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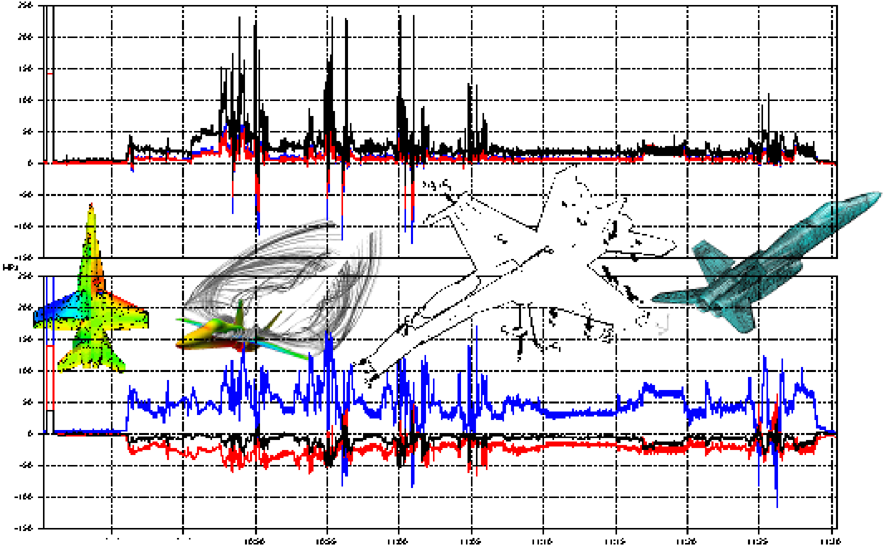

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A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND DURING THE PERIOD FEBRUARY 2001 TO MARCH 2003

Presented at the 28th Conference of the International Committee on Aeronautical Fatigue (ICAF), Lucerne, Switzerland, 5-9 May 2003

Customer:	Finnish Air Force Headquarters Aircraft and Weapon Systems Division

Edited by
Aslak Siljander

VTT TECHNICAL RESEARCH CENTRE OF FINLAND

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Title

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Summary

This document was prepared for the delivery to the 28th Conference of the International Committee on Aeronautical Fatigue scheduled to be held in Lucerne, Switzerland on 5-9 May 2003.

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 Ltd. Aircraft Business Unit (PFA), the Technical Research Centre of Finland (VTT), Helsinki University of Technology's (HUT) Laboratory of Lightweight Structures (HUT/LLS), Laboratory of Applied Thermodynamics (HUT/LAT) and Laboratory of Aerodynamics (HUT/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 (tabled in ICAF 2001, Toulouse, France) up to March 2003.

Date Espoo 29 April, 2003

Harri Soininen	Aslak Siljander	Keijo Koski
Research Manager	Chief Research Scientist	Checked

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Espoo, 29 April 2003

Editor

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1 Introduction

The year 2003 marks the 85th anniversary of the FiAF. During the writing of this report, approximately 36 000 FH have been flown with the 63 F-18C/D fighters, about 188 000 FH with the 51 Mk.51 Hawk jet trainers and roughly 118 000 FH with the 28 Valmet Vinka primary trainers. Although this national review will concentrate on the Hawk and Hornet structural activities only, it is worthwile to mention that the Vinka's Life Expension Program (LEP), as briefly described in the previous review [ICAF 2001], has progressed into the implementation phase, ***Fig. 1***.

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. 2*** (Hornet) and ***Fig. 3*** (Hawk). Although no aircraft of these type designations have been lost in Finland due to structural issues, Figs 2 and 3 clearly demonstrate the need to further develope 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 March 2003 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 Ltd., Aircraft Business Unit, FIN-35600 Halli; Finland
HUT/LLS	Helsinki University of Technology, Laboratory of Lightweight Structures; P.O. Box 4300, FIN-02015 HUT; Finland
HUT/LAT	Helsinki University of Technology, Laboratory of Applied Thermodynamics, P.O. Box 4400, FIN-02015 HUT; Finland
HUT/LAD	Helsinki University of Technology, Laboratory of Aerodynamics, P.O. Box 4400, FIN-02015 HUT; Finland
FinFlo Ltd.	FinFlo Ltd., Tekniikantie 12, FIN-02150 Espoo; Finland
Emmecon Ltd.	Embedded Measuring and Control, Ltd., P.O. Box 35, FIN-53851 Lappeenranta; Finland
VTT	VTT Industrial Systems, Product Performance, Aircraft Structures, P.O. Box 1705, FIN-02044 VTT; Finland

2 FiAF fatigue management policy and the ASIMP

The fatigue management policies currently used in the FiAF fleet management were outlined in the previous Finnish national review [ICAF 2001]. Since then, a development effort has been initiated within the FiAF to introduce more rigorous damage tolerance based principles into the fleet fatigue management in the form of formal Aircraft Structural Integrity Management Plans (ASIMP). It is foreseen that the Finnish Military Aviation Authority will issue a framework document together with the first version of the FiAF F-18 ASIMP late 2003. Subsequently, this will be expanded to cover the rest of the FiAF fleet.

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 above FiAF fleet management principles. The ASIMP aims at managing the FiAF aircraft integrity using a single cover document including structural, mechanical systems and engine integrity requirements. Structural integrity will be handled with a separate and more detailed document with recommendations of damage tolerance utilization. The essential integrity documantation of each aircraft type of the FiAF is to be collected to a type specific handbook.

3 Hawk Mk.51 and Hawk Mk.51A

3.1 Repair methods development

The structural repair and inspection method development for the known structural damage scenarios as reported earlier [ICAF 2001 para. 4.1.3] and developed by Patria and the FiAF, are being implemented in the Hawk fleet. ***Fig. 4*** summarizes the structural areas onto which these methods are being applied, either as pre-emptive repairs / modifications during routine aircraft maintenance or as they appear. The following chapters summarize some of the associated efforts.

3.2 Fatigue crack growth analyses of the composite reinforced centre fuselage region

As a follow-on to the many activities associated with the centre fuselage strength and durability conducted by Patria, HUT and VTT and as described earlier in [ICAF 2001 para 4.3.1]), the numerical simulations of the fatigue crack growth rates were conducted parallel by VTT [Koski 2001] and Patria [Raunio 2001]. The crack growth calculations for the original and the composite reinforced main fuel tank area were carried out. The calculations considered the multi-site-damage (MSD) effects - cracks in the rivet row. The composite facing decreased the appearing stress levels as expected. The calculated lifetime of the composite reinforced centre fuselage region was 8-37 times higher than that of the original configuration. The scatter in the predicted residual life values depends on the used flight mission - spectrum content.

Based on the results, a modified inspection program for the area was planned. It includes only three fleet leaders to be monitored. The rest of the FiAF Hawk fleet aircraft are not inspected, because the reinforcement modification (fleetwide application) makes the area damage tolerant and crack growth before 6000 FH is slow enough.

To achieve a better understanding of expected damage cases before reaching the 6000 FH, a statistical analysis was made. The result was that without any actions about 15 % of the fleet had been affected. The DDRV (dual datum fuel pressure relief valve) decreases the probability further to some 10 % of the fleet. Adding to this the beneficial effect of the composite protection, further reductions in the damage probability is obtained. However, the major influence is the increase in crack growth time. [Keinonen 2001].

3.3 Flight measurements of the composite reinforced centre fuselage configuration ("Mini-OLM III")

The analyses of the flight measurment results, as mentioned earlier in [ICAF 2001 para 4.3.2], have been completed by VTT [Liukkonen, Teittinen, Siljander 2001]. The analyses concentrated on the comparison of results between the original structure (unreinforced centre fuselage) and the composite reinforced configuration. Based on the comparisons of ground tests (fuel tank pressure calibrations) and flight tests (flight test program nearly identical to the flight tests of the original structure), it could be concluded that majority of the structural responses were lower in magnitude in the reinforced configuration.

3.4 OLM programme (Phase 1) completed

In 1998 the FiAF contracted with BAE SYSTEMS (BAES) to undertake an extensive Operational Loads Measurement (OLM) programme with two FiAF Mk.51/51A Hawk aircraft, tailnumbered HW-348 and HW-319. Generally, the aim of the program was to gather in-flight strain and associated flight parameter data to determine the effects of flying on the structure of the aircraft. The in-flight data were gathered from typical FiAF service within the FiAF squadrons. The OLM system, mainly based on the RAF Hawk OLM program, was designed and supplied by BAES. PFA was contracted to prepare the two aircraft for the OLM modifications. PFA was also responsible for installing the flight test instrumentation equipment and preparing the two aircraft for flights. The installation of the aircraft parameter transducers and cable routing was undertaken by PFA as well. The strain gauge installation and their maintenance, calibration and system commissioning activities were VTT's responsibility. Also, the gathered data were analyzed with e.g. BAES developed software by VTT. Further details of the OLM program and the background activities can be found in [ICAF 2001]. After the first 200 good flights were analysed with results reported, the OLM "Phase 1" ended [Liukkonen, Viitanen, Laakso, Siljander, Teittinen, Bäckström 2002]. An overview of the OLM program is provided in ***Fig. 5.***

3.5 OLM follow-on program

The Hawk OLM is intended to be a rolling programme continuing until the retirement of the Hawk from the FiAF service. The first short term objective of the 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 aircraft embodiments will be finalized early 2004, and a recertification of the new life limits is foreseen during 2003. The OLM system will also be used to develop flight training practices with respect to the structural life expenditure.

In view of statistical reliability, the original number of analyzed flights was too small and since there were significant variations in damage in certain mission codes, the analysis of more flights was required. The OLM follow-on assignment covered the analysis of another 200 good flights, "OLM Phase 2". At the moment, Phase 2 data collection is complete at VTT.

The analysis activities of the flown flights with the two OLM aircraft formed one avenue of activities at VTT, while another included the annual calibration of the onboard systems [Liukkonen 2002a; Liukkonen 2002b]. However, the main goal of the follow-on program was to develop and tailor the ground station analysis environment to better suit to the future needs of the FiAF. Debugging of the analysis software for possible error correction, optimisation and streamlining of the various stages of the analysis chain, creation of the OLM results database and the addition of "auto features" (scripts) to replace routine analysis stages were among the developing and tailoring activities. The need of these analysis environment adjustment activities was experienced early on in the program, as the data analysis could not be done at the rate the flights were flown. Apart from the "bottleneck" effect, the groundstations, software, onboard recording systems, data quality etc. worked reasonably well. Within the follow-on activities, some analysis modules (e.g. the undercarriage analyses) of the original OLM system were skipped from further analysis, as the adequacy of these data was noted after the Phase 1. Further, the data archiving and bookkeeping were rationalized. At present, the most time consuming parts are the uncertain reading process of the flight tapes together with the data quality check from the A3-plotted timehistories.

3.6 OLM follow-on program's planned continuation

Future activities will include the further development of the ground analysis environment and a review of the onboard system. Parallel activities will include the analysis of all data that will be flown with the two aircraft.

Options to transfer the analyses into VTT's standard analysis environment - within which it is easier to process gathered timehistories and create more streamlined computational procedures - will be investigated. Examples of these options include e.g. the analysis environment expansion with new modules, function libraries or user's own functions. From comparisons between how critical locations are loaded in real use versus e.g. the Full Scale Fatigue Test / Life Extension Fatigue Test (FSFT / LEFT) results of BAES, the need to e.g. add the fracture mechanics approach and more general S-N and ε-N modules to the future analysis environment is deemed evident. Also, when characterizing a set of analysis data, statistical aspects should be considered. Further activities include also the updating of the OLM database, which is planned to contain the results of the analyses with associated flight log data. In addition to this, the flight sorties giving especially high or low damage rates should be investigated to ascertain the reasons for the high or low values.

3.7 Neural network activities

There are two mainstreams of activities when determining the life of a component. The first deals with direct fatigue life determination on the basis of measured local (strain) quantities. The second deals with measured global (strain) quantities.

In the case of local quantities, a transfer function from the strain gauge location to the fatigue critical local "hot spot" location is needed and it is, generally, of the form $\sigma_{crit} = K \times \sigma_{gauge}$. Often a refined sub-model from a global FE model is enough for this purpose. A limited flight program is minimum required to collect flight loads (strain) data, from which average usage parameters are derived. The results are often applicable to that particular critical structural location only.

In the case of global quantities, the transfer function needed (to an anticipated structural "hot spot" location) is more complex, requiring input from global strains and flight parameters; global strains could be measured from an aircraft equipped with OLM type sensors. Therefore, the transfer function in the global case is of the form $\sigma_{crit} = f(\{ \sigma_{gauges} \}, \{u\})$, where {u} indicates the vector including flight parameters. The method requires a global FE model, a family of realistic load cases and detailed enough sub-models from the structural areas of interest. With an aircraft equipped with e.g. an OLM type instrumentation suite, most structural locations can be analyzed in view of fatigue life. Further extrapolated, and assuming that a tailnumber specific database with flight parameter data exists, in principle any structural detail from a given tailnumber (aircraft) coud be analyzed in view of fatigue - assuming the relation $\sigma_{crit} = f(\{u\})$ can be defined. With this background, studies at PFA are underway to come up with a neural network application, into which one could feed multiple inputs; these inputs could vary in view of e.g. linearity and timing. Some of the above aspects are highlighted in ***Fig. 6***. Similar studies are underway at VTT as well.

3.8 Fatigue life evaluation of critical locations in aircraft structures using virtual fatigue test

The fatigue life of critical structural locations in the wing of the FiAF Hawk jet trainer was estimated. This was done by using calibration coefficients determined by means of a virtual fatigue test.

The load distribution and load history of the manufacturer’s Full Scale Fatigue Test (FSFT) was first reproduced by using an FE model. The peak-through histories of the stresses in the critical structural locations were determined. The calculated histories were then used as an input in the virtual fatigue test calculations.

A fatigue life calibration coefficient, based on the ratio of virtual fatigue test estimates versus FSFT results, was calculated. It was determined separately to each selected critical location. On the basis of flight measurement data, aerodynamic loads calculation and FE models were calibrated and the stress histories of critical items in average usage by the FiAF were determined.

By correcting the results of the fatigue life analyses using the calibration coefficients produced by the virtual fatigue test, more accurate fatigue life estimates in the FiAF usage could be made. The calibration of results against in reality detected structural damages improves the accuracy of analytical methods allowing the correction of differences between the actual structure and the idealized FE model. ***Fig. 7*** summarizes the procedure [Tikka 2002].

3.9 Hawk centre fuselage fatigue life – comparison between calculated and test results

Fatigue life consumption of the Finnish version of Hawk's centre fuselage section is dominated by fuel tank pressure cycles. These cycles are caused by pressure refueling and by maneuvers with high vertical rate. Most critical locations are frame 15 lower beam below fuel tank floor and side skins of the tank.

Relating to a co-European research project AHMOS (see para. 5.5.2), a constant amplitude fatigue test of a scrapped Hawk centre fuselage section was conducted. Primary aim in the project was to test new sensor techniques in crack detection. In the same test it was also possible to collect good amount of test data of the structure's fatigue behavior.

First detected damages in the test were frame 15 lower beam cracks. Patria's fatigue life analysis gave an estimate of 4550 flight hours (FH) to initial crack (50% of beams cracked). Statistical scatter analysis predicted that first findings should be made after 3500 FH. In the fatigue test the floor beam cracked at 9000 cycles, which correlates to about 4400 FH. The crack growth time was very short in the test. In the fleet cracks have been found at 3500 and 3600 FH, which agrees very well with analysis results.

In a more detailed investigation, cracks were detected also in frame 13 web corners and in upper and lower corner lists. Calculated result for web corners was 4000 fh and for corner lists a pessimistic estimate was over 2000 fh.

Until this far centre fuselage test has shown to be representative compared to the FSFT and fleet findings. In the future also the side skin multi-site damage area will be tested until cracking as well as ceiling [Keinonen 2001; Tikka 2003a; Tikka 2003b].

3.10 Lower wing skin fatigue tests

To verify experimentally the analysis results of the wing details [Tikka & Keinonen 2001; Tikka 2001; Tikka 2002; Tikka 2003c], limited number of fatigue tests were conducted. The test spectrum consisted of time histories from selected six FiAF flights captured with the OLM-installation. By weighing the number of different flights, a representative spectrum for the FiAF typical usage was constructed. The transfer function from the OLM installation's strain gauge location to the critical location was determined from the Mini-OLM III results, which were combined with FE models to the OLM installation. Due to the fuel pressure influence, acting on the critical location in transversal direction, special attention was paid to proper load introduction and grip design. VTT conducted a series of fatigue tests: first with simplified specimens and finally with details cut from a scrapped wing. Crack initiation was monitored with eddy current and visual inspections. For a part of details residual strength test were conducted to determine allowed crack size. Additional crack initiation monitoring was provided by a monitoring system similar to that reported in para. 5.5.1 [Bäckström et al 2003]. An overview of the test set-up is provided in ***Fig. 8***.

