraft Business Unit.*

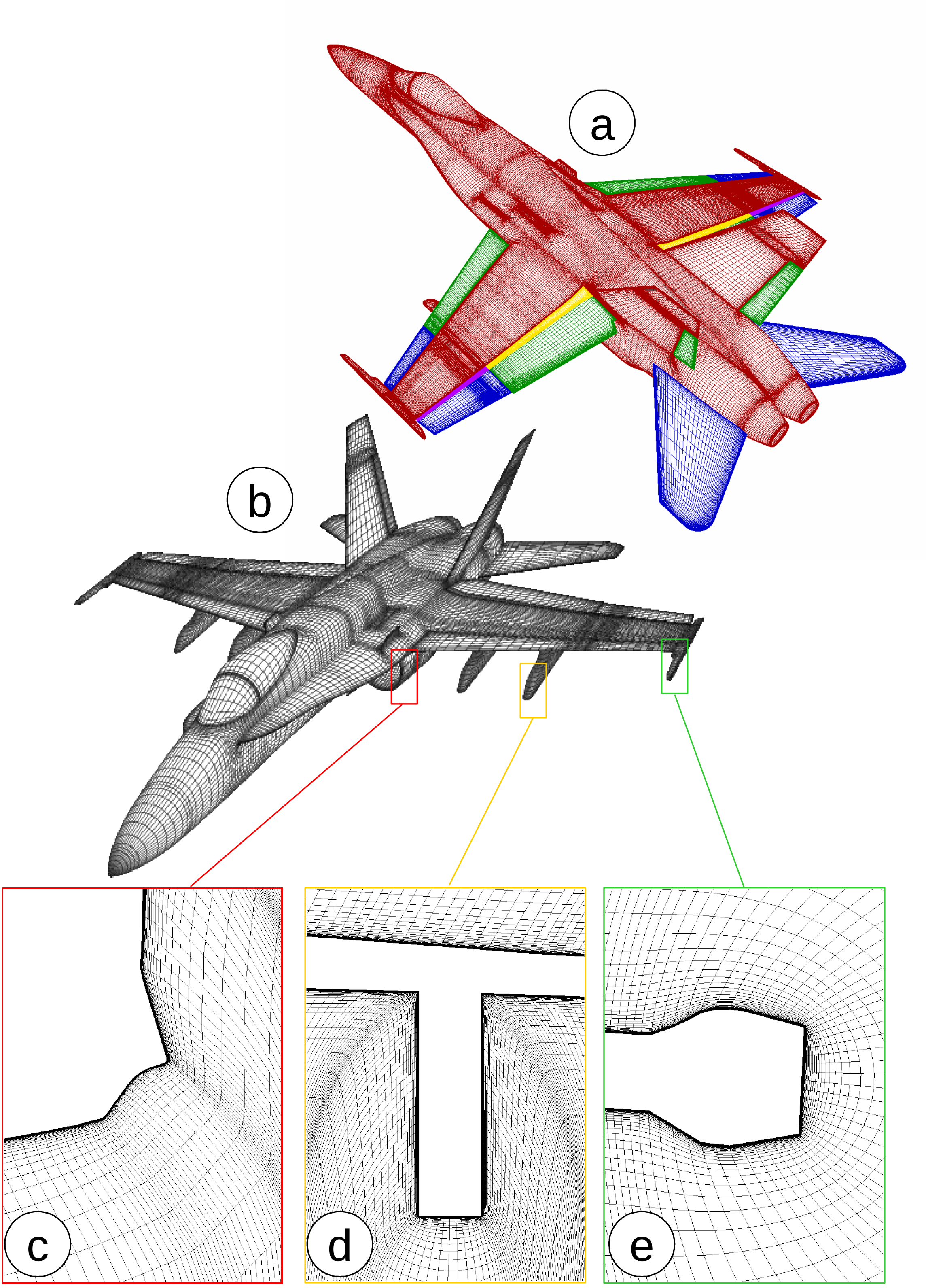


Figure 8. *An overview of the new geometric details within the new Hornet CFD model. The computational grid size of the new model is 16 million cells.* ***a)*** *All control surfaces (other than red color) are adjustable (Chimera);* ***b)*** *An overview of the surface grid. Some details of the model:* ***c)*** *fuselage station near engine inlet;* ***d)*** *outer underwing launcher;* ***e)*** *wing tip launch rail. Courtesy of Finflo Ltd.*

