A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND
MAY 2005 – APRIL 2007

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Preface

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

Emmecon	*Emmecon Oy:* Risto Hedman
FIAFAMC	*The Finnish Air Force, Air Materiel Command:* Ari Kivistö, Pekka Palomäki
FIAFHQ	*The Finnish Air Force Headquarters, Armaments Division, Aircraft Section:* Riku Lahtinen, Risto Pajuniemi, Ilpo Paukkeri, Kalle Vaaraniemi, Ari Välikangas
FIAFSAC	*The Finnish Air Force, Satakunta Air Command:* Peter Ylinen
Finflo	*Finflo Oy:* Timo Siikonen
Patria	*Patria Aviation Oy:* Mika Keinonen, Jussi Kettunen, Antero Miettinen, Jukka Raunio, Jarkko Tikka, Marko Ylitalo
TKK / KRT	*Helsinki Univerity of Technology, Laboratory of Lightweight Structures:* Jarkko Aakkula, Olli Saarela, Markus Wallin
TKK / LAD	*Helsinki Univerity of Technology, Laboratory of Aerodynamics:* Jaakko Hoffrén
TUT/ISP	*Tampere University of Technology, Institute of Signal Processing:* Juha Jylhä
VTT	*The Technical Research Centre of Finland:* Esko Arilahti, Mika Bäckström, Harri Janhunen, Juha Juntunen, Keijo Koski, Risto Laakso, Kari Lahdenperä, Sauli Liukkonen, Sakari Merinen, Markus Porthin, Tony Rosqvist, Eetta Saarimäki, Jorma Salonen, Tuomas Teittinen, Tomi Viitanen, Päivi Varis, Juha Veivo, John Öström

Espoo 25 April 2007

Editor

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13.1 INTRODUCTION

The year 2007 marks the 89th anniversary of the Finnish Air Force (FIAF) – one of the oldest independent air forces in the world. It was founded as an independent service on the 6th March 1918 [FIAF 2007].

The punctual highlight of the 89th anniversary of the FIAF was manifested e.g. as the arrival of the service's first EADS CASA C-295M transport aircraft in Finland. The Air Force has placed an order for two Spanish transports [SPG Media 2007] – tail numbered as CC-1 and CC-2 – to replace the current Fokker F.27s [Fokker 2007]. The reconfigurable C-295M – the largest aircraft ever in the history of the FIAF – are suited for the transport of troops and material both in Finland and abroad as part of international missions. They will also be available for medical and other evacuation tasks in connection with civil crisis management missions, ***Fig. 1***.

Figure 1: *An overview of the largest aircraft ever in the history of the FIAF: EADS CASA C-295M.* ***a)****: The first landing of the CC-1 in Tikkakoski, Finland on the 6th March 2007 at 10:26 [Flightforum 2007];* ***b)*** *The onboard fatigue tracking system;* ***c)*** *Inside view of the cargo bay;* ***d)*** *Example of cargo loading (F-18 engine);* ***e)*** *Cargo bay modified to medical needs. Courtesy of the FIAF (b-e).*

In addition to the above light transports, there are also on-going studies (within the FIAF) to define options for the purchase of heavy airlift capacity. On the rotary wing side, the NH90 helicopters [NHIndustries 2007] being assembled by Patria[1] all possess an on-board fatigue tracking system. More details will be provided e.g. in future ICAF reviews once in-country experiences are collected.

13.1.1 Scope of the review

Apart from the above new acquisitions in addition to the approximately 160 existing aircraft of the FIAF, this national review on aeronautical fatigue concentrates on the aircraft inventory of the FIAF related to fighter jets and related pilot training aircraft. Currently there fly 62 F-18C/D Hornet fighters[2], 49 Mk.51/51A Hawk jet trainers and 28 Valmet Vinka primary trainers within the FIAF. During the writing of this review, approximately 72 000 FH have been flown with the Hornets, 212 000 FH with the Hawks and 135 000 FH with the Vinkas. No FIAF aircraft of these type designations have been lost due to structural issues.

The severity of the Finnish usage in view of structural fatigue with the two jets of noteworthy manoeuvring capability can be seen in ***Fig. 2*** (Hornet) and ***Fig. 3*** (Hawk). Figs 2 and 3 clearly demonstrate the need to further develop and apply concrete and systematic efforts on a national level to cope with the structural deterioration effects of these two aircraft types.