After the tests, corrections for slight differences in secondary bending were made as well as backward calculations for fatigue crack growth. As a result, the statistically estimated crack initiation and growth time in typical FiAF usage were reported as well as the critical crack size. Proposal of modifications for inspection program were also made [Tikka 2003c]. From the results, the observation that the test results for crack initiation were inside the scatter band of calculation results from the virtual fatigue test [Tikka & Keinonen 2001] was surprising. The tested crack growth time was, as expected, longer than calculated due to conservative estimate of K_I in the complicated 3D structure.

3.11 Hawk 2003-2007 structural plan

In line with the ASIMP plan (see para. 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 key research and development activities necessary to cope with the post-midlife structural issues.

4 F-18C/D Hornet

4.1 Modeling the Flight Control System (FCS)

This study is concentrated on a flight simulation software, presenting a modern fighter aircraft, intended to support fatigue analysis. For structural fatigue analysis, one must determine the aerodynamic loads under maneuvering. For this, control surface deflections for the examination time are needed. Because of the FCS, the determination of the deflections is not straightforward. The control system is time-variant and the preceding flight path, current loading configuration and aircraft's response during the maneuver have an effect on the deflections. Hence the FCS cannot be analyzed separately and a full flight simulation is needed to accomplish the goal.

As a part of the FCS research, a flight simulation software, which handles complex control systems, has been developed. The control surface deflections and the parameters describing the aircraft's state obtained from the simulation can be used as initial data for the calculations made using Computational Fluid Dynamics (CFD) program. A real-time controllable flight simulation is produced as a by-product. Currently a self developed Matlab / Simulink based flight simulation program is in use. The program calculates aircraft's flight over flat earth and includes suitable visualizations. The basic program includes an atmospheric model, non-linear six degree-of-freedom rigid-body motion equations, determination of forces and moments and other routines required by the simulation. In addition to the basic program the discussed aircraft has to be modeled. The aircraft model has to describe aircraft's aerodynamic properties, FCS, mass distribution and propulsion system at a highest possible accuracy.

Aerodynamic forces and moments are calculated from a wind-tunnel and flight test -derived database of stability derivates using table look-ups with linear interpolation. Current F-18 aerodynamic model includes the "Fighter Escort Mission" -loading in the maneuvering configuration as documented by the McDonnell Aircraft Company (MDC). The aerodynamic database has an angle-of-attack range of -10° to +90° and a sideslip range of -20° to 20°. Elastic deformation effects are incorporated in a quasi-static-elastic manner, with no dynamic simulation of the elastic degrees of freedom.

A slightly simplified model of the F-18 Hornet digital control laws (v10.5.1) is implemented, including only the Auto Flap Up (AFU) flight mode at this point. The digital FCS has been modeled both in its continuous and original multirate discrete form as documented by the MDC. The system is assumed to work without failures thus no failure modes or failure logic has been modeled.

The aircraft's mass, inertial moments and center of gravity change as a function on fuel mass and current loading configuration. These parameters are calculated in the mass distribution model using simple equations and table look-ups.

In the engine model, the throttle-commanded steady-state thrust level is determined from a table look-up. Simple dynamic response characteristics are added by using first degree transfer functions. Fuel flow is modeled using a table look-up as well.

Combining the introduced models a complete flight simulation describing the aircraft can be formed. The simulations can be controlled by using variables, files or joystick and the results present the aircraft's state, flight path, attitude and control surface deflections. These parameters are used in the computational determination of aerodynamic loads in fatigue analysis.

Validation of the simulator is a vital part of this study. FCS validation is made by comparing control surface deflections to known data. The MDC documents contain frequency domain data of the system which has also been used in the validation process. Frequency domain considerations with closed aerodynamic loop have been made. Aircraft response characteristics comparisons between the simulation results, MDC document time histories and test flight data have been used in validating the whole simulator. Real-time controlled simulations are used for experimental aircraft handling qualities evaluation throughout the flight envelope. The above is summarised in ***Fig. 9***.

4.2 The HOLM program - update

The definition of detailed work packages and the activities therein, under the HOLM program (Hornet Operational Loads Measurement) as reported earlier [ICAF 2001 para 5.2] has been refined. An overview of the current HOLM program work packages is provided in ***Fig. 10*** and in the paragraphs below.

4.2.1 Determining balanced fatigue loads from flight test data

During the load development course held in Boeing's St. Louis facilities, balanced fatigue loads were computed for seven different flight maneuvers. These maneuvers consist of three symmetric and four asymmetric maneuvers performed in two different flight conditions (Ma = 0,9 & Alt = 10000 ft and Ma = 0,8 & Alt = 5000 ft).

Due to differences between the USN and FiAF configurations, corrections for center of gravity and weight were made for wing and horizontal tail flight test data loads. Aerodynamic forces and moments for all major components, except for the center fuselage, were then determined by subtracting calculated inertia loads from the measured net loads.

Distributed air load for forward and aft fuselage was determined by fitting wind tunnel test data to correspond forward fuselage aerodynamic moment. Wing pressure distribution was calibrated to match all the flight control surface hinge moments and wing root and wing fold bending and torsion moments.

Loads necessary to balance the airplane were distributed to center fuselage. Balanced loads were also converted to point loads [Heinemann, Lahtinen, Orpana 2002; Heinemann, Lahtinen, Orpana 2002b; Heinemann, Lahtinen, Orpana 2002c; Heinemann, Lahtinen, Orpana 2002d; Heinemann, Lahtinen, Orpana 2002e; Heinemann, Lahtinen, Orpana 2002f; Heinemann, Lahtinen, Orpana 2002g].

4.2.2 Determination of the aerodynamic loads using FINFLO

The aerodynamic loads for the Hawk and the Hornet aircraft are obtained using the FINFLO code, a state-of-the-art CFD-solver owned by Finflo Ltd. This code has been originally developed at HUT. The flow solver is based on the standard methods related to structured grids. A compressible form of the Reynolds-averaged Navier-Stokes equations is used. The scheme is cell-centred and based on a multiblock grid topology. Geometry modelling can be enhanced by a Chimera technique and discontinuous block interfaces. The code contains several possibilities for turbulence modelling. In the present cases two-equation k-epsilon- and k-omega -models have been applied. The solution methods of FINFLO are described in more detail in [Siikonen 1995].

Since the actual state of the flow field is in some cases, e.g. in a case of a pull-up, time-dependent, suitable approximative approaches are utilized. The pull-up condition is modelled by setting the external flow field to rest and putting the grid into circular motion. For this purpose the flow equations are tranformed into a rotating reference frame. The aircraft can be considered to be attached to the end of a whirling arm pivoted at a point somewhere above the aircraft [Siikonen, Rautaheimo, Salminen 2000].

At symmetrical flight conditions a half of the aircraft is modeled. The computational grid for the Hawk consists of 3.8 million cells. The corresponding grid for the Hornet has 4.2 million cells. A new model is being developed for the Hornet that will include more geometrical details, ***Fig. 11***. The grid size of the new model is estimated to be about 16 million cells.

For the Hornet aircraft, simulations using the rotational grid method has been made e.g. at Ma = 0.9 at the height of 3000 m and at the sea level at Ma = 1.1, ***Fig. 12***. Results have been compared with the data available and the agreement has been good.

4.2.3 Hornet's FE model

Development of the global (coarse) FE model of the FiAF F-18C Hornet began in spring 2000. The aircraft was partitioned into appropriate sections for the modeling effort. At the moment the models of the forward fuselage, center fuselage and aft fuselage and the horizontal and vertical tails are completed. The models of the wing and leading edge extension are scheduled to be completed in the fall 2003.

The left hand side of the aircraft is modeled and the right hand side is created by mirroring, except where significant unsymmetry of the structure exists. The primary element type used is shell (skins, bulkheads, formers, longerons, major supports/fittings) but, also, 3D (core of sandwich plates), beam (minor stiffeners, flanges in formed sheet structures), constraint (connections between parts) and mass (heavier devices and equipment, additional distributed mass as needed) elements are used. Pure linear elastic material models are used: isotropic for metallic materials and 2D/3D-orthotropic materials for composite plates and honeycomb core of sandwich plates. Each section of the model is modeled in the coordinate system of the aircraft and the nodes, elements, constraint and mass elements and unisotropic materials of each section are numbered into separate number domains. So the sections can easily be combined as one model, if desired.

The FE model of the whole aircraft will include about 260 000 nodes, 300 000 elements and 1 300 000 DOFs and it is expected to :

- give good results for internal load distributions and stiffness of the structure – adequate e.g. for strength analysis of repairs of structure
- provide realistic boundary conditions for the adjacent sections of the model and for detail models used in fatigue analysis
- give, to some extent, indication of the critical areas of the structure

The completed sections of the FE model have, so far, been verified only preliminary by comparing the mass distribution, eigenfrequencies and stress analysis results to those from Loads Development Course (by Boeing) and MDA Stress Analysis Reports [Tikka, Kosonen 2002; Malmi 2002a; Malmi 2002b; Malmi 2002c; Miettinen 2002; Orpana 2002; Liius 2002; Malmi 2003]. Final verifications and adjustments of the model will be made after Mini-HOLM test flights (during next years) by comparing and matching the results from the test flights and FINFLO CFD-analyses and FE calculation. An overview of the above is provided in ***Fig. 13***.

4.2.4 Load transfer between aerodynamic model and FE model

Modern computational fluid dynamics (CFD) software can calculate very accurate pressure distributions on the surface of aircraft. Calculation is done by using millions of cells which leads to huge amount of results data. Also FE models used today include tens of thousands elements which makes manual load transfer from CFD results to an FE model practically impossible. To overcome this problem Patria has developed two in house software for automatic load transfer: one which can interpolate CFD results for wing like FE models in Mach number (Ma) – angle of attack (α) space and the other which can handle whole aircraft without interpolation capabilities. Both programs use geometric interpolation which allows small differences between models geometry.

Interpolation software uses five nearest available CFD result cases (in Ma - α space) and makes parabolic interpolation. Geometric interpolation from CFD grid to FE mesh is done first in chordwise direction and after it spanwise. This method models the pressure peak near leading edge properly. The program writes pressures automatically into the MSC Nastran input file. An overview of the procedure is provided in ***Fig. 14***.

The transfer program for whole aircraft needs minimum manual input. It requires as an input CDF grid and results files and MSC Nastran input file. It compares surface normals in the CDF grid and FE mesh and selects parallel enough combinations. Next criteria is selection of nearest CDF cell and two neighbour cells for geometric results interpolation to the FE mesh. Results are written directly to Nastran input file [Keinonen & Tikka 2001; Tikka 2000]. The FiAF has contracted Patria for the further development of the load transfer software.

4.2.5 Assessment of fatigue critical structural locations

As a part of the ongoing Hornet Operational Loads Measurement (HOLM) program, the assessment of the F-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, when possible, will be compared to the FiAF usage and modification level.

The database currently includes over 700 Part Number/Notices of Structural Deficiency (NSD) based records, which have been extracted from the results reports of the OEM's full scale fatigue tests: FT01, FT93L, DT01/FT22/FT23/ST19, FT01/ST16/FT93/FT24 and the teardown inspections of FT93L, FT93R and FT01/ST16/FT93/FT24. In addition teardown inspection results of the left- and right-hand fleet inner wing have been included.

The test results have been collected into MS Excel® and they are visualized by the Graphical User Interface (GUI). The GUI is a browser-based application, which includes the OEM's "Clear Form Cs" (i.e. NSDs) in a form of portable document format. The GUI also illustrates all necessary fatigue information of the single part or sub-assembly. The notices have been categorized with parts according to their criticality as Fracture, Maintenance or Non-Critical NSDs. Each record has also been classified by the type of the anomaly.

Since the database includes the results from only a part of the OEM's fatigue tests, the near future plans include efforts to include the information from the missing fatigue tests as well as make an assumption about the fatigue critical locations of the F-18C/D structure, when the modification level of the current FiAF F-18C/D fleet has been evaluated [Viitanen, 2001; Viitanen & Siljander, 2001; Viitanen, 2002; Viitanen, 2003; Viitanen, 2003b]. An overview of the Graphical User Interface is provided in ***Fig.* 15**.

4.2.6 MINI-HOLM activities

Via the onboard/ground based fatigue tracking system development, one of the main goals of the MINI-HOLM activities is to gain understanding of the FiAF F-18 structural behavior and to allow reliable fatigue life predictions for any FiAF F-18 structural detail of interest. Structural responses (strains in particular, also e.g. accelerations and pressures) are to be measured. These responses will be needed in subsequent analyses, such as FE model verification, external loads estimation and fatigue life predictions. The responses will be measured from global net sections as well as from local structural details. The fatigue critical structural location assessment activities (described above) together with international cooperative acitivities will serve as basis to quide instrumentation activities in view of local measurands. The local quantities will be used to direct fatigue life predictions. Measurements will be conducted during test flights. The test flight definition will utilize the experience of the FiAF and PFA of the FAF F-18 usage.

4.2.6.1 The MINI-HOLM proof-of-concept successfully tested

As a part of the FiAF F-18 Hornet Operational Loads Measurement Program (HOLM), a project consisting of a series of dedicated test flights has been done. In the first phase of the Mini-HOLM project, a new concept for the test flight measurement system was designed. The design is based on the existing OEM delivered ALBUS system, which monitors and captures the sensor information from the aircraft MIL-1553 bus. The ALBUS is in standard use in the FiAF Flight Test Centre. A separate Data Acquisition Unit (DAU) has been integrated into the ALBUS measurement system to capture a moderate number (50-100) of strain gage signals, as well as other flight parameters, not covered by the ALBUS system [Liukkonen & Teittinen 2002a; Liukkonen & Teittinen 2002b; Liukkonen & Teittinen 2003].

A small selection of strain gage sensors were fitted into fairly easily accessible locations for the test flights. The placements of the strain gages were chosen to serve Patria's needs of the life evaluation of the TEF/AIL hinges and the repair of the mid-air collided HN-413 aircraft. The functionality of the Mini-HOLM measurement system concept was tested with a small test flight program consisting of ten carefully chosen standard FiAF training program flights to represent the FiAF fleet usage. One of the flights consisted of one non-standard test flight, in which the goal was to capture extreme loads for the hinges and other measured locations. The representative FiAF average usage was composed using separate weight factors for the test flights. These "proof-of-concept" flights were flown in the fall 2002. An overview of the MINI-HOLM proof-of-concept is provided in ***Fig. 16***.

The next phases of the Mini-HOLM project, after the completion of the measurement system development and testing, are the actual Mini-HOLM instrumentation and test flights, scheduled to start during 2003

4.2.6.2 Preliminary fatigue life evaluation of TEF & AIL hinges

Detailed FE models of the TEF OB and Aileron IB hinges were produced by Patria to be able to define the stress transfer functions between the strain gauge locations and the critical locations of the hinges.

For the TEF hinge, the three strain gages were placed so that all three components of the hinge lug load could be calculated from them (linear relations). Then approximate transfer functions (nonlinear) between the lug loads and the stresses at the critical spots of the hinge were generated. Using these two relations, “virtual” measurement data of lug load components and critical spot stresses were afterwards produced at every instant of measurement (2000 Hz sample rate).

For the AIL hinge, one strain gauge was very near the (by assumption) most critical spot. Although the transfer function (factors) for tensile and compressive stresses differed significantly, the stress state was so tension dominant that a constant transfer function of the tensile stress was deemed adequate for this preliminary life evaluation. The other two AIL hinge strain gauges were placed considering the calculation of the hinge lug loads – if deemed necessary later.

For the TEF hinge, the minimum and maximum values of the most significant, vertical, component of the lug load agreed very well with the values given by Boeing in the Hot Spot Analysis Report for their test flights, but, the transverse and especially the longitudinal components differ significantly from that of Boeing. The maximum critical spot stresses achieved, calculated using a linear elastic material model are very high in view of the yield strength of the material.

According to the fatigue analyses conducted by PFA, the safe life of the TEF OB and AIL IB hinges in the average FiAF usage seems to be approximately 2000 FH. Therefore, the recommended initial inspection should be carried out before or at about 1000 FH. Follow-on activities include e.g. the crack growth analysis in the FiAF usage to determine the inspection interval [Keinonen and Lähteenmäki 2003]. An overview of the preliminary fatigue life evaluation is provided in ***Fig. 17***.