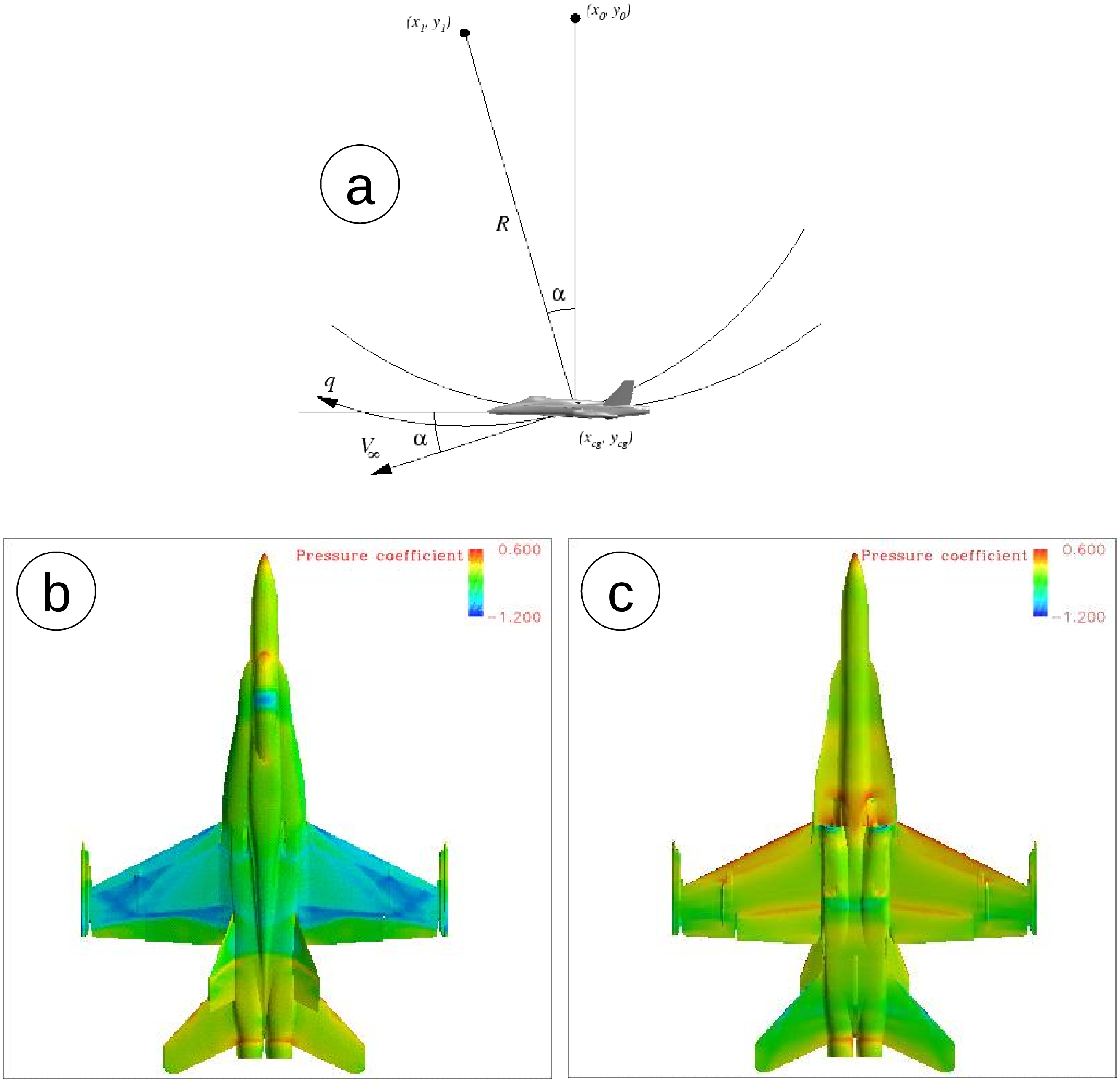


Figure 9. *An overview of the results obtained using the new CFD model of the FiAF Hornet.* ***a)*** *A steady-state pull-up is simulated using a quasi-steady assumption, where the aircraft is in a circular motion. Pressure distribution results in a case of a pull-up:* ***b)*** *top surface;* ***c)*** *bottom surface. Courtesy of Finflo Ltd.*