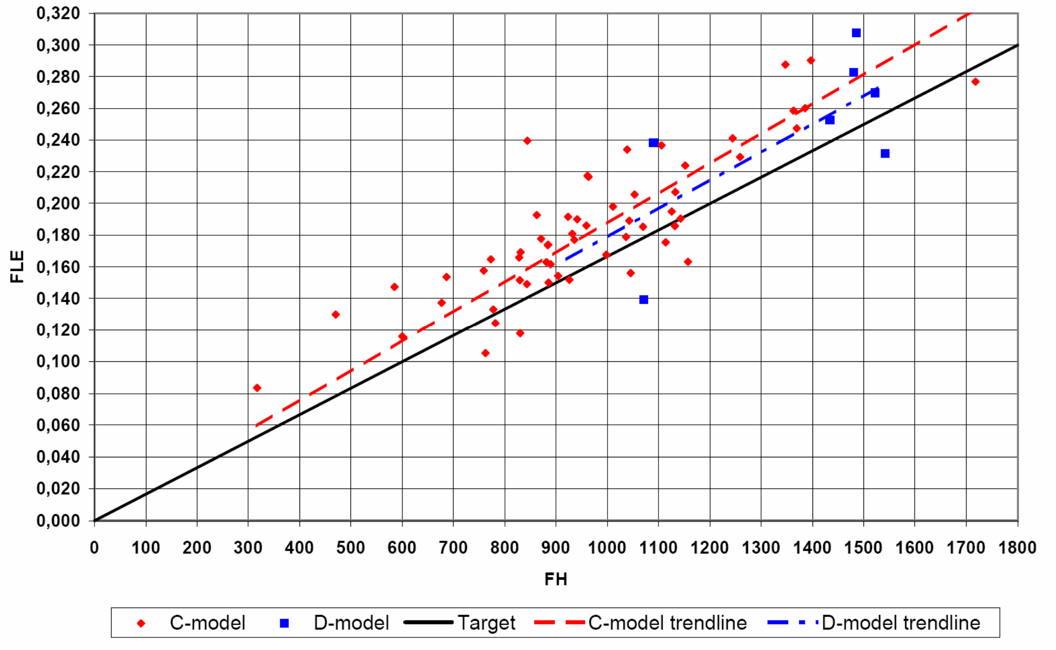

Figure 2: *Summary of the wing root fatigue life expended (FLE) of the FIAF F-18 fleet at the end of 2006 (data from all 64 aircraft included, as ranked according to the data obtained from the current onboard strain recording system. Courtesy of the FIAF.*

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[1] Patria is responsible for assembling 50 NH90 helicopters for Sweden, Finland and other operators. The Finnish assembly line is the 4th operational assembly line for the NH90, beside the ones based in France, Germany and Italy [Patria 2007].

[2] In addition to the existing 62 FIAF F-18C/D Hornets, another one – the 63th FIAF Hornet, tail number HN-468 – is being modified at Patria Aviation from an F-18C into an F-18D [FINSE 2006].

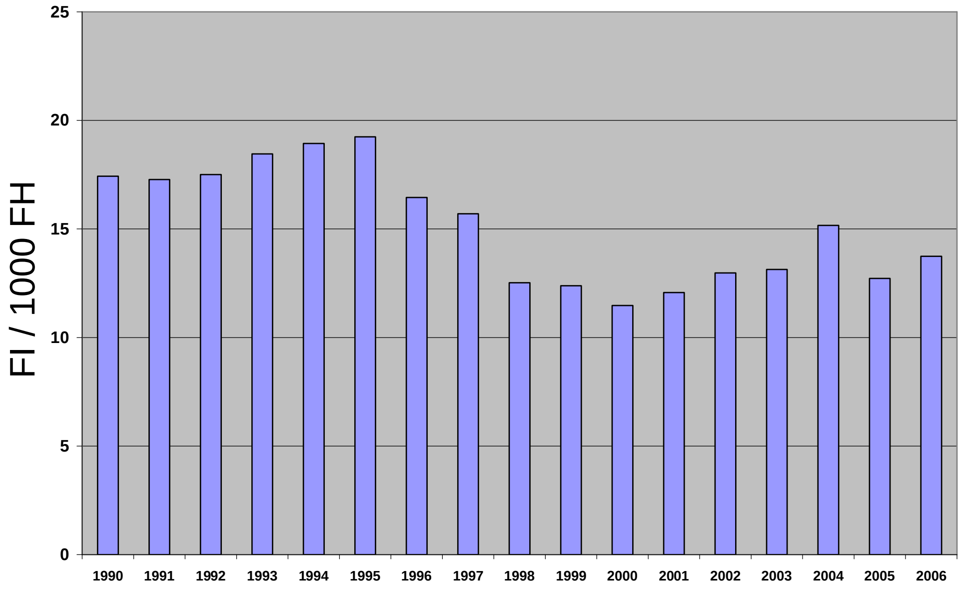

Figure 3: *Fatigue Index (FI) development of the FIAF Hawks at the end of 2006 (fleet average; data from all 57 aircraft included, as ranked according to the a/c centre of gravity normal acceleration. Courtesy of the FIAF.*

During 2005, the International Committee on Aeronautical Fatigue (ICAF) formally welcomed Finland as a full member of the ICAF. Thus, Finland became the 13th full member of the ICAF. This Finnish national review of current aeronautical fatigue investigations up to April 2007 – although the 4th review but the 1st review as a full member – was compiled by Aslak Siljander (VTT). The review comprises inputs from the organisations listed below (in alphabetical order).

Emmecon	Emmecon Oy., P. O. Box 35, FI-53851 Lappeenranta, Finland (http://www.emmecon.fi/)
FIAFAMC	The Finnish Air Force, Air Materiel Command, P. O. Box 210, FI-33101 Tampere, Finland (http://www.ilmavoimat.fi/index_en.php)
FIAFHQ	The Finnish Air Force Headquarters, Armaments Division, P. O. Box 30, FI-41161 Tikkakoski; Finland (http://www.ilmavoimat.fi/index_en.php)
Finflo	Finflo Oy., Tekniikantie 12, FI-02150 Espoo, Finland (http://www.finflo.fi/)
Patria	Patria Aviation Oy, Systems and Services business unit, Aviation & Systems, FI-35600 Halli, Finland (http://www.patria.fi/index2.htm)
TKK/KRT	Helsinki University of Technology, Laboratory of Lightweight Structures, P. O. Box 4300, FI-02015 TKK, Finland (http://krt.tkk.fi/indexENG.html)
TKK/LAD	Helsinki University of Technology, Laboratory of Aerodynamics, P. O. Box 4400, FI-4400 TKK, Finland (http://www.aero.hut.fi/Englanniksi/)
TUT/ISP	Tampere University of Technology, Institute of Signal Processing, Korkeakoulunkatu 1, FIN-33720 Tampere, Finland (http://sp.cs.tut.fi)
VTT	VTT Machine and Vehicle Industries, P. O. Box 1000, FI-02044 VTT, Finland (http://www.vtt.fi/?lang=en)

13.2 FIAF FATIGUE MANAGEMENT POLICY AND THE ASIMP

The fatigue management policies of the FIAF have been outlined in previous national reviews [ICAF 2001; ICAF 2003; ICAF 2005]. The ASIMP preparation has been a more demanding process than expected. Thus, the first official version of the FIAF Aircraft Structural Integrity Management Plan – the ASIMP, which will be used as a tool in structural life cycle management – will be published in 2009 for FIAF F-18 Hornet and Mk50 & 51A Hawk aircraft. The Finnish industry will have a more important role in the development work.