5 Related activities

5.1 F-18 radome cover cracking investigations

Radome cracking observations have been experienced in Finland. The cracks, which have formed during flights, can be observed visually from the outer and inner surface of the cone. The cracks have been observed also in previously repaired cover structures. Although the cracks are not considered to be critical in the structural strength or durability sense, the repair efforts tie manpower and reduce aircraft availability. Also, the repair can be done only on the outer layers of the structure, i.e. it is possible that small crack-like defects are left in the inner structure after repair (from which the crack growth could happen again, requiring new repairs). Further, as there were many speculations of the cause of cracking and the associated cracking mechanisms, investigative efforts were initiated at the FiAF AMC.

In the first phase of the investigation, the research efforts were focused to finding out the cracking mechanisms. It is believed that the minute flaws form during the flight into the cone structure due to air friction induced electric discharge, and these flaws grow through the cone structure. The flaw or crack growth is believed to be driven by a combined effort of temperature and electric discharge effects. The temperature effect is driven by moisture ingress in the flaws at above zero temperatures and the crack expansion due to moisture freezing (and subsequent crack expansion) at below zero temperatures. The electric discharge effect is driven by the localised moisture, from which the electric discharge is believed to initiate. The first phase will tentatively be concluded during summer 2003.

Another phase of the study deals with investigating the effects of various repair schemes on the cracking behaviour and on the radar performance. Among the repair scemes are e.g. the sealing up of the cone surfaces, coating of the cone surface with either a conductive paint or with a conductive polymer. Once the various repair schemes are ranked, some of the most potential methods will be implemented in a selection of the FiAF F-18 fleet and hence more long term experience will be gained to guide fleetwide applications [Kivistö 2003; Lindström 2002; Saarimäki 2002; Aakkula 2002; Wallin & Kosonen 2002; Mäkelä & Kosonen 2003a; Mäkelä & Kosonen 2003b; Huhtinen 2002; Aakkula et al 2002; Aakkula 2003; Aakkula & Lumppio 2003a; Aakkula & Lumppio 2003b; Aakkula & Paukkeri 2003].

5.2 SIF solution activities of 3D fatigue cracks

The goal was to create a straightforward approach for the fatigue analysis for airframe structural components starting from the global FE model. This straightforward approach means that reliable Stress Intensity Factor (SIF) solution particularly for 3D crack cases in reasonable time can be obtained and the analysis can be repeated routinely in order to change some parameters e.g. loading, crack configuration etc.

Typically, the airframe structural components are complex in view of their 3D characteristics (geometry and loading). Therefore, the known reference SIF solutions can not always be applied. The SIFs for these kind of realistic 3D cases are evaluated using numerical methods, which in practice means either the Boundary Element (BE) or Finite Element (FE) method.

A prerequisite for a straightforward approach was the exploitability of the airframe components' FE models with the local cracked model. Therefore, the attention had to be paid particularly to the generation of cracked model(s) within a local model and the interface aspects between the local and global model. The following steps were used while approaching the process:

I Screen and rank available computer programs capable for the SIF and CG calculation.

II Apply the selected program(s) to a straightforward case study with known SIF solutions under specific loading conditions.

III Apply the selected program to a realistic case study with the complex geometry and loading.

According to the results of the first step BE method was chosen for that numerical method. The second step focused procedures - how to take into account interface aspects between the local and global model. The results of the first and second steps was applied a realistic case study (described also in para. 3.10), ***Fig. 18***.

The BE method seemed to be an appropriate tool to evaluate 3D cracked components. It is powerful because only outer surfaces of the component are needed to model and user friendly tools have been developed to add a crack to the BE model. The lacks of the BE method were experienced that the enough large BE model was able to be created and the SIF values are evaluated using crack tip displacements [Koski & Bäckström 2001a; Koski & Bäckström 2001b; Koski 2002].

5.3 LEFM and total life cycle

The applicability of Linear Elastic Fracture Mechanics (LEFM) is being investigated to assess the total life cycle of the airframe structural components. The common approach for the total life cycle estimation is to use the cumulative damage approach verified by the results of the full scale fatigue tests. However, in practise, fatigue damages also emerge from structural details which can not be verified by available fatigue test data. The fracture mechanics would be an excellent tool in order to manage these kinds of the targets. However, the capability of the LEFM is constricted to take into account crack initiation or so called small crack behaviour. In practice, small crack behaviour can be considered by two manners:

1. Equivalent Initial Flaw Size (EIFS) approach and
2. small crack calculation model.

The state-of-the-art report of the EIFS approach was accomplished early 2003 [Koski 2003]. The future goal is to apply the EIFS approach for fatigue critical weepholes of wing. The component fatigue tests have been performed for the weepholes (see para. 3.10). The information of the fatigue test can be utilized in order to establish the EIFS for the weepholes of the wing. When the EIFS is known the total life cycle can be assessed based on the LEFM.

5.4 Fatigue life estimation of structures using probabilistic methods

The investigation on probabilistic fatigue life estimation methods was initiated in 2000. The first phase was ended in the beginning of 2001. Based on a literature survey the analysis methods were categorized into two groups: methods based on deterministic approach and methods based on economic life concept. An example analysis based on deterministic approach demonstrated the applicability of probabilistic analysis and revealed the main problem areas. The crack growth equation was Paris equation and the real shape function for stress intensity factor was simplified to exponential approximation. This was due to the requirement in the software used that the probability equation had to be applied in a single closed form equation. The load spectrum used in the analyses was reduced to constant amplitude loading using the root-mean-square –value of the load range. This value was used as a random variable. The statistical properties for the random variable (distribution and deviation) were estimated. The significance of these estimates was reviewed.

The investigation was continued on deterministic based approach in the end of 2001 with a research program concentrating on two major topics: 1) definition of probability function for fatigue life estimation and 2) definition of statistical properties for variable amplitude load spectrum. The purpose of the first topic was to allow the use of sophisticated crack growth equations as well as complicated shape functions for stress intensity factor. In the second topic the load spectrum was used as a random variable and the statistical properties were determined based on actual data without excessive assumptions or special factors used as random variables. The load spectrum was assumed to be rainflow counted.

The software used in research program was NESSUS. It is developed by Southwest Research Institute. The previous limitations on the form of crack growth equations or shape functions for stress intensity factor were solved by implementing a numerical integrator in external subroutine of the software. The subroutines were developed for both one and two dimensional integration. The statistical properties of the load spectrum were determined by treating the rainflow matrix as a sample and fitting statistical distribution to the data. Mathematical methods exist to fit the rainflow matrix to both one and two dimensional statistical distribution. However, it was found out that the load spectrum cannot be treated as a random variable as originally planned. Statistical method to describe the loading can be used but the loading model must be included in the integration routines. This can be done easily in one dimensional case (if only load range is considered). In two dimensional cases (mean stress effect included) the analysis becomes more complicated and more work is required before the model can be used in fatigue life estimation. Mean stress effects must be included in the analysis to take full advantage of more sophisticated crack growth equations [Wallin, Hämäläinen, Liang 2003].

5.5 WEAG RTP 3.20 "AHMOS"

The joint European Research and Technology Program (RTP 3.20 "AHMOS"; **A**dvanced Structural **H**ealth **Mo**nitoring **S**ystems) under the auspices of Western European Armament Group (WEAG) is near completion. The overall goals and project participants can be found in [ICAF 2001]. Within the AHMOS program, Finland's activities are briefly described in the two paragraphs below.

5.5.1 Embedded microcontroller based networked measurement and analysis system with strain gages tailored to fatigue crack detection

A fatigue damage detection system can - at least in principle - be achieved with several sensing techniques. To successfully realize the principles, the prerequisites for a reliable fatigue damage detection system include at least the following items:

- an adequate understanding of the monitored structure's mechanical behavior within the envelope of the operational and environmental loads;
- proper placing of the sensors in the vicinity of the structural hot spots in view of fatigue such that the sensors are able to detect structural changes;
- proper tuning of the data acquisition parameters i.e. the ADC resolution and it's speed;
- tailored algorithms to analyze the data to come up with reliable indications of structural deterioration, which then would trigger proper maintenance actions.

In addition, the operational requirements and end user requirements to guide the definition of a structural health monitoring system within the SOCRATE Research and Technology Programme RTP 3.20 AHMOS included the requirement to use various sensing techniques with associated algorithms, such as burst and/or continuous sampling using multiple sampling parameters (in which the frequency content varies by several decades and the resolution requirement is a variable) and requirements concerning online and/or offline analyses. These requirements may make the use of a common interface electronics difficult if not impossible. On the other hand, while each AHMOS partner would develope their own sensor specific interface and algorithms, it would be beneficial to have certain software and hardware as common as conveniently possible (e.g. data transfer between various sensor modules). As the functional "wish list" was noteworthy and the resources always are limited, the concept solution chosen was based on the principle of modularity, in which a custom design sensor interface electronics can be connected to a common microcontroller electronics via a ‘standardized’ interface.

As the capability to tailor the concept solution to various sensing needs was required, an embedded microcontroller based networked measurement and analysis system concept, in which the benefits of commercially available components and modularity were tailored, will be presented. Although the system concept uses strain gauge signals as input, it is believed that the modular solution allows the integration of other type of sensors as well (e.g. optical fibres and/or acoustic sensors etc.) developed by other AHMOS European partners. The developed modular concept solution was then successfully applied to monitor the damage growth of a scrapped aircraft part which was fatigue tested in laboratory conditions. The above items will be highlighted in [Hedman, Siljander, Tikka 2003] in view of an electronic designer's point of view. An overview of these aspects and activities are sketched in ***Fig. 19.***

5.5.2 Strain gage capabilities in crack detection

The real time sensor data processing during flight can be done using various ways. If the data processing logic is developed according to FE predictions and the data acquisition parameters are tuned based on component level tests, the aircraft could in principle be continuously and automatically monitored. Finally, some traditional NDT inspections could be replaced by automated inspections on the basis of the sensor responses. To employ such an automated system onboard an aircraft, the chosen system must first be defined, developed and tested in laboratory conditions.

The fleet experience of the Finnish Air Force (FiAF) and the manufacturer's full scale fatigue test experience as well as Patria's dedicated FE analysis experience of the Hawk jet trainers centre fuselage region were combined by Patria to predict the region's fatigue critical structural locations and the numerical stress/strain variations therein using various crack geometries. These experiences and data were then used to allow VTT to instrument sensors (strain gauges) onto the 'hot spot' areas of a scrapped centre fuselage of the FiAF. Fatigue tests of the centre fuselage were then conducted by Patria, during which the functionality of an embedded microcontroller (uC) based networked measurement and analysis system, developed in the AHMOS project by Emmecon and VTT, was tested for structural health monitoring (SHM) purposes. The experience gained showed noteworthy potential for the strain gauge based SHM system to be further developed into a flying prototype in an anticipated follow-on project, as the formation and growth of fatigue cracks could be detected early enough in view of maintaining the flight safety.

With this background and goals, the research done by Patria, VTT and Emmecon, as a part of a European cooperative research and technology program AHMOS will be highlighted in [Tikka, Hedman, Siljander 2003]. An overview of these activities is provided in ***Fig. 20***.

6 Summary

It is believed that the structural experience gained within the national network and briefly described in this document during the past years gives a solid foundation to tackle with the challenges ahead. One of the near future activities will be to tailor the network's know-how into Finland's newest acquisition decision of airborne equipment, namely the tactical transport helicopter NH90.

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8 Figures

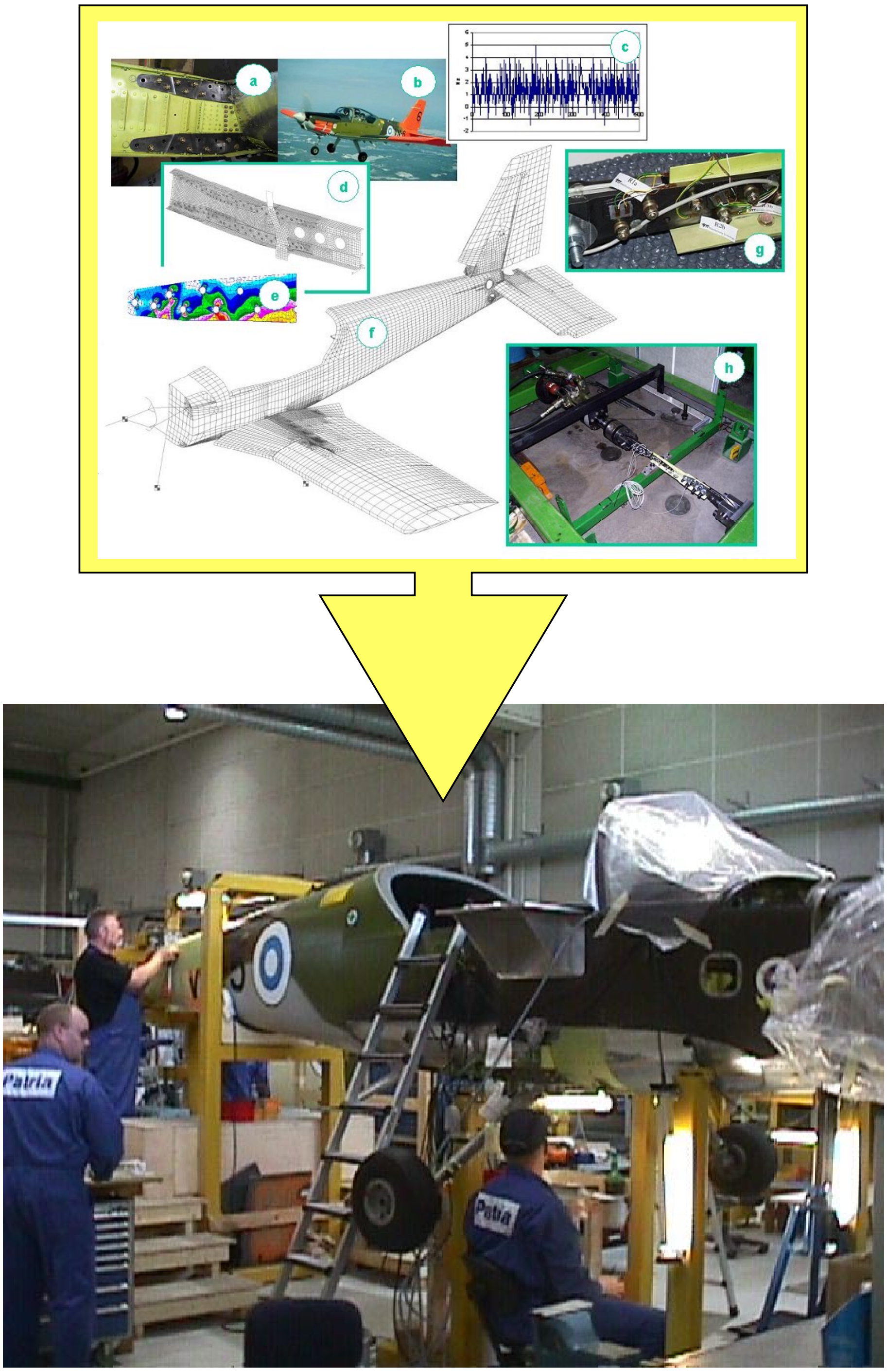


Figure 1. *The Life Extension Program (LEP) of the Valmet Vinka primary trainer, as described in [ICAF 2001] and shown above, has progressed into the implementation phase. Courtesy of Patria Aviation, Aircraft Business Unit.*