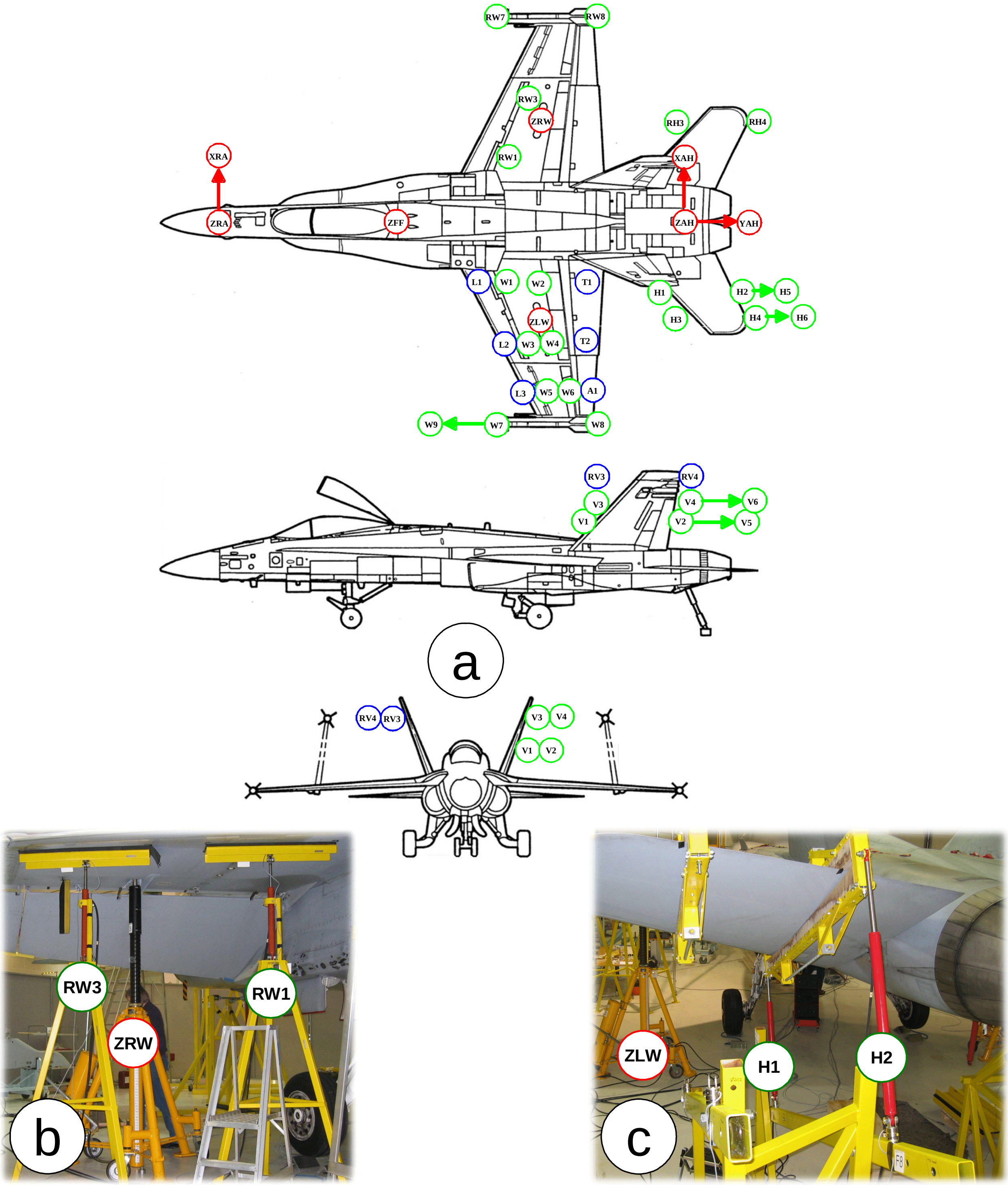


Fig 10. *An overview of the mechanical calibration activities within the Mini-HOLM I project.* ***a)*** *The loading point map;* ***b)*** *R/H inner wing loading in progress;* ***c)*** *L/H horizontal tail (-24° position) loading in progress. Courtesy of Patria Aviation, Aircraft Business Unit and VTT Aircraft Structures.*