13.3 VALMET VINKA

The elementary and basic pilot training of the FIAF has been outsourced to Patria Aviation Oy since September 2005 [Patria 2005]. The training in Tikkakoski base includes elementary and basic flight training according to the FIAF's flight training syllabus for conscripts, cadets and flight instructor trainees. Also the technical support and scheduled maintenance of the fleet are included, excluding the daily maintenance for 10 Vinkas used as liaison aircraft.

The Life Extension Program (LEP) of the Valmet Vinka primary trainer has been reported previously [Pirtola 2001; ICAF 2001 Chapter 3]. A more recent summary has since been prepared by Patria Aviation [Pirtola 2006] – the document, assigned to the document number 2409 by ICAF, is the first "licensed" ICAF document from Finland. In connection with the LEP activities, all primary trainers have now been equipped with onboard g counters. An example is provided in ***Fig. 4***. Individual aircraft have been assigned to "fleet leader" roles to provide e.g. early warnings of possible structural fatigue scenarios [Pirtola 2006b].

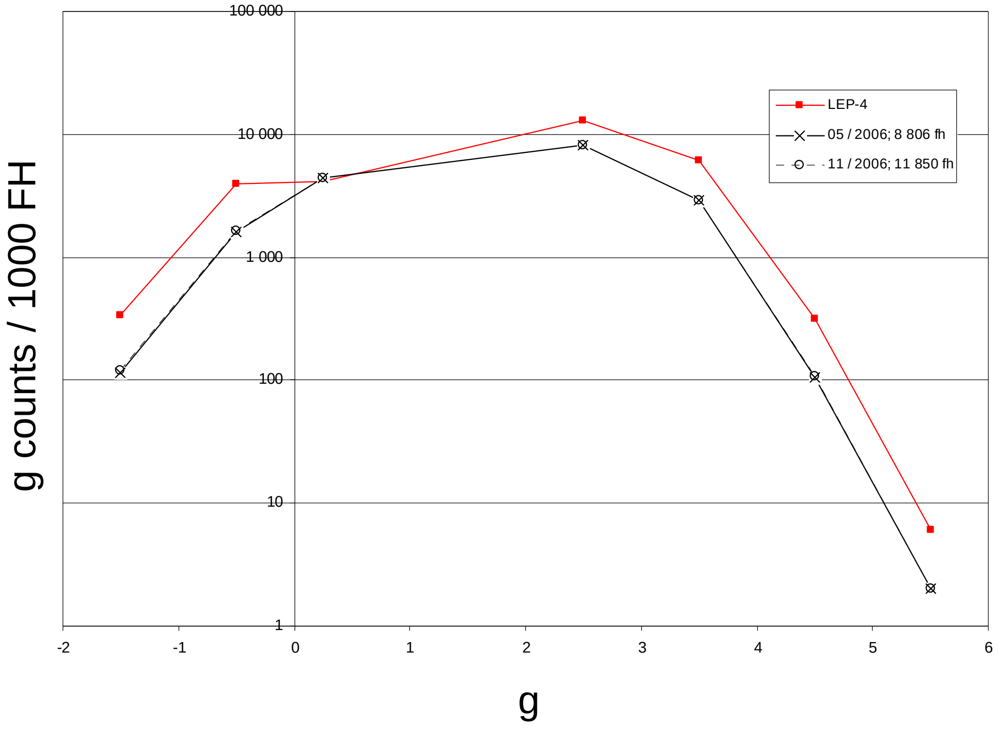

Figure 4: *The g counts per 1000 FH of the Valmet Vinka.* ***LEP-4****: The spectrum representing the LEP design assumptions;* ***-x-****: The post LEP g counter spectrum as of May 2006;* ***-○ -****: The post LEP g counter spectrum as of November 2006. The curves (****-x-*** *and* ***-○ -****) represent the fleet average from all Vinkas, as ranked according to the a/c centre of gravity normal acceleration. Courtesy of Patria Aviation.*

13.4 HAWK MK.51 AND HAWK MK.51A

Patria Aviation is upgrading 30 Hawk jet trainers and one simulator from the FIAF. The upgrade aims to further increase the quality of flight training by creating the Hawks’ mission planning, recording and debriefing capabilities. Additionally cockpits of 15 Hawks will be modernised to better meet the requirements of a modern cockpit. These modernisations improve Hawk jet trainers’ training efficiency and enable their use in certain training purposes in which Hornet interceptors now have been used [Patria 2006; CMC 2007].

The FIAF Hawks have been concentrated from the operational fleet bases to Kauhava, Finland [DEFMIN 2006]. In view of the ICAF national review, the structural issues – including possible changes in the airframe stressing due to the Kauhava-based Hawk pilot training activities which will be followed using the OLM aircraft – are summarised below.

13.4.1 Wing teardown inspection – an update

The structural cracking indications found during the wing teardown inspection [ICAF 2005; Chapter 3.3] have since been investigated by Patria Aviation. The cracking anomaly of interest was located within the wing attachment lug, in the corner of the attachment bolt hole, in upper flange of the lug. As these lugs are not included in any periodic inspection requirements, and since these areas are not accessible (e.g. for inspection) without first removing the entire wing (and then the actual lug from the wing!), there was a concern of adequate structural durability margins with the presence of fatigue cracks. The cracks observed were confirmed to be due to fatigue from cyclic stressing, determined from fractographic samples prepared and analysed by TUT [Tikka 2005b].

Since initial analytical calculations indicated unacceptable structural life estimates, more detailed numerical analyses (FEA) including crack growth rate analyses were performed by Patria [Lähteenmäki 2005]. On the basis of the results of the analyses, the critical crack size and crack growth time were very short. In order to allow longer crack lengths, the amount of conservatism in analytical results had to be verified empirically. An overview of the wing teardown associated with the wing attachment lug is provided in ***Fig. 5***.