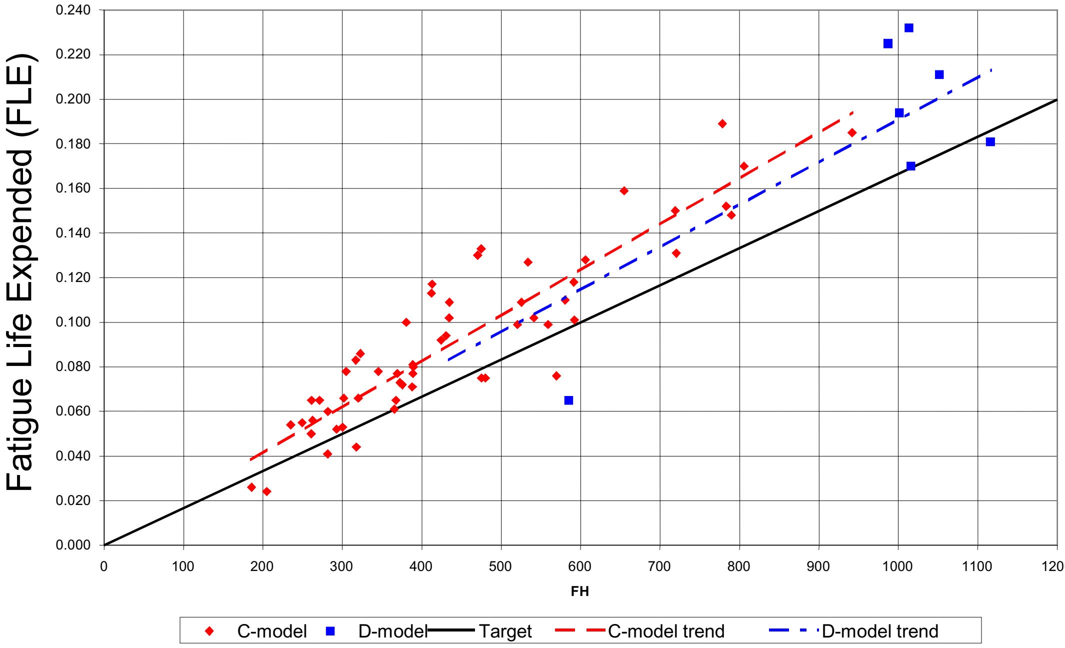


Figure 2. *Summary of the wing root fatigue life expended (FLE) of the FiAF F-18 fleet as ranked according to the data obtained from the current onboard strain recording system. Courtesy of the FiAF HQ.*

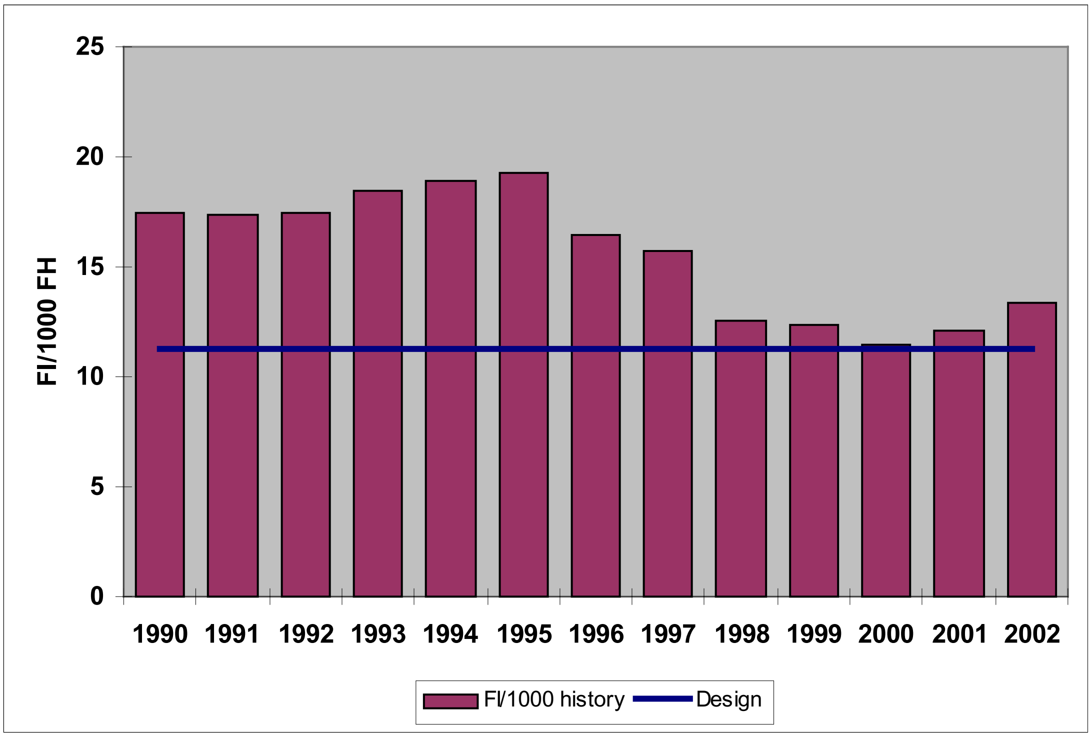


Figure 3. *Fatigue Index (FI) development of the FiAF Hawks (fleet average). Courtesy of the FiAF HQ.*

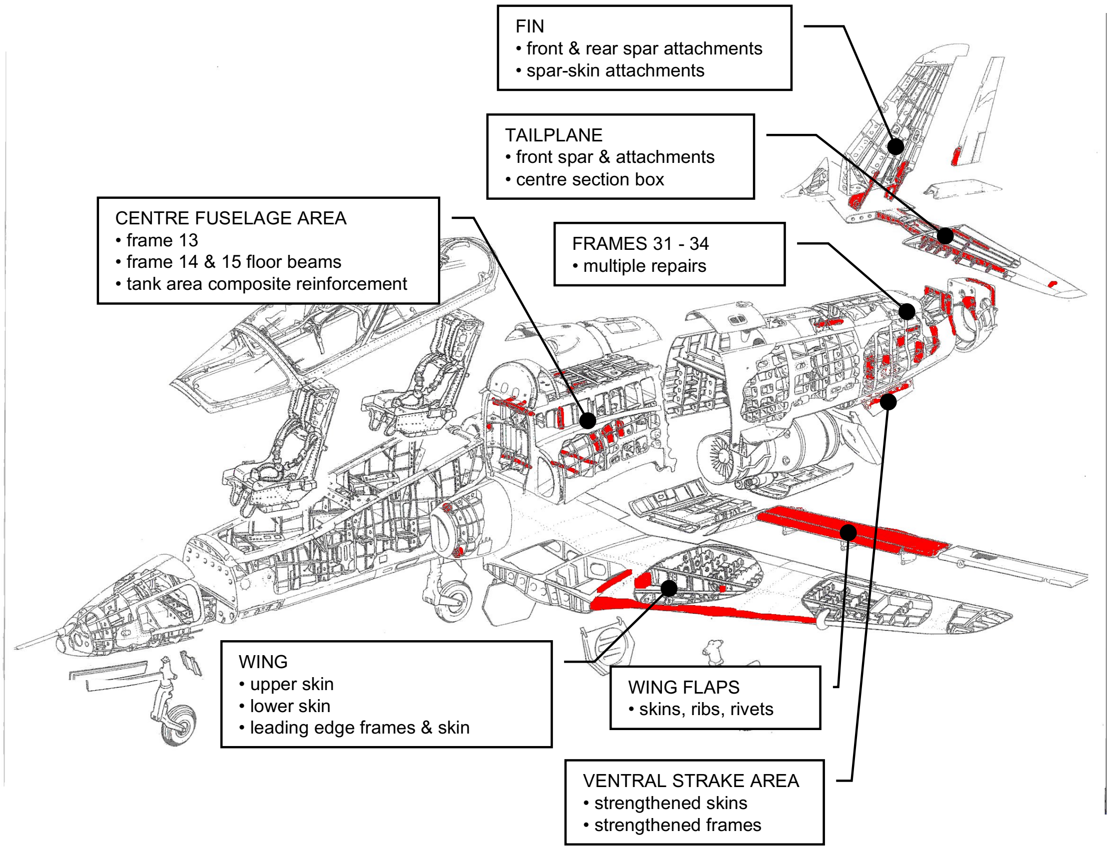


Figure 4. *Summary of the major structural areas (red colour) of the Finnish Hawks, for which the repair methods and modification kits were developed by PFA and the FiAF. Courtesy of Patria Aviation, Aircraft Business Unit.*

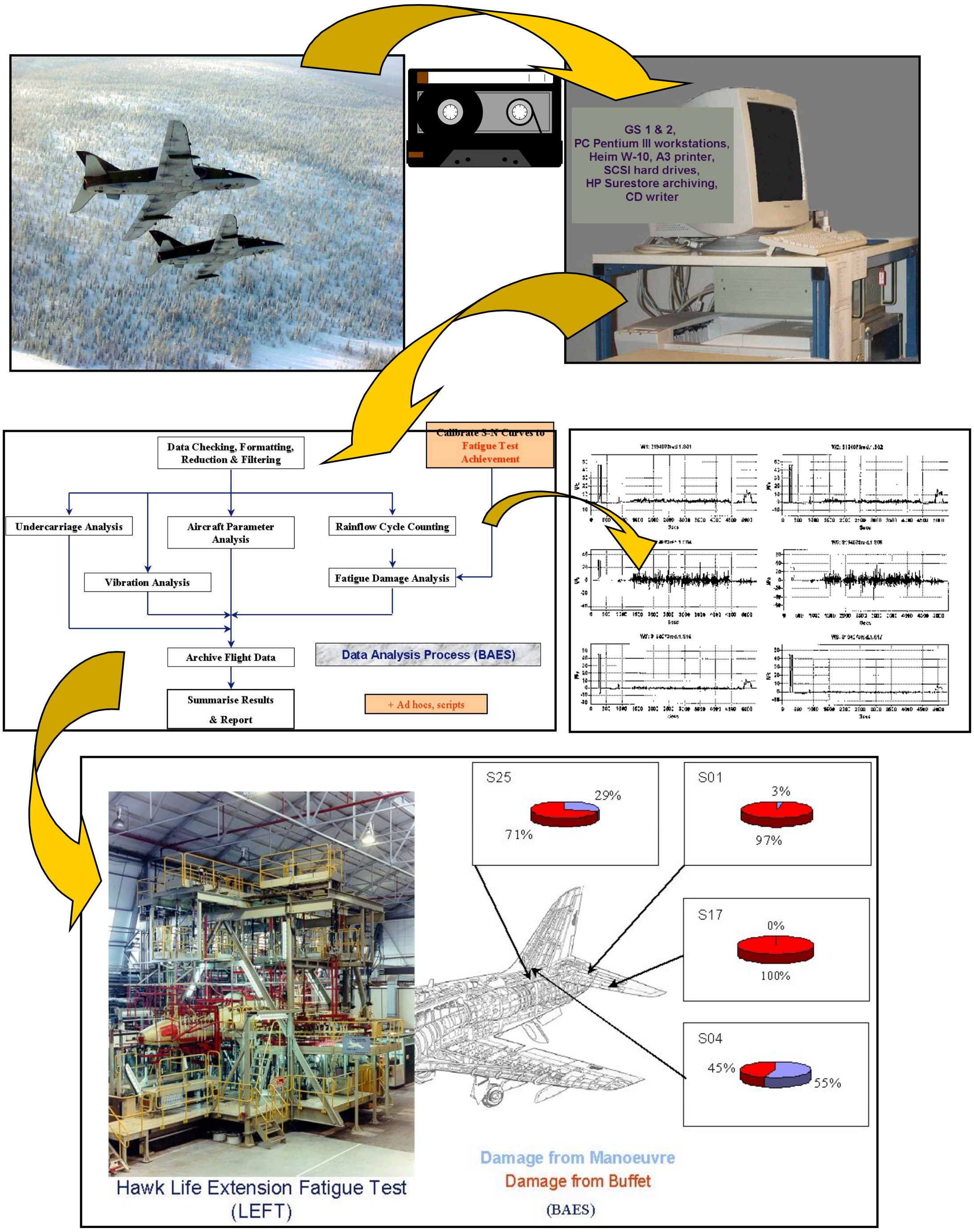


Figure 5. *A schematic of the Hawk Mk.51/51A OLM program (Operational Loads Measurement), phase I. Courtesy of BAE SYSTEMS, the FiAF HQ, VTT.*

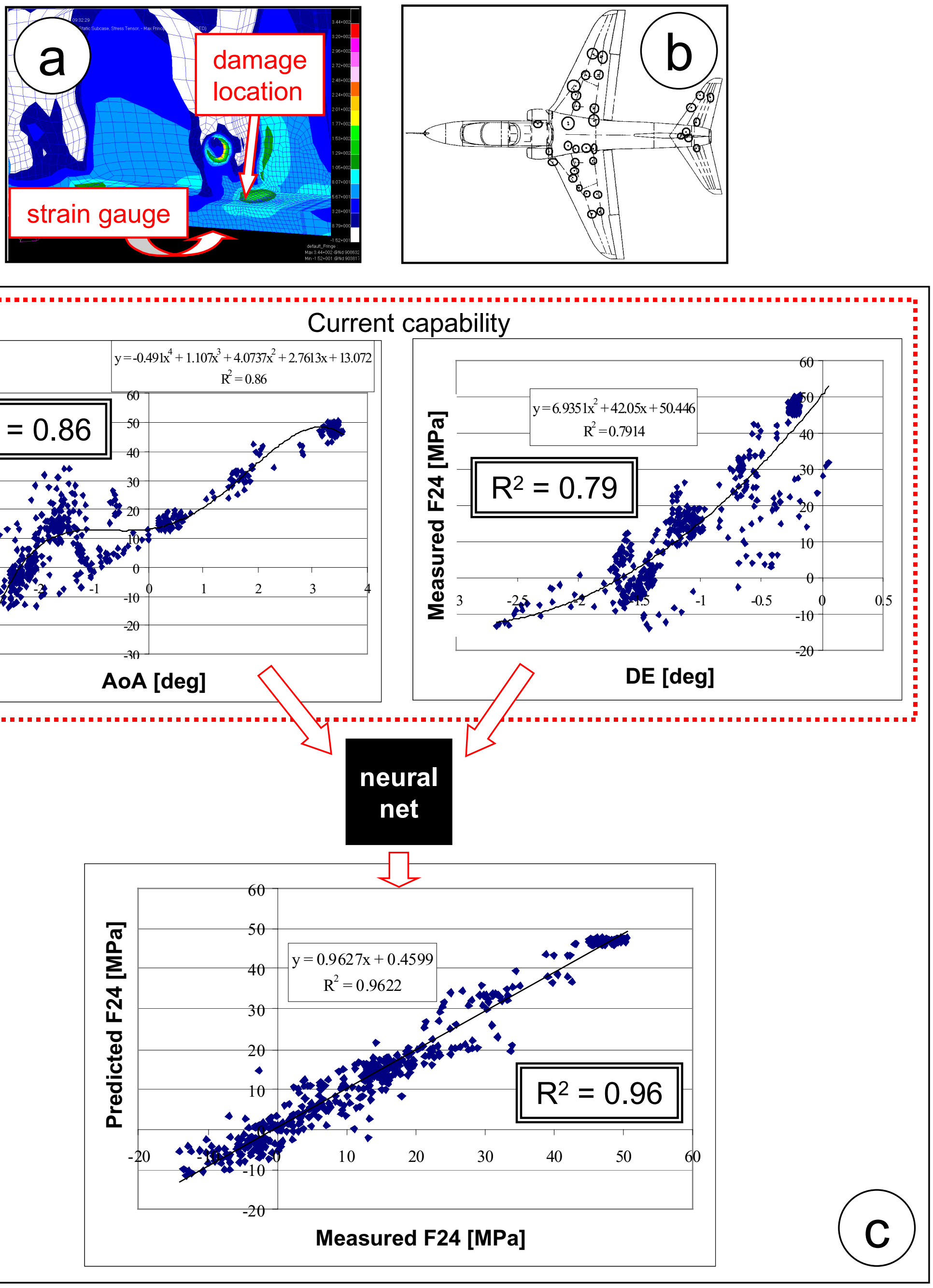


Figure 6. *A schematic of the neural network approach:* ***a)*** *operational loads (local strains) are measured as near as possible from the fatigue critical "hot spot";* ***b)*** *global strains are measured and the transfer functions are determined using the global strains and flight parameters;* ***c)*** *an example of a neural network application to predict wing bending moment on the basis of angle of attack (AoA) and tailplane deflection (DE). Courtesy of J. Tikka (Patria Aviation, Aircraft Business Unit).*