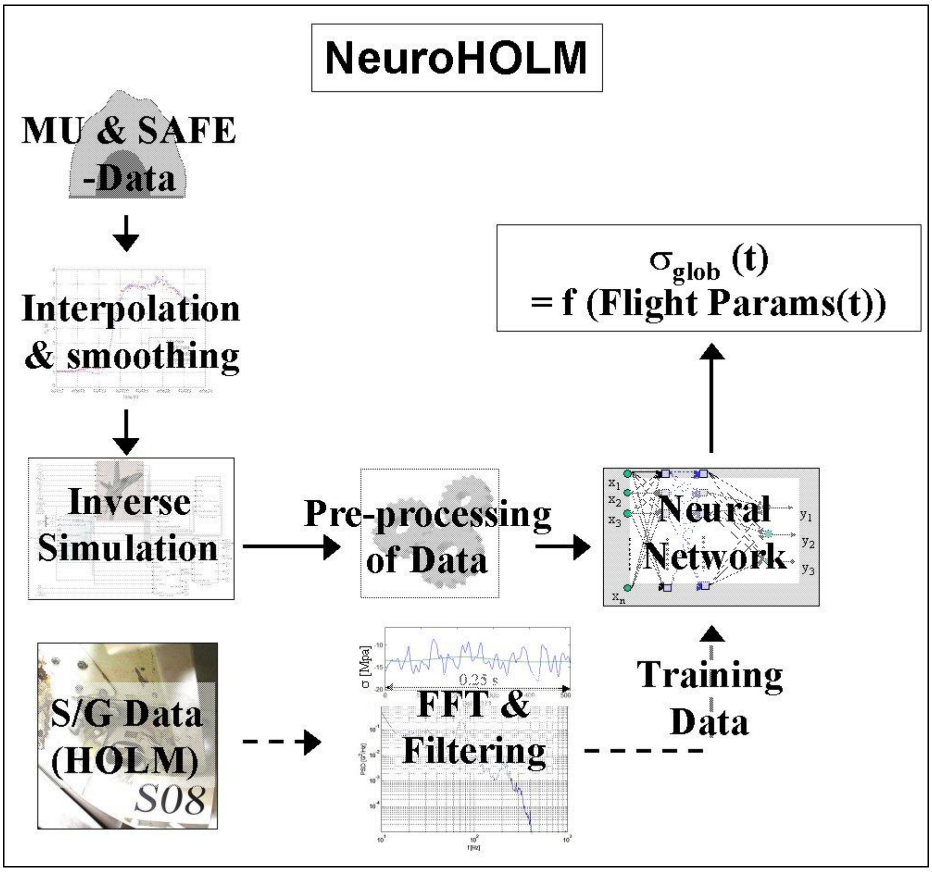


Fig 11a. *An overview of the process to solve the stress state as a function of flight parameters in the FiAF F-18 case, within the flight parameter -based fatigue life analysis of aircraft structures. Courtesy of Patria Aviation, Aircraft Business Unit.*