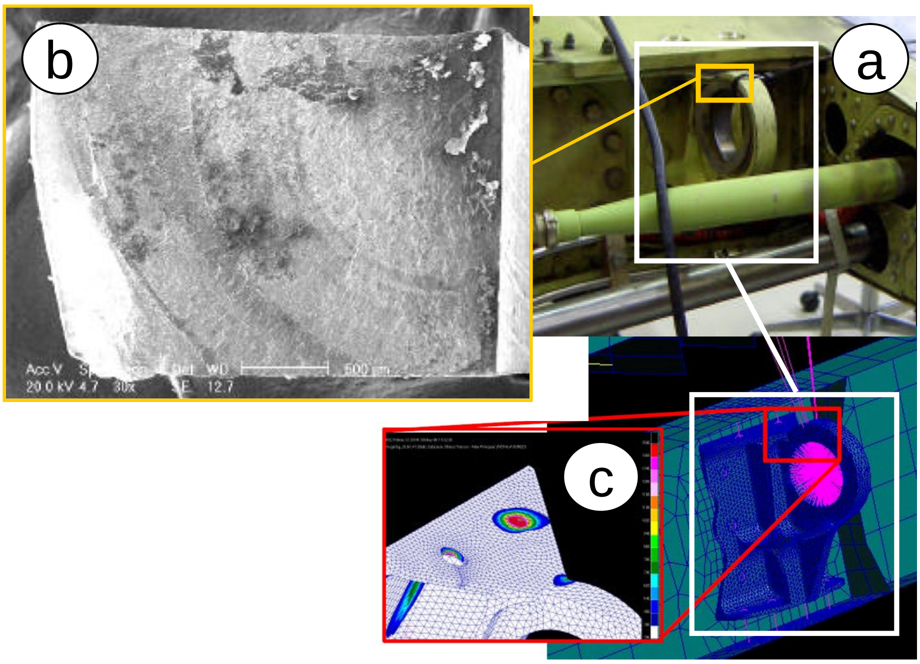

Figure 5: *An overview of the fatigue crack found within FIAF Mk.51 Hawk premod 999 wing teardown: **a)** Actual wing attachment lug from which the cracking indication was made (starboard side); **b)** Fatigue crack surface of the lug (beach marks visible); **c)** FE model detail of the lug area with cracks modelled. Courtesy of Patria Aviation Oy.*

13.4.1.1 Residual strength test (RST) of a pre-cracked Hawk wing attachment lug

Due to reasons described above, a decision was made at the FIAFAMC to try and confirm the analysis results experimentally (residual strength test – RST). The aim of this study was to verify the residual strength of a cracked wing attachment lug of the FIAF Hawk Mk51 aircraft. The RST was designed by Patria and conducted at VTT. An overview of the test set-up is provided in ***Fig. 6***.