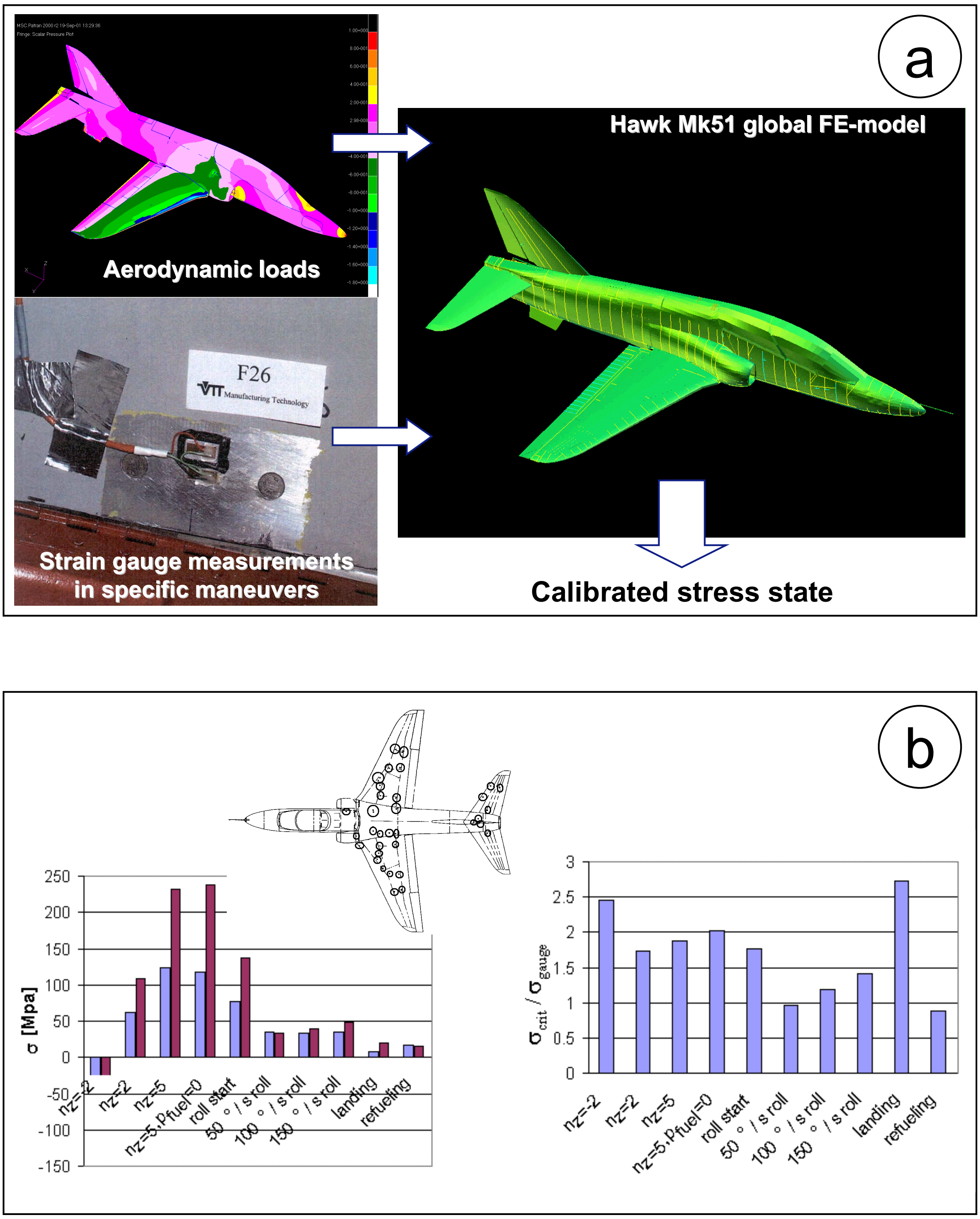


Figure 7. *An overview of the fatigue life evaluation of aircraft's fatigue critical structural locations using virtual fatigue test:* ***a)*** *model calibration, with which it is possible to obtain within 10% (global FE model) and 5% (detailed sub-models) error marginal between measurements and analyses;* ***b)*** *transfer functions (constant values if only Rainflow data and no time history data available) are determined from nearest OLM strain gauge location to each fatigue critical location. Courtesy of Patria Aviation, Aircraft Business Unit.*

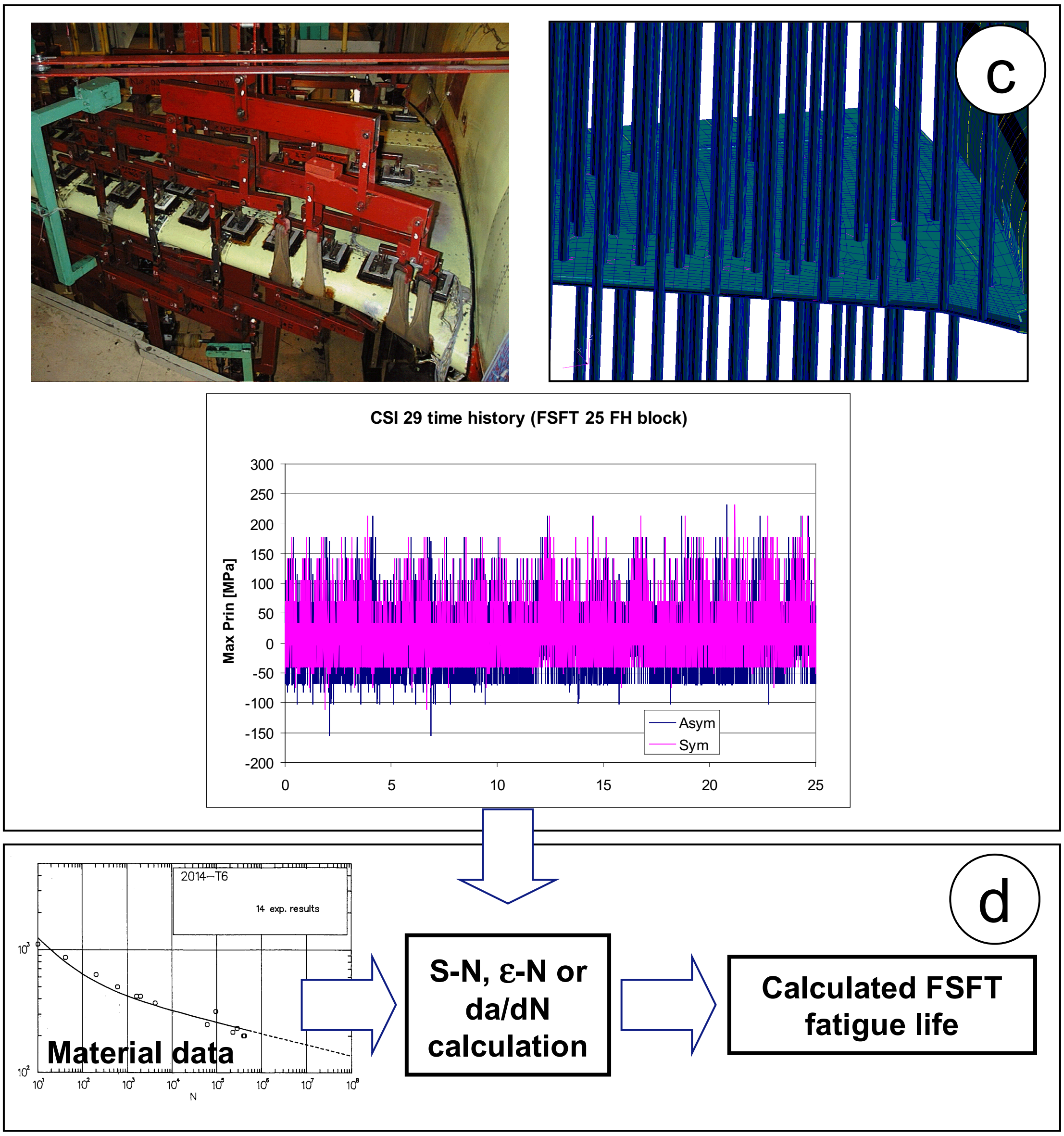


Fig 7 (cont'd). ***c)*** *a 25 FH load history block was constructed (consistent with the original FSFT sortie pattern) and a flight maneuver time history for every sortie was made, from which the hydraulic loading actuator time histories were created for each maneuver and then inserted in the 25 FH block;* ***d)*** *for all locations, a calculated fatigue life in the virtual FSFT was established. Courtesy of Patria Aviation, Aircraft Business Unit.*

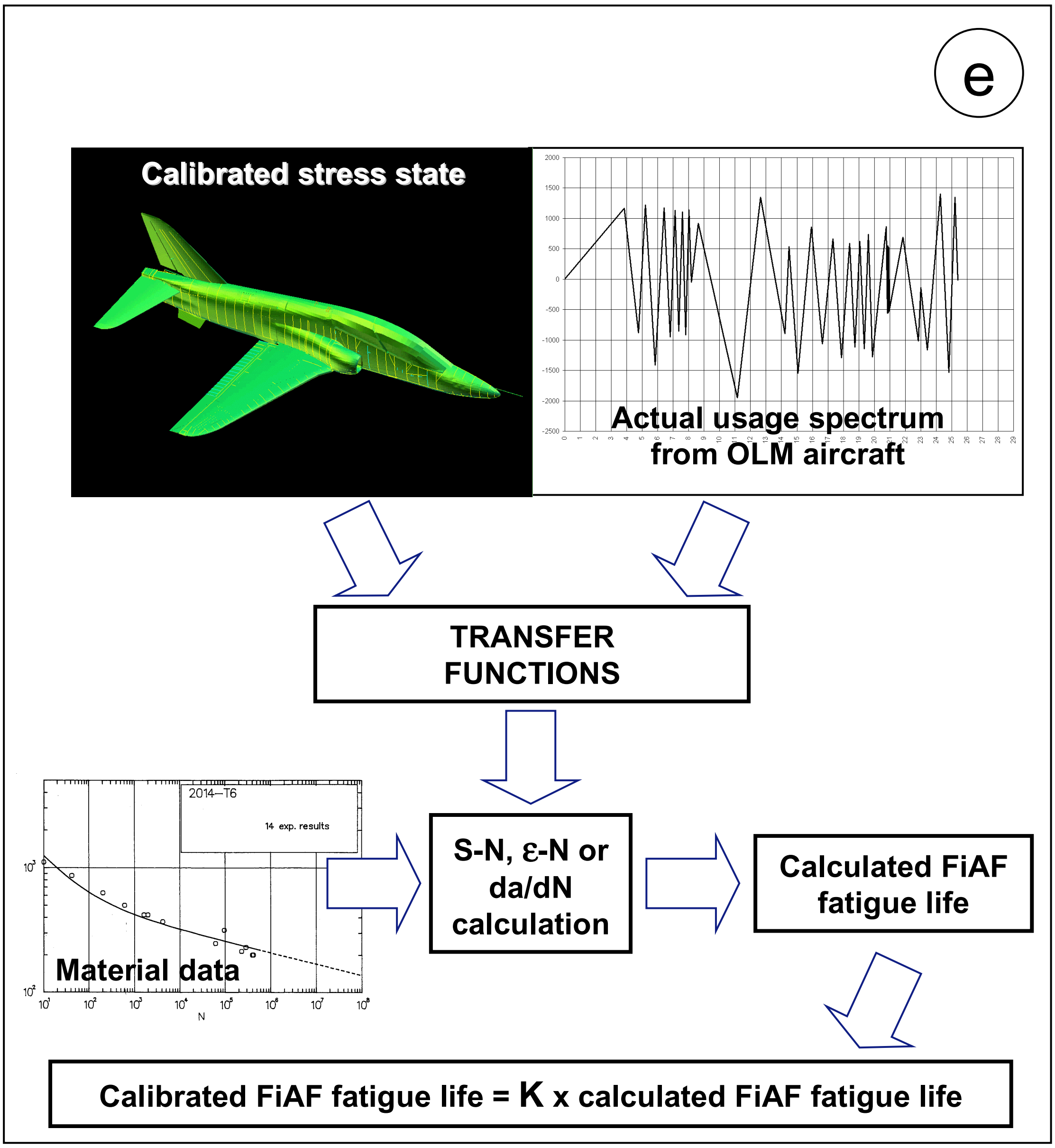


Fig 7 (cont'd). ***e)*** *finally, the calibrated FiAF fatigue life = K x calculated FiAF fatigue life is obtained (the correction coefficient K = measured fatigue life / calculated fatigue life). Courtesy of Patria Aviation, Aircraft Business Unit.*

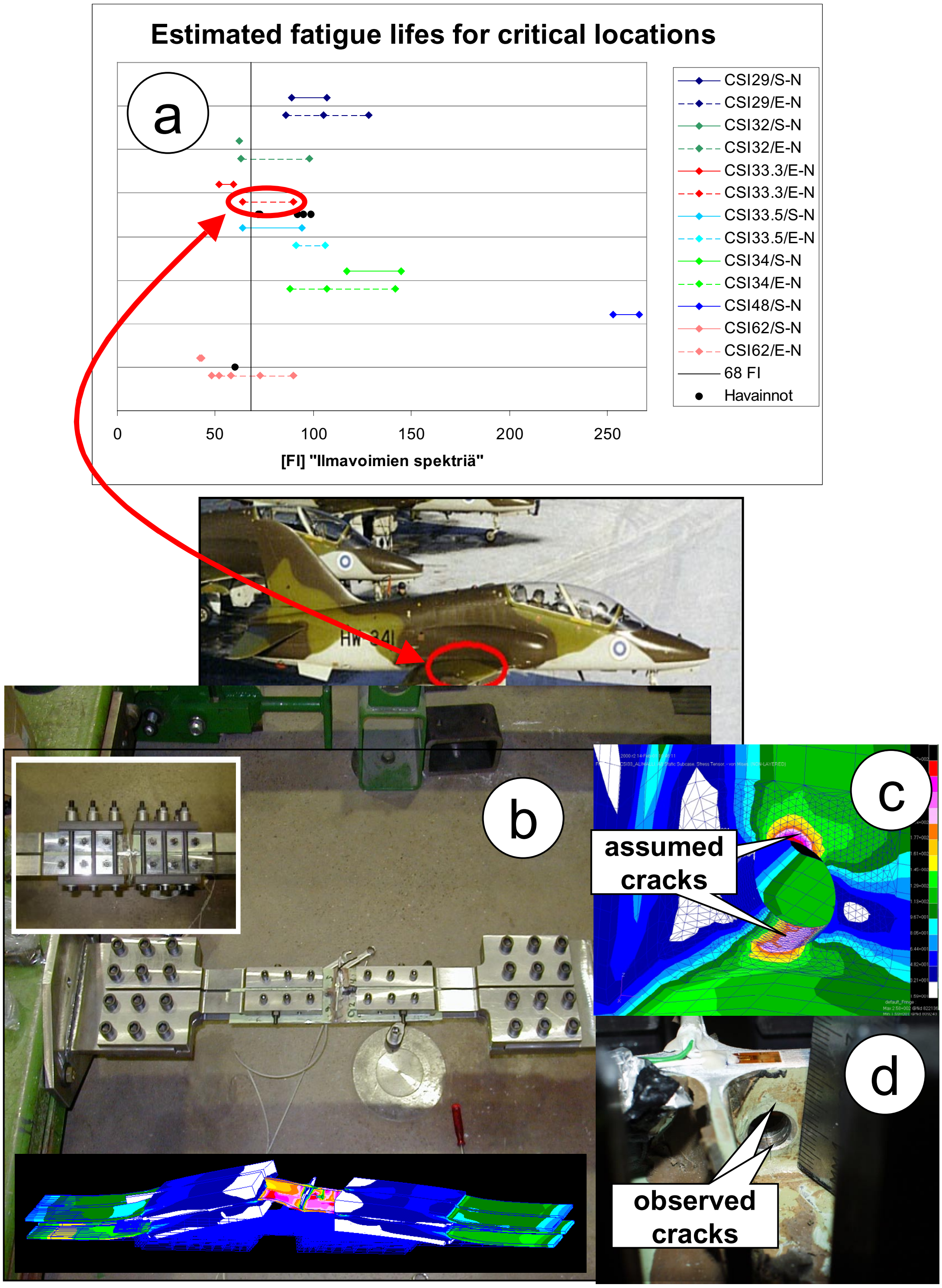


Figure 8. *Experimental verification of the Hawk wing detail:* ***a)*** *estimated fatigue lives for critical locations - wing detail circled (courtesy of Patria Aviation, Aircraft Business Unit);* ***b)*** *an overview of the Hawk lower wing skin spectrum fatigue test set-up on the strong floor of VTT Building and Transport;* ***c)*** *stress distribution as predicted (courtesy of Patria Aviation, Aircraft Business Unit);* ***d)*** *physical cracking observations support the predicted behaviour.*