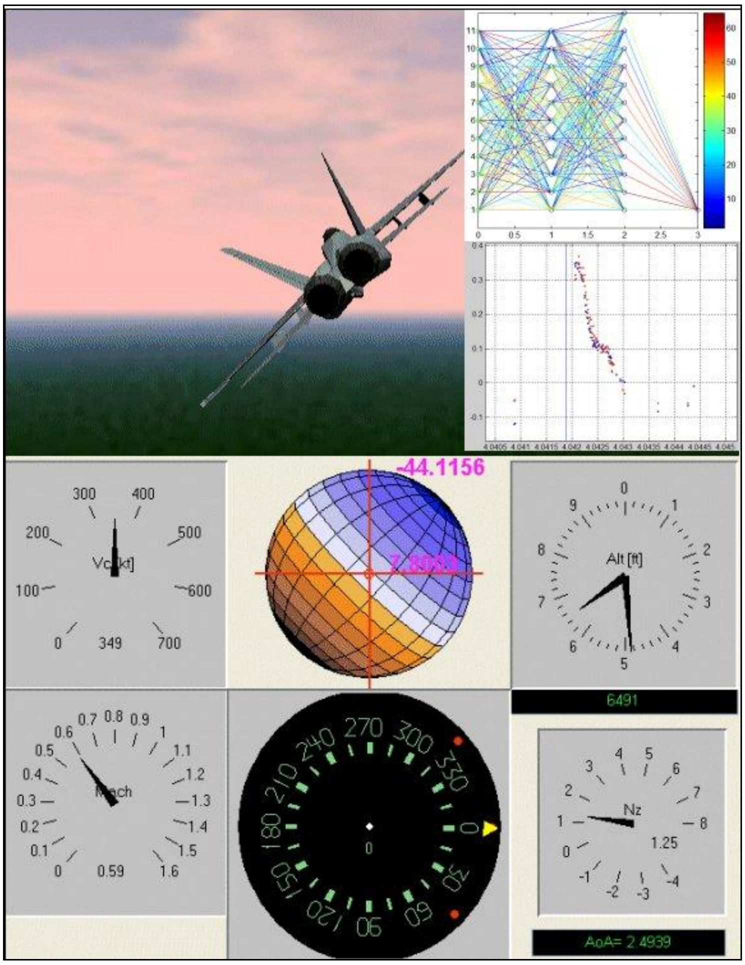


Fig 11b. *The analysis environment used to recognize possible sources of problems, within the flight parameter -based fatigue life analysis of aircraft structures. Courtesy of Patria Aviation, Aircraft Business Unit.*

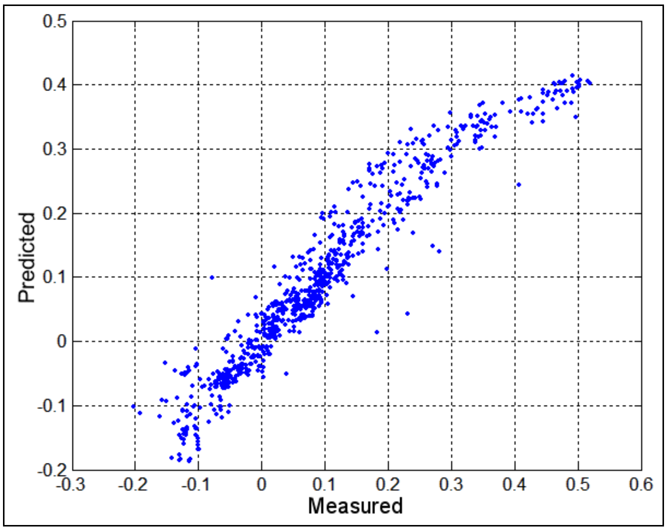


Fig 11c. *The modeling capability of one tested network (one whole flight). Courtesy of Patria Aviation, Aircraft Business Unit.*