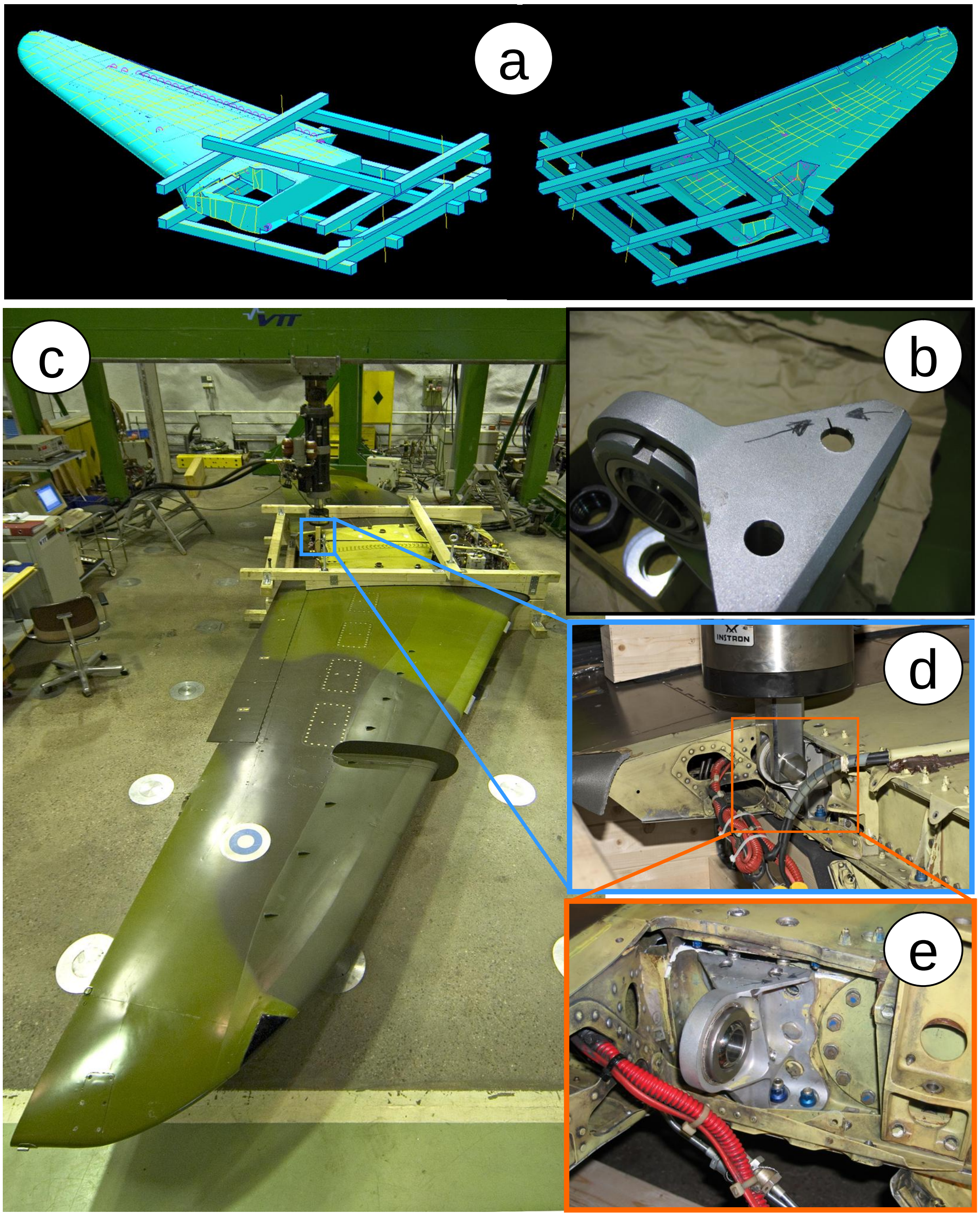

Figure 6: *An overview of the RST of the FIAF Mk.51 Hawk premod 999 wing attachment lug:* ***a)*** *Design principle of the full scale test set-up;* ***b)*** *Manufactured lug (port side) with an artificial crack;* ***c)*** *Actual test set-up;* ***d)*** *Close-up of the load introduction at the lug (port side);* ***e)*** *Close-up of the lug (port side) without load introduction. Courtesy of Patria Aviation Oy.*

The test article – retired from the FIAF squadron service – consisted of an entire wing, control surfaces and landing gear components removed prior to the test. As the test article did not possess fatigue cracks similar to the indications observed from the wing subjected to teardown activities, two artificial cracks were machined in the attachment lugs [Kettunen 2006]; an example is shown in ***Fig. 6b***.

The wing was then fixed to a test stand and a loading cylinder with a load (force) transducer attached to the pre-cracked lug, ***Figs. 6c, d***. The actual static RST test was conducted separately for the port and starboard lugs [Juntunen 2006].

The damages which occurred during the test proved that the pre-cracked attachment lugs were not the most critical parts of the structure but the rear spar which they were attached to. The breakage load was 14 % higher than required. Therefore, the RST results confirmed the adequate residual strength in the presence of manufactured cracks, as was analytically predicted. On the basis of the results, allowable crack length was increased and a reasonably long inspection period was established [Kettunen 2006].

13.4.2 Teardown inspection for a retired tailplane

The teardown inspection of a tailplane, retired from the FIAF service, was conducted by Patria Aviation in 2005. The purpose of the teardown inspection was to see if there are such structural anomalies (unexpected fatigue cracks) for which no approved repair schemes or repair instructions exist.

The tailplane inspected had logged over 4 000 FH, and it had previously been overhauled at approximately 2 000 FH. Therefore, the inspected article could also be used to assess not only the integrity of the repairs conducted, but also the remaining safe service life. All but one fatigue crack found was of previously known type, for which recommendations were made to be included in the periodic inspection instructions [Raunio 2005].

13.4.3 The HW OLM program

Intended to be a rolling program continuing until the withdrawal of the entire Hawk Mk51 & 51A fleet from the FIAF service, the Operational Loads Monitoring (OLM) program of the Hawks has been running since 1998 [ICAF 2001 Chapter 4.4; ICAF 2003 Chapters 3.4 - 3.6; ICAF 2005 Chapter 3.4]. An overview of the HW OLM program in relation to the other major flight programs carried out over the years in Finland is provided in ***Fig. 7***. An update of the HW OLM program is provided below.

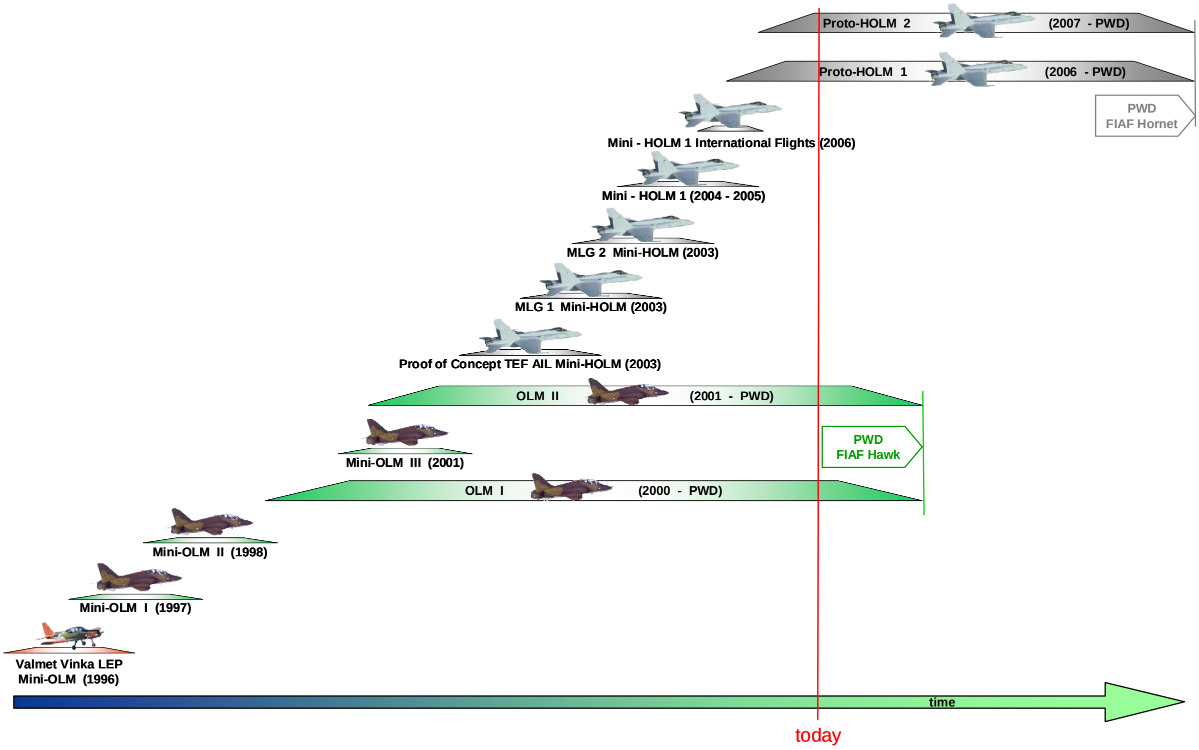

Figure 7: *The HW OLM rolling program {OLM I (2000-PWD) & OLM II (2001-PWD)} continuing until the planned withdrawal of the FIAF Hawk fleet, and it's relation to other major flight programs carried out over the years in Finland between the FIAF, Patria Aviation and VTT. Picture courtesy of VTT.*

13.4.3.1 The onboard system

Both OLM instrumented jets (HW-348 & HW-319) are in use at Kauhava base. Regarding the HW-319 aircraft, the tailplane region strain gauges are currently inoperative due to temporary horizontal stabiliser (tailplane) replacement. Other than that, the onboard OLM strain gauge instrumentation suites for the two aircraft (HW-348 & HW-319) have survived the squadron flights as operational since the modifications completed [ICAF 2005 Chapter 3.4.2].