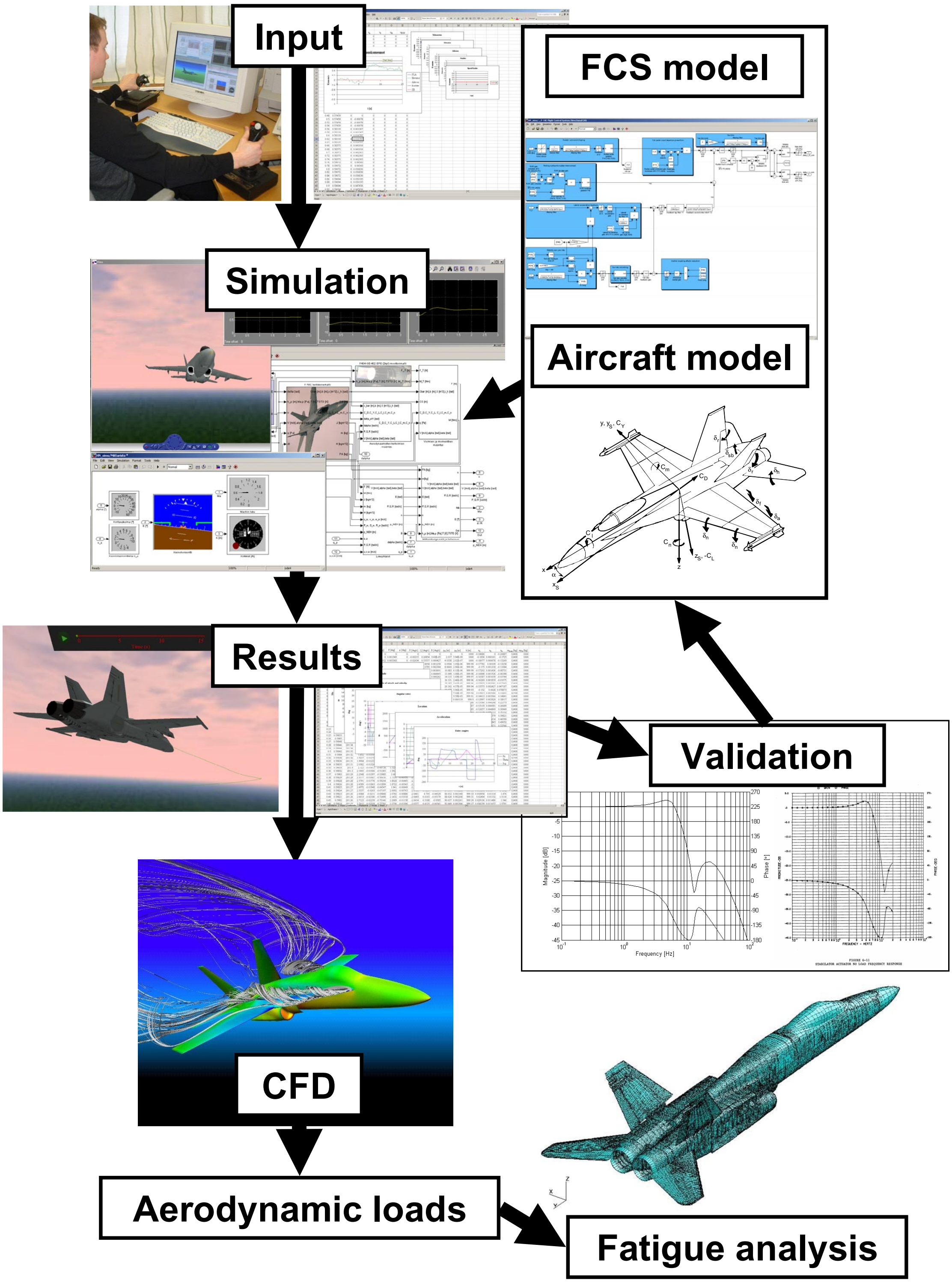


Figure 9. *A schematic of the FiAF F-18 Flight Control System activities. Courtesy of HUT/LAD.*

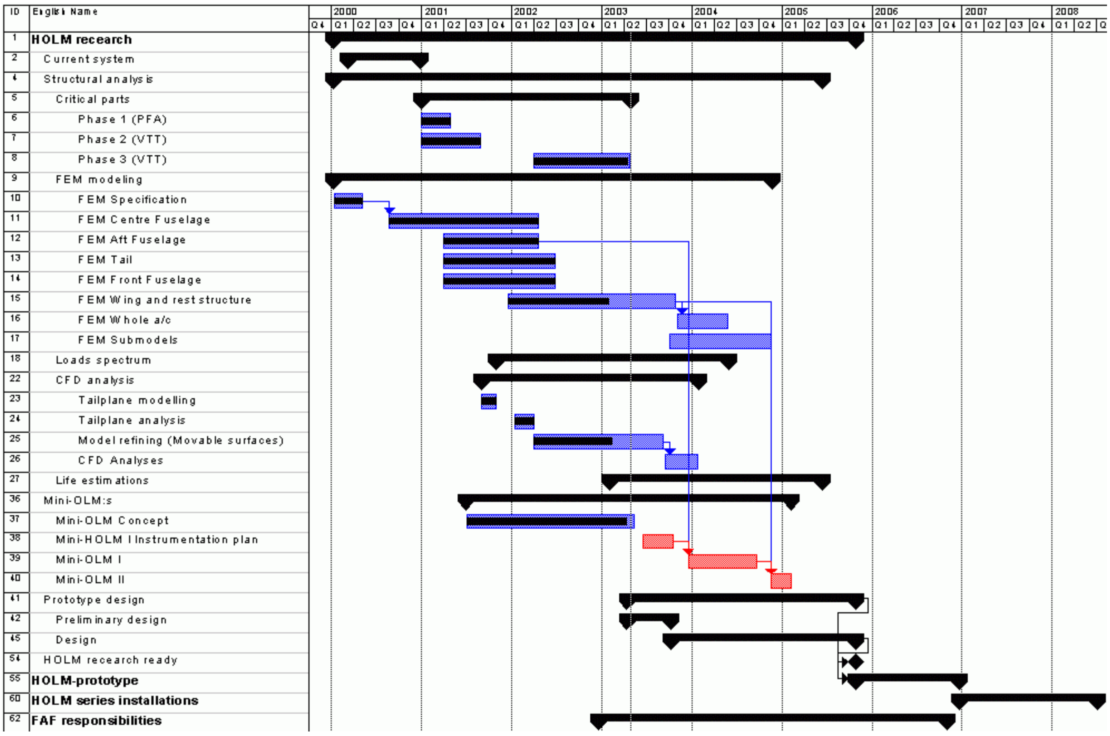


Figure 10. *A schematic of the HOLM program. Courtesy of the FiAF HQ.*

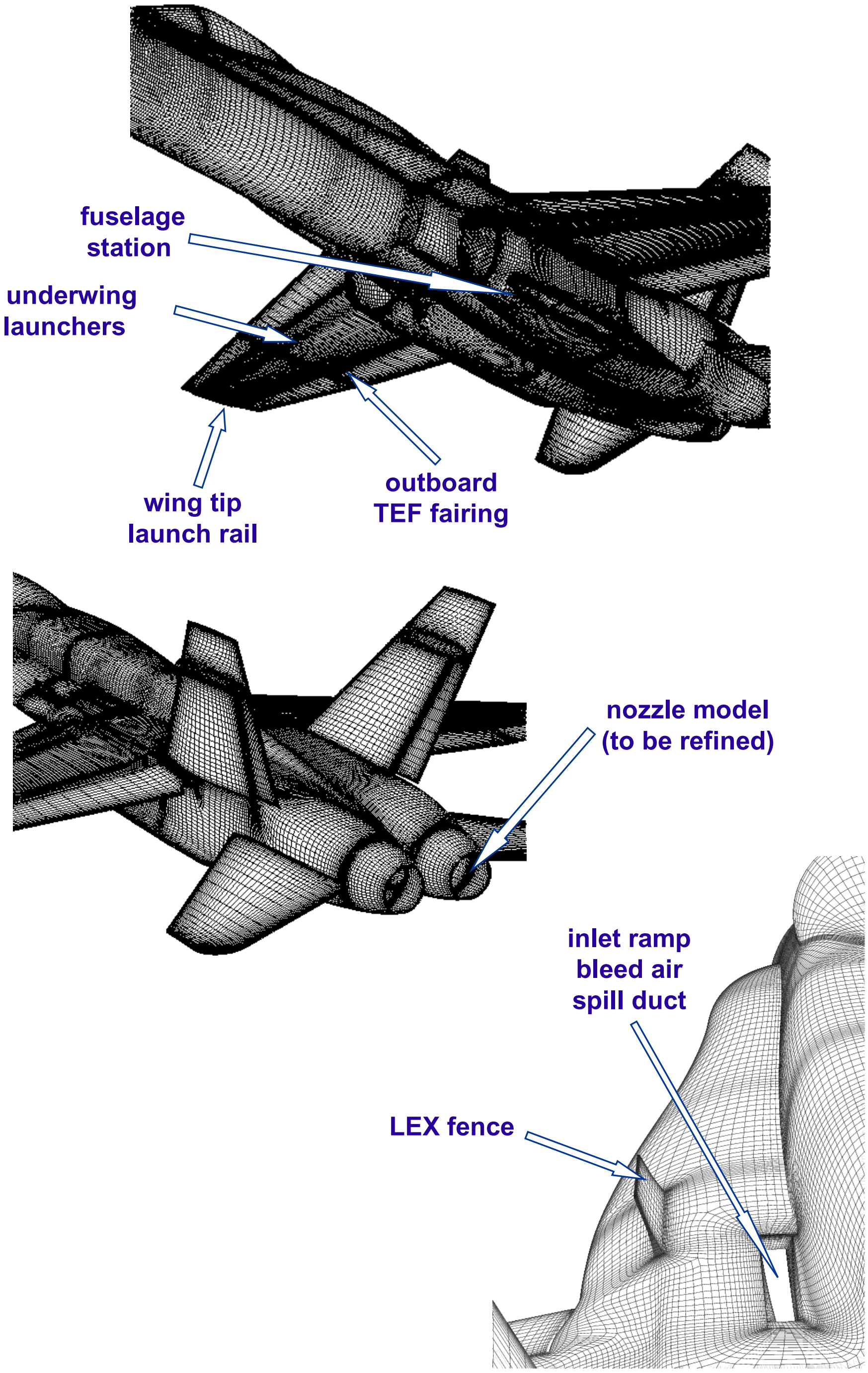


Figure 11. *An overview of the new geometric details within the new Hornet CFD model. The grid size of the new model is approximately 16 million cells. All control surfaces (LEFs, TEFs and their shrouds, rudders, horizontal stabilators) are adjustable. Courtesy of FinFlo Ltd.*

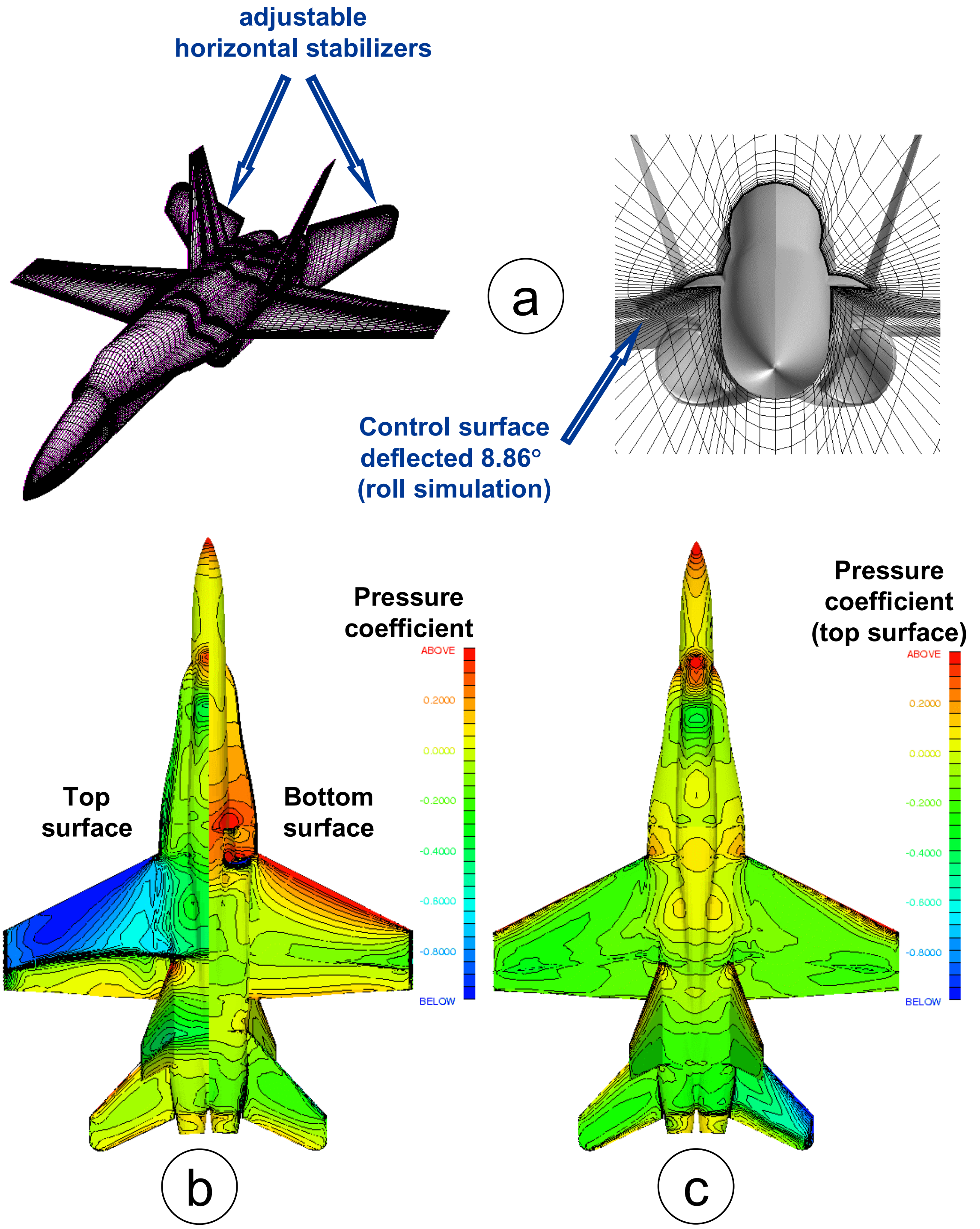
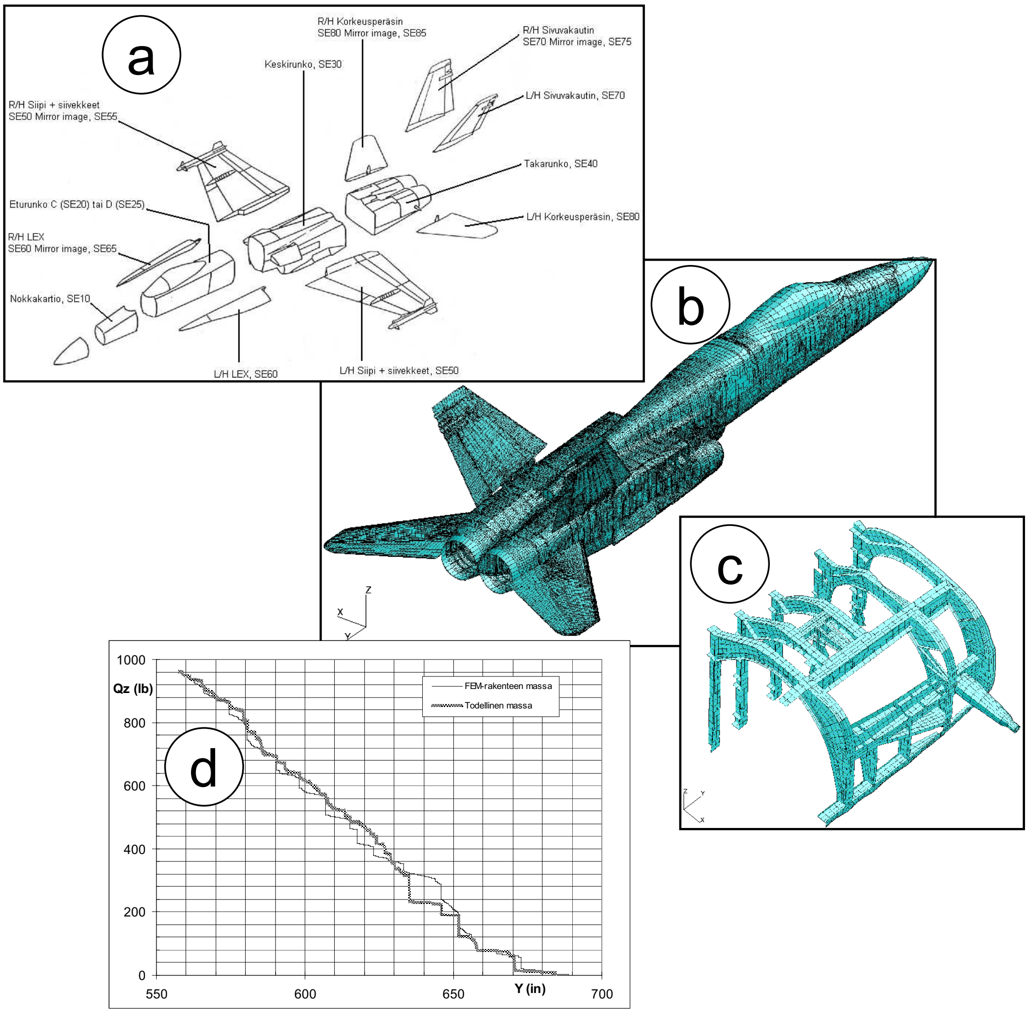