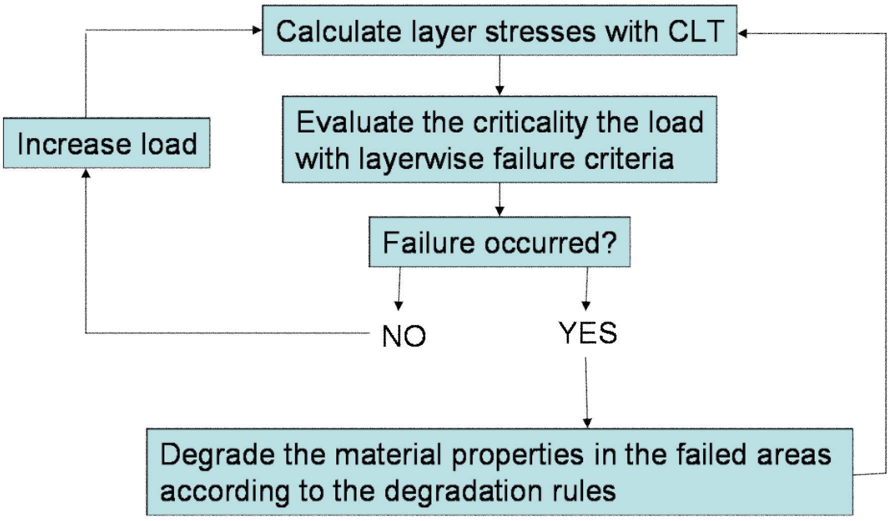


Fig 12a. *Progressive failure analysis principle of laminated composites. Courtesy of Helsinki University of Technology, Laboratory of Lightweight Structures.*

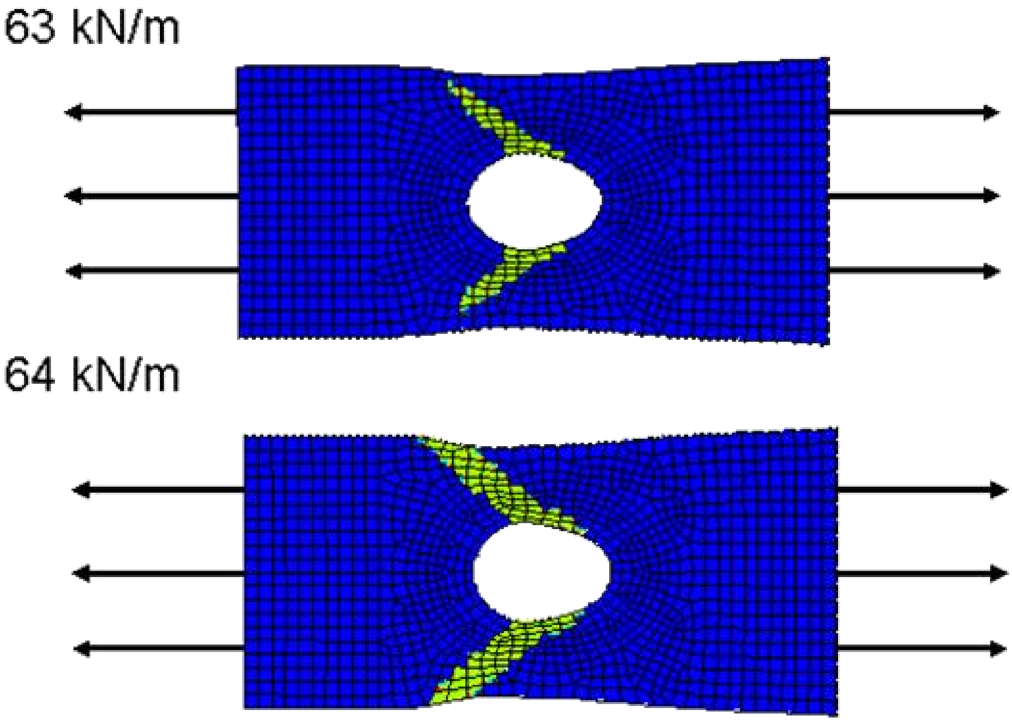


Fig 12b. *Damage progression in notched ±45º laminate. Courtesy of Helsinki University of Technology, Laboratory of Lightweight Structures.*