Apart from the above and occasional yet predictable pauses in flight data collection caused by periodic maintenance activities, the overall percentage of OLM flights not found on tapes has remained at approximately 10 %. Plans for replacing the onboard data storage units (data tape) with solid state recorders are being prepared. The only activity of the onboard OLM systems includes the annual calibrations, e.g. [Bäckström 2005].

13.4.3.2 The ground analysis environment

The goal of the ground analysis environment development activities at VTT is to support the existing life cycle support infrastructure at Patria and the FIAF by integrating flight data, proven durability analysis methods and modern data mining tools into one platform. The ground analysis environment is such designed and being built that aircraft specific structural life consumption for e.g. the OLM Hawks (FI consumption) and the HOLM Hornets (FLE consumption) of the FIAF can be analysed. An overview of the analysis environment structure and associated modules is provided in ***Fig. 8***.

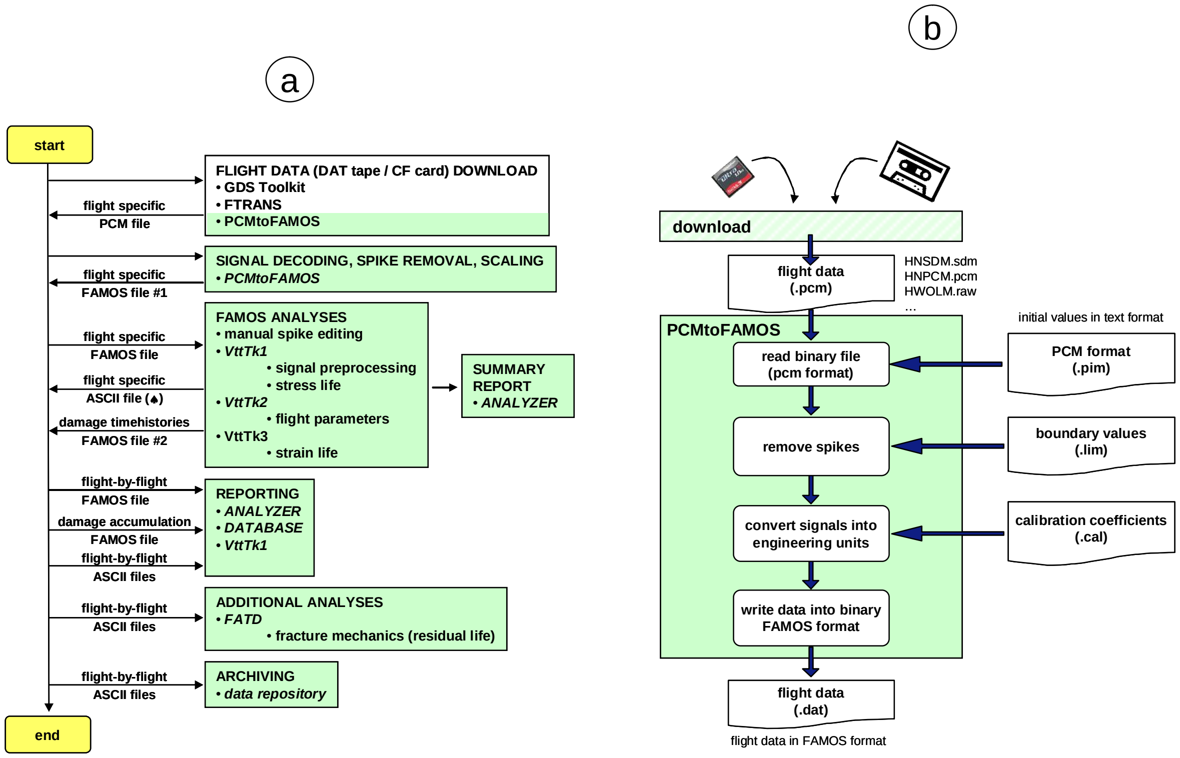

Figure 8: *An overview of the current ground analysis environment as used by VTT (modules developed in-house are shown in green colour): **a)** The structure; **b)** PCMtoFAMOS, which converts PCM data into FAMOS® format, is currently applicable for the Hawk OLM data, Hornet SDM data (ALBUS) [ICAF 2003 Chapter 4.2.6.1] and Hornet PCM data. Courtesy of VTT.*

The modules of the analysis environment contain elements built in-house, which in turn are integrated in a selection of commercially available (COTS) software modules. For example, the analysis capabilities of FAMOS® (by imc Germany) have been expanded with DLL functions built in-house. The durability estimates can now be done with stress-life ("full life"), strain-life ("infinite life") and fracture mechanics ("residual life"). In addition to the durability estimates, improved understanding of the analyses and aircraft behaviour is obtained as there now are tools to identify individual flight manoeuvres and investigate pilot actions. All previous features combined, it is now possible to identify flight events (manoeuvres) consuming structural life, as emphasised in [ICAF 2001 Chapter 2]. An overview of the combined in-house + COTS modules is provided in ***Fig. 9***.