Figure 12. ***a)*** *An overview of the existing Hornet's CFD model. The grid size of the model is approximately 4.2 million cells. Examples of results:* ***b)*** *Steady-state pull-up (Ma = 0.9, NAC = 6g, ALT = 3000 m, AOA = 6.2°);* ***c)*** *Left roll (port wing downwards, Ma= 1.1, ALT = seal level, AOA = 0.8°). Courtesy of FinFlo Ltd.*



Frame Y615		-- t0.063 --								
	El.no(MDA)	(tau) 18	(tau) 19	(tau) 20	(tau) 21	(tau) 22	(tau) 23	(tau) 24	(tau) 25	(tau) 26
e	Stress(MDA)	4.54	5.11	5.16	5.27	5.21	4.40	3.86	4.54	5.10
	Stress(FEM)	3.55	3.69	3.31	4.05	4.32	3.84	2.94	3.62	3.42
	Diff. (%)	**-22**	**-28**	**-36**	**-23**	**-17**	**-13**	**-24**	**-20**	**-33**
Y646 Drop Link		------- A = 1.80*0.10 ------			------------ A = 1.80*0.12 -------------				-- A = 1.80*0.09 --	
	El.no(MDA)	84	85	86	87	88	89	90	91	
	Stress(MDA)	-37.60	-41.90	-49.60	-51.80	-53.30	-54.10	-46.80	-54.40	
	Stress(FEM)	-31.30	-38.90	-49.20	-47.10	-50.20	-51.90	-45.10	-40.10	
	Diff (%)	**-17**	**-7**	**-1**	**-9**	**-6**	**-4**	**-4**	**-26**	

Figure 13. *An overview of the Hornet FE model:* ***a)*** *The partitioning principle of the aircraft into appropriate sections - each section is modeled in the coordinate system of the aircraft;* ***b)*** *the port side (fuselage, vertical tail and horizontal stabilator) is modeled and the starboard side is obtained by mirroring but signinificant unsymmetries are modeled individually;* ***c)*** *a detail of the aft fuselage inner structure with the stabilator spindle;* ***d)*** *aft fuselage model verification in view of mass distribution;* ***e)*** *aft fuselage model verification in view of stresses. Courtesy of Patria Aviation, Aircraft Business Unit.*

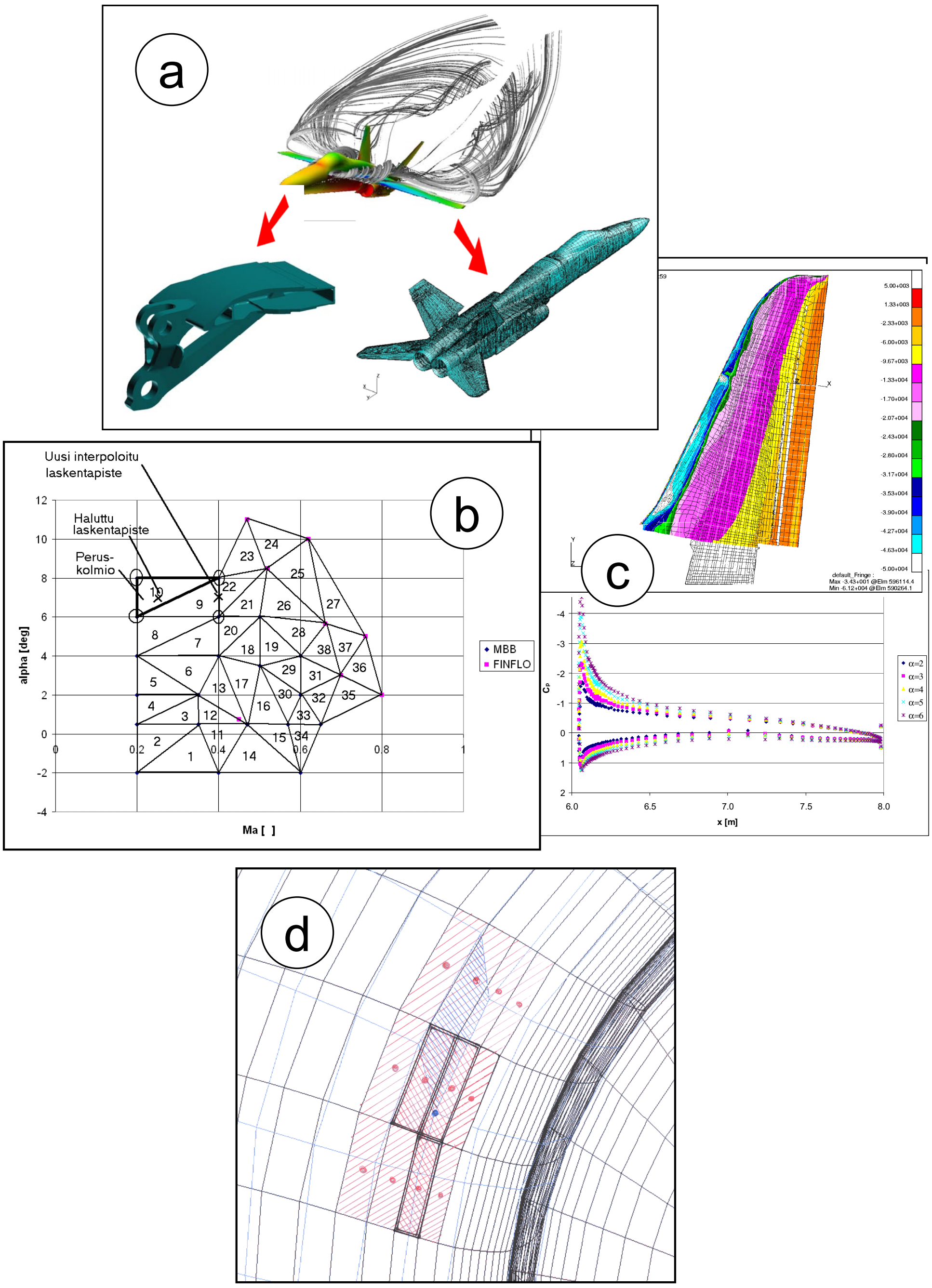
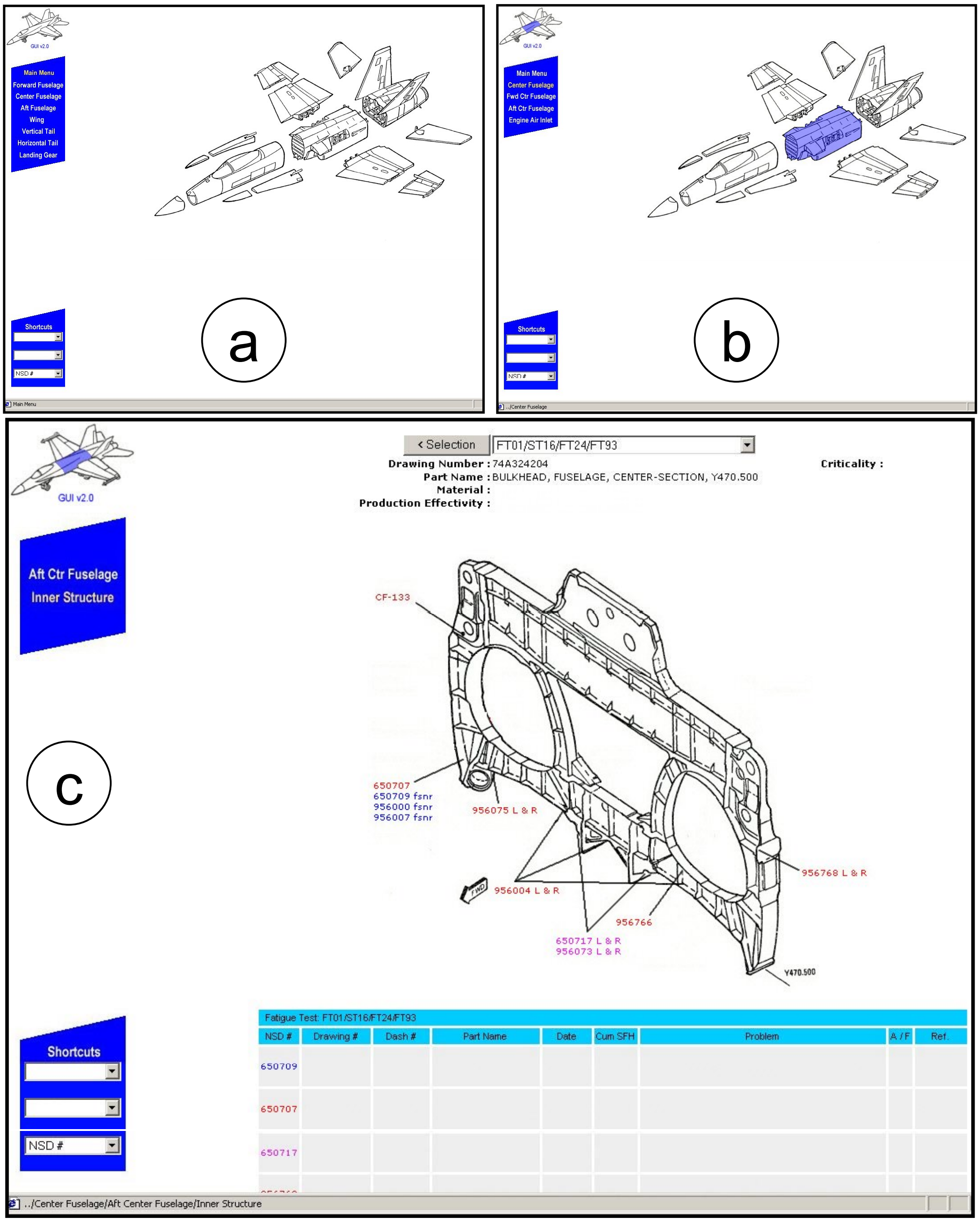


Figure 14. *An overview of the load transfer procedure between a CFD model and an FE model:* ***a)*** *Pressure distributions obtained from CFD and transfered as load cases to FE models ;* ***b)*** *principle of interpolation of CFD results between the FinFlo and MBB solutions in Ma-AOA space;* ***c)*** *geometric interpolation from CFD grid to FE mesh from chordwise to spanwise;* ***d)*** *an example of a "from-CFD-to-FEA-load-case-transfer", in which the pressure solution is coarsely targeted as a function of coordinates and element numbers. Courtesy of Patria Aviation, Aircraft Business Unit.*



< Selection FT01/ST16/FT24/FT93

Drawing Number : 74A324204
Part Name : BULKHEAD, FUSELAGE, CENTER-SECTION, Y470.500
Material :
Production Effectivity :
Criticality :

Fatigue Test: FT01/ST16/FT24/FT93

NSD #	Drawing #	Dash #	Part Name	Date	Cum SFH	Problem	A / F	Ref.
650709								
650707								
650717								

Figure 15. *An overview of the GUI (Graphical User Interface): **a)** the structure is divided into zones by physical boundaries as shown in the main view; **b)** center fuselage selected by the user; **c)** the fatigue information of a single part - every NSD number contains a link to a "clear form C" pdf document. Courtesy of VTT.*

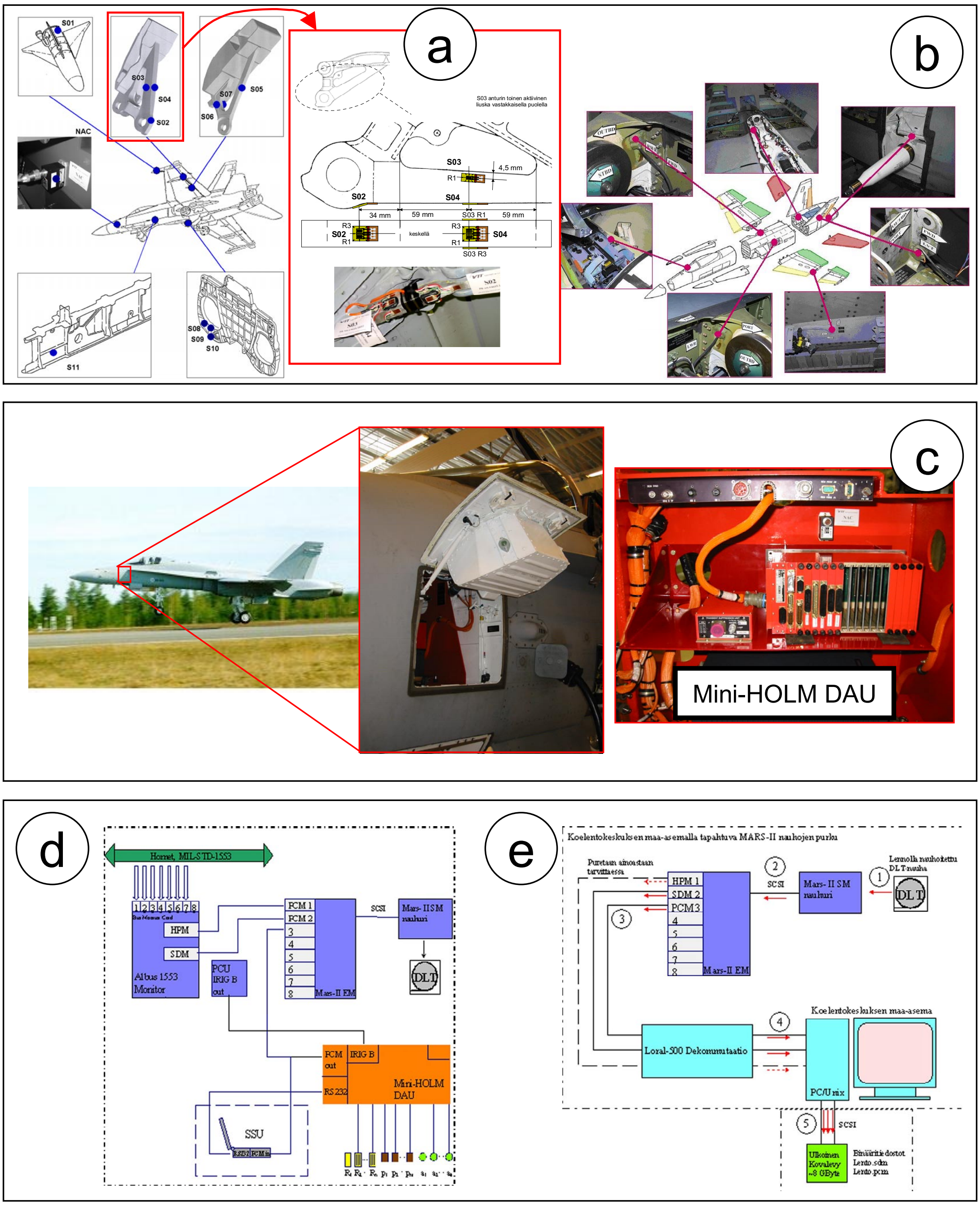


Figure 16. *An overview of the MINI-HOLM proof-of-concept measurements: **a)** new sensors instrumented; **b**) existing onboard sensor locations; **c)** Data Acquisition Unit location; **d)** schematic of the onboard recording system; **e)** schematic of the ground system. Courtesy of VTT.*