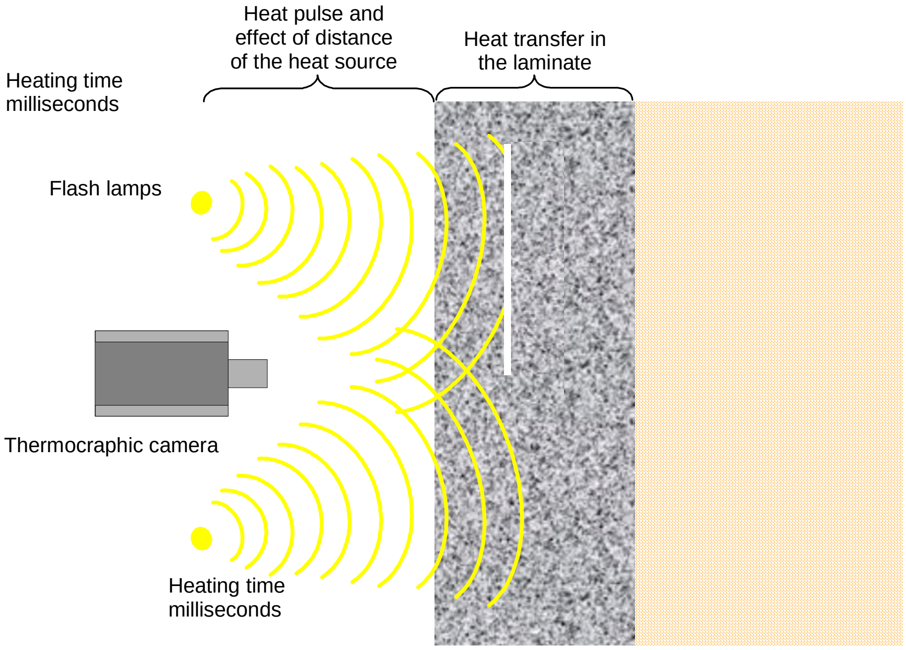


Figure 13a. *Principle of system assembly with pulse thermography (flash method). Speed of the heat penetration changes at the defects. E.g. delamination slows the heat penetration speed and defect can be seen as warmer indication whereas water can be seen as colder indication compared to the surrounding structure. Courtesy of VTT Processes.*

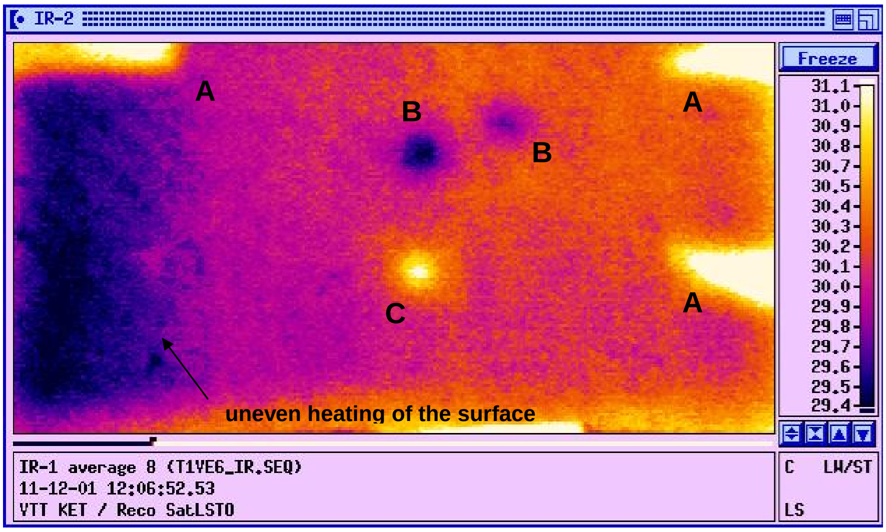


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Figure 13b. *Three different types of defect indications at the same time with pulse thermography (flash method). A) delamination, B) penetrated water and C) lack of material. Courtesy of VTT Processes.*