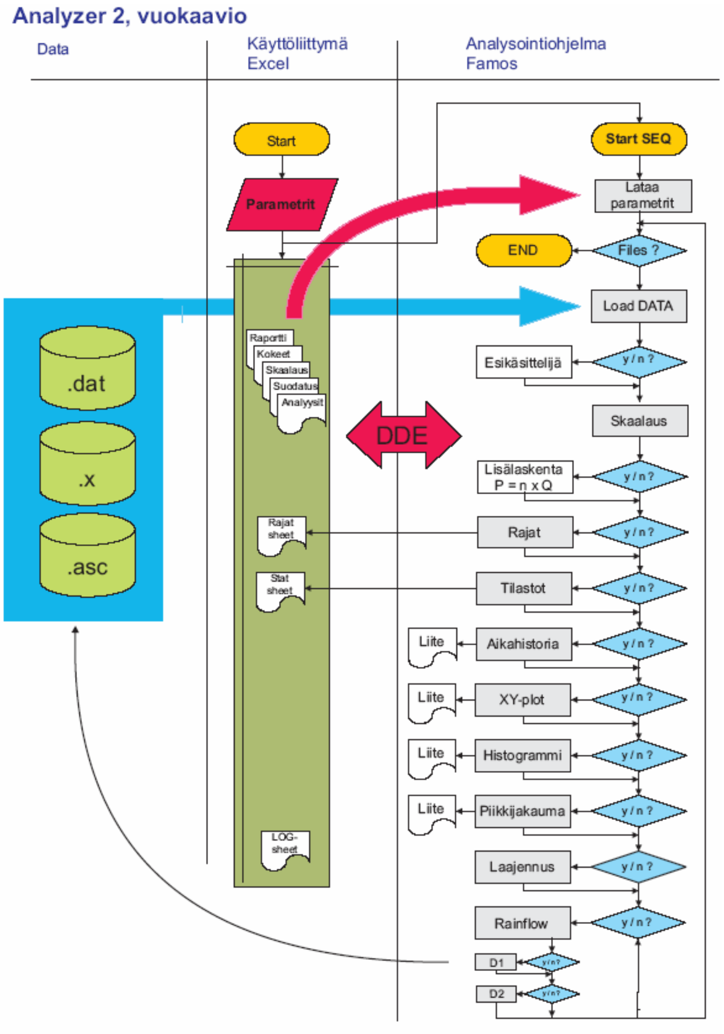

Figure 9: *The “ANALYZER” contains many software modules ("system of systems") e.g. FAMOS® + EXCEL® + FTRANS® + PCMtoFAMOS + DASYLAB®. Routine analysis stages are automated. Files to be analysed are located either on analysis PC or local intranet. Courtesy of VTT.*

13.4.3.2.1 Analysis environment verification efforts using Hawk data

Since the previous highlights [Viitanen *et al* 2005], much efforts have been spent with basic cases (e.g. simple test strain signals, half and full cycles with varying amplitude and mean) and actual flight data (strains) to come up with an experimentally verified analysis chain. The aircraft parameter analysis modules were verified separately against flights flown previously with a test flight equipped aircraft [ICAF 2001 paras. 4.2.1 & 4.3.2] whose “vintage” data were converted to the format requirements of the new ground analysis environment. The calculated pressure altitude (ALT), indicated airspeed (IAS) and Mach number (Ma) followed very well with measured quantities. The aircraft’s mass approximation (W) worked adequately well in view of cases investigated. The calculated angle of attack (AOA) followed the measured quantity well between 5°… 15° excluding low dynamic pressure regions. An overview is provided in ***Fig. 10***.

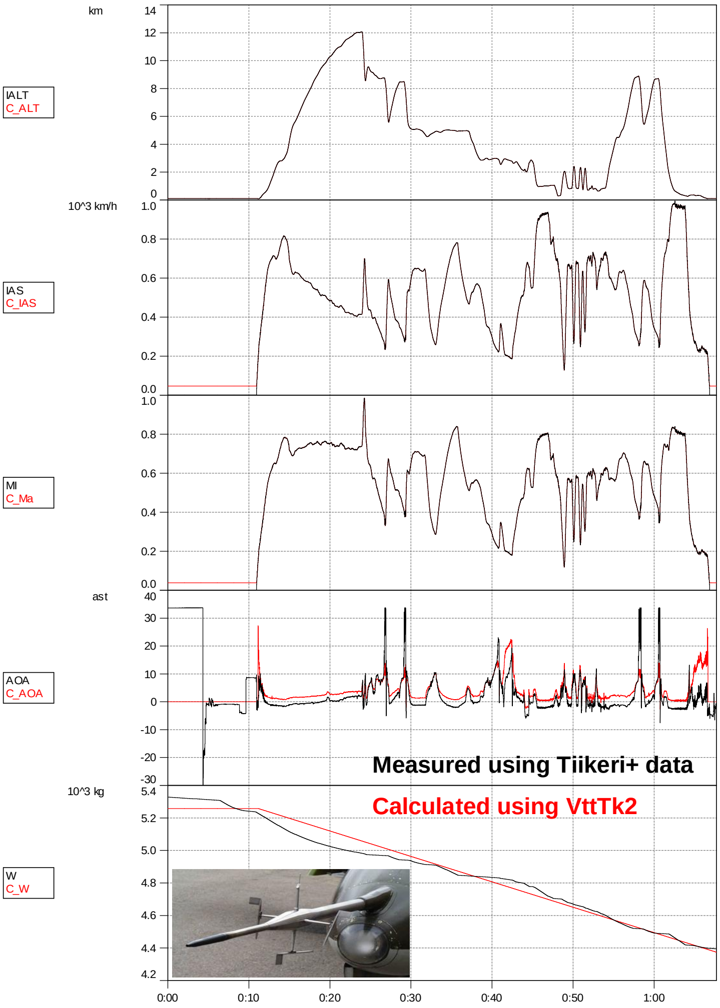

Figure 10: *An overview of the aircraft parameter analysis module's (VttTk2) verification results. The previously measured flight data time histories (black colour) were obtained from a flight test aircraft (the small insert photo) routinely operated by the FIAF Flight Test Centre. The calculated flight data time histories (red colour) were obtained from the ground analysis environment of VTT. Courtesy of the FIAF and VTT.*

13.4.3.2.2 Flight manoeuvre identification (FMI) efforts using Hawk data

Flight manoeuvre identification (FMI) is a necessary step in a meaningful fatigue management policy: "*Successful fatigue management requires that the piloting techniques used by the aircrew and the contents of flight training syllabi are brought to a level at which any life expenditure which is not justified by operational or training objectives has been omitted.*" [ICAF 2001 Chapter 2]. Since the previous review [ICAF 2005 Chapter 3.4.3], advances in identifying individual flight manoeuvres from a given OLM flight have progressed. An overview is provided in ***Fig. 11*** for a flight for which the detailed enough flight report (typical to flight tests) was available, thus allowing the successful FMI.