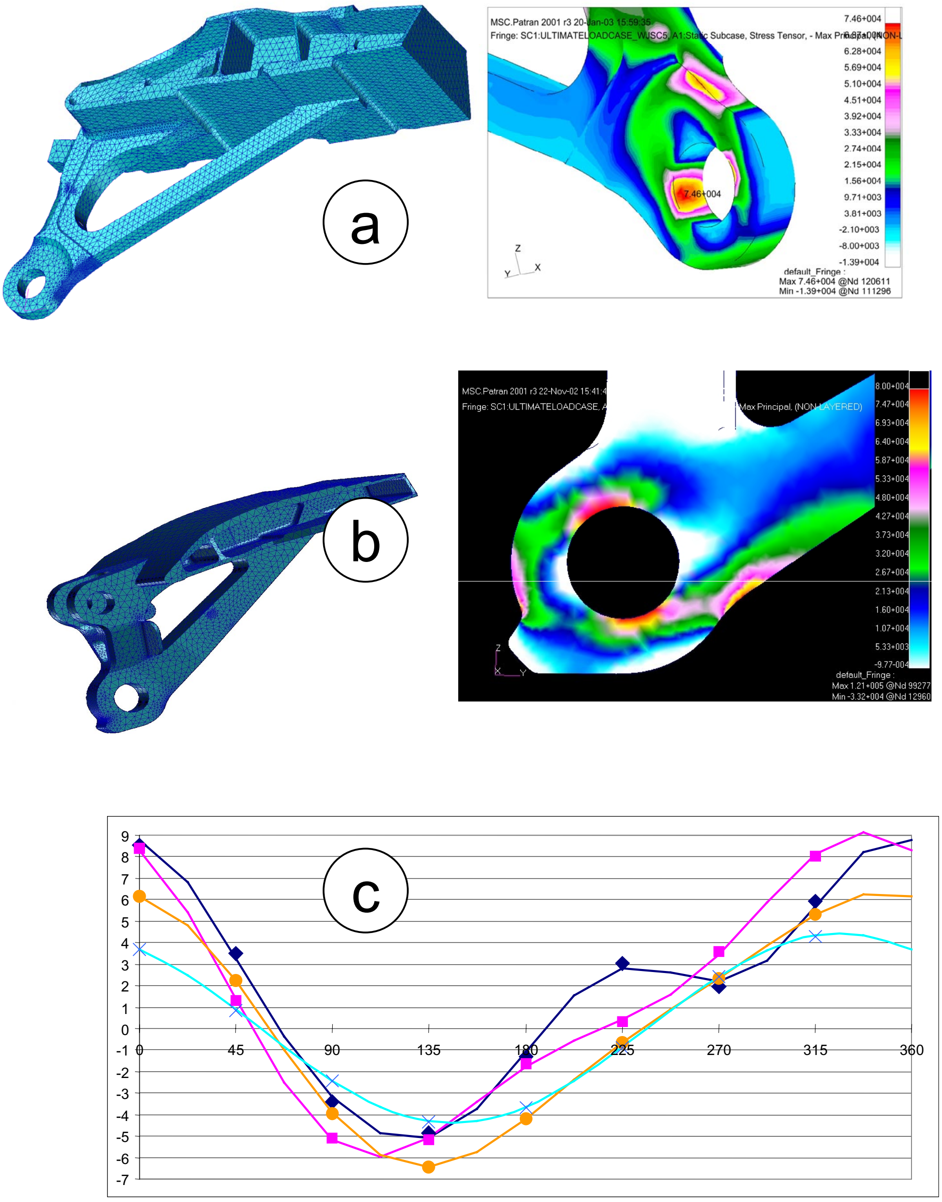


Figure 17. *An overview of the preliminary fatigue life evaluation process:* ***a)*** *trailing edge flap outboard (TEF OB);* ***b)*** *aileron inboard (AIL IB) hinges;* ***c)*** *stress transfer functions between strain gage locations and fatigue critical hot spots of the hinges as generated using the FE models.Courtesy of Patria Aviation, Aircraft Business Unit.*

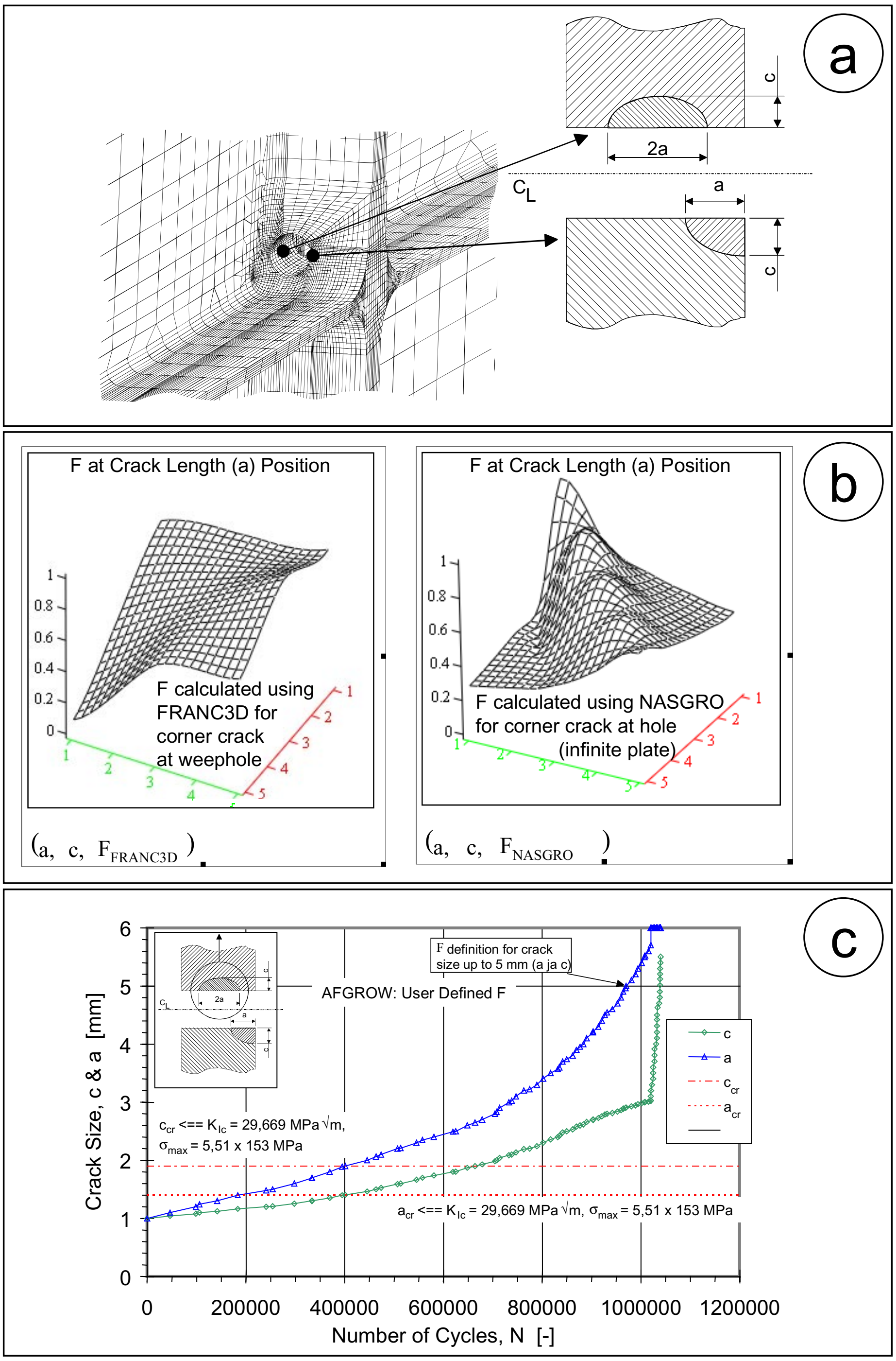


Figure 18. *An overview of the determination of Stress Intensity Factor solutions for a case study:* ***a)*** *the weep hole of the Hawk wing and the modeled crack geometries (surface crack and corner crack);* ***b)*** *examples of the crack shape factor (F) determinations using FRANC3D (left) and NASGRO (right);* ***c)*** *crack growth curves (surface crack case) for the a and c with the AFGROW-defined crack shape factor (F). Courtesy of VTT.*

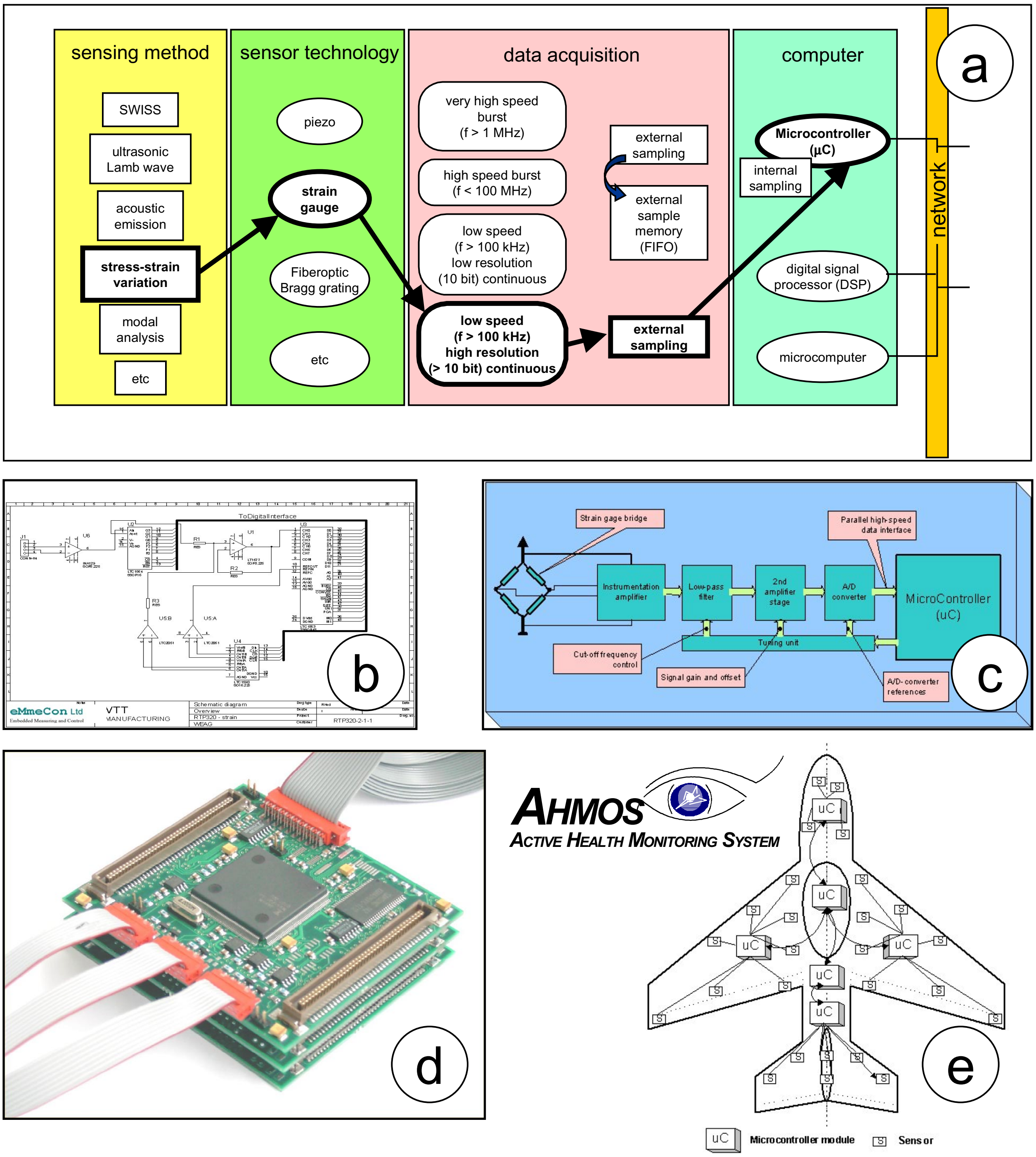


Figure 19. *An overview of the embedded microcontroller based networked measurement and analysis system for fatigue crack detection, developed under the auspices of SOCRATE RTP 3.20 AHMOS:* ***a)*** *an example of the definition of requirements process for the strain gage sensor application;* ***b)*** *electrical design;* ***c)*** *sensor interface diagram;* ***d)*** *physical realization (about cigarrette box size);* ***e)*** *a schematic of a modular and distributed (e.g. signal sampling and analysis locally) structural health monitoring system for an aircraft application. Courtesy of VTT/Emmecon Ltd.*

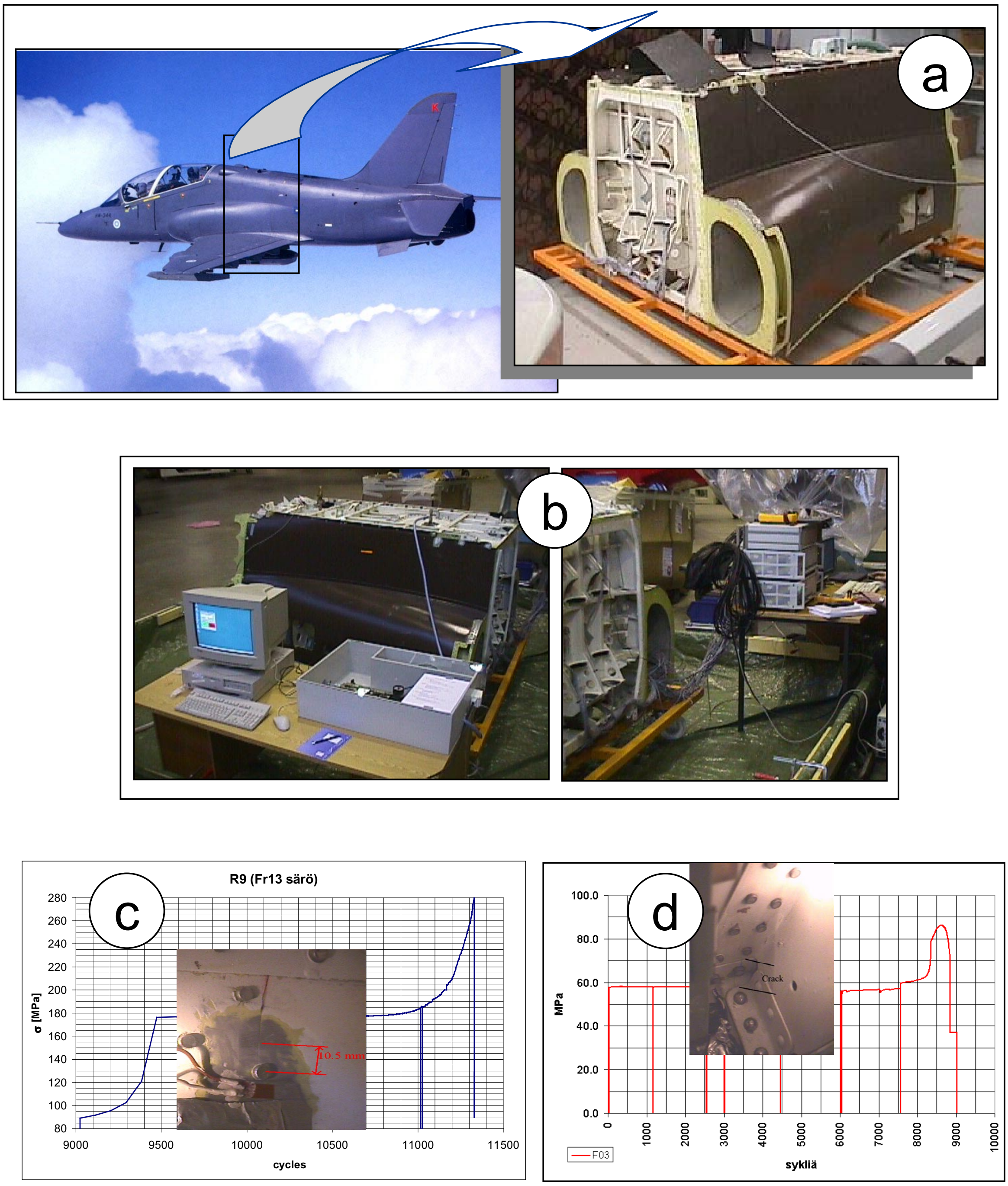


Figure 20. *An overview of a demonstration test bed where the functionality of the structural health monitoring system of Fig. 18 was tested under the auspices of SOCRATE RTP 3.20 AHMOS:* ***a)*** *The FiAF Hawk's centre fuselage;* ***b)*** *fatigue test set-up at Patria;* ***c)*** *fatigue damage (crack growth) development from a sound structure to a rivet hole, then a long stable period, further damage growth until failure from the other edge of the rivet hole;* ***d)*** *fatigue damage development from a sound structure until failure. Courtesy of Patria Aviation, Aircraft Business Unit.*