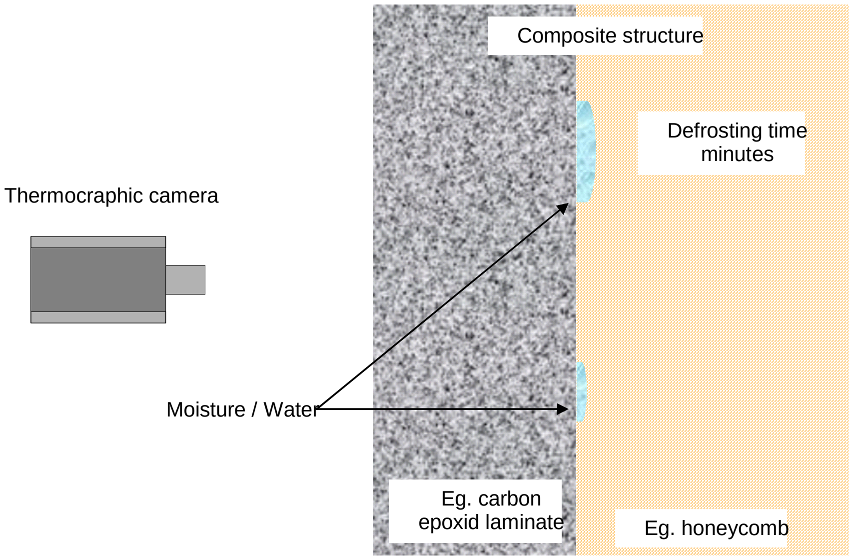

Figure 13c. *Three different types of defect indications at the same time with pulse thermography (flash method). A) delamination, B) penetrated water and C) lack of material. Courtesy of VTT Processes.*

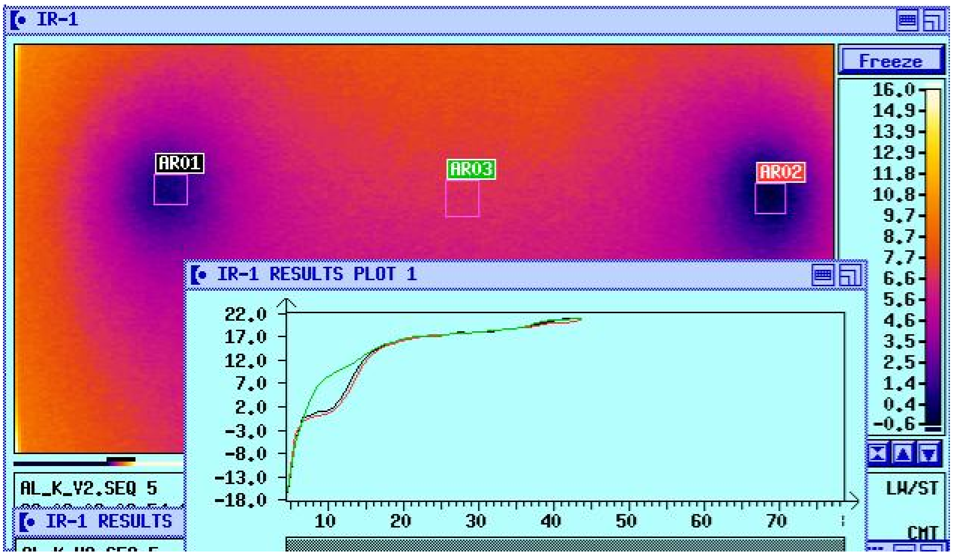

Figure 13d. *Warming up of the wet (black and red curves) and dry (green curve) aircraft composite structure can be seen in the time analysis of the thermographic inspection. Figure in the background is taken 5 minutes after the start of the inspection and shows areas of the measures in time analysis. Courtesy of VTT Processes.*