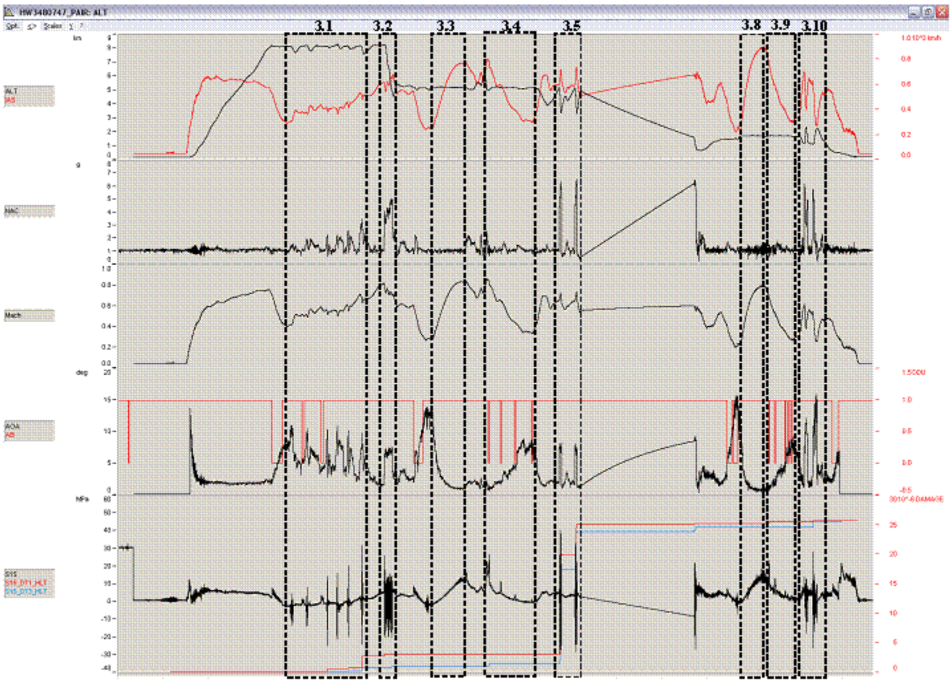

Figure 11: *Examples of a successful use of the aircraft parameter analysis module in the flight manoeuvre identification (FMI) from the OLM data.* ***3.1****: Pulls to manoeuvring limit at constant speed (Mach);* ***3.2****: Dogfight; head-on attack with wide separation and spiral (with high G);* ***3.3****: Level acceleration at 5000 m /15000 ft;* ***3.4****: Use of airbrake at 5000 m / 15000 ft;* ***3.5****: Split-S (note significant structural damage evolution!);* ***3.8****: Level acceleration at 1500 m / 4500 ft;* ***3.9****: Use of airbrake at 1500 m (4500 ft);* ***3.10****: Manoeuvring at 1500 m / 4500 ft. Note the malfunction of the onboard data storage unit (data tape) between events 3.5 – 3.8. Courtesy of the FIAF and VTT.*

Among the lessons learned of the above is that successful FMI is extremely time consuming even for a skilled analyst or to someone with a pilot's background if the flight reports for the flights to be analysed are not available. This is particularly the case with the Hawks, as some vital parameters (heading, pitch and roll angles) are missing from the current OLM data stream and the analyses therefore must be based on the time histories e.g. shown in ***Fig. 11***. As the flight reports for the majority of OLM flights are not available for the analysts, more advanced methods are required for successful FMI.

13.4.3.2.3 Analyses using Hornet data

<u>Same ground station for the OLM Hawks and HOLM Hornets:</u> Dictated by the goal of having the analysis capability for the Hawks and also (but not limited to) for the Hornets using the same ground analysis environment [e.g. ICAF 2005 Chapter 3.4.1.2], changes to the analysis modules were implemented. The ground analysis environment can now download data from the Hawk (OLM) and Hornet (HOLM) data streams. On top of the existing full life (SN) and residual life (da/dN) modules, the local strain (εN or the strain-life) module and associated materials data have been integrated in the analysis environment to facilitate "Hornet typical" durability analyses.

<u>Towards "real" data mining tools:</u> A move away from spreadsheet applications towards true database applications has been realised: The need of the "true" database was observed with the two OLM jets (FIAF Hawks), as the limits of the spreadsheet application can be seen with the 1000+ OLM flights data (each Hawk flight typically produces a raw data file size of approximately 400 MB). The amount of data (raw data file sizes) obtained from the two HOLM aircraft (FIAF Hornets) are approximately the same size as those obtained from the two OLM jets.

Flight manoeuvre identification (FMI): As pointed out in previous Chapter, more advanced methods are needed for a successful FMI in cases where flight reports are not available. The parameters stored onboard the HOLM Prototypes contain data from over 200 flight parameters. A selection of these parameters is used as inputs for a visualisation tool[3], with which the flight or parts of it can be visualised and various manoeuvres identified. To ease the analyst's workload, various criteria have been created and implemented such that e.g. anticipated flight manoeuvres can be searched in an automatic manner. An example of this for a split S manoeuvre is provided in ***Fig. 12***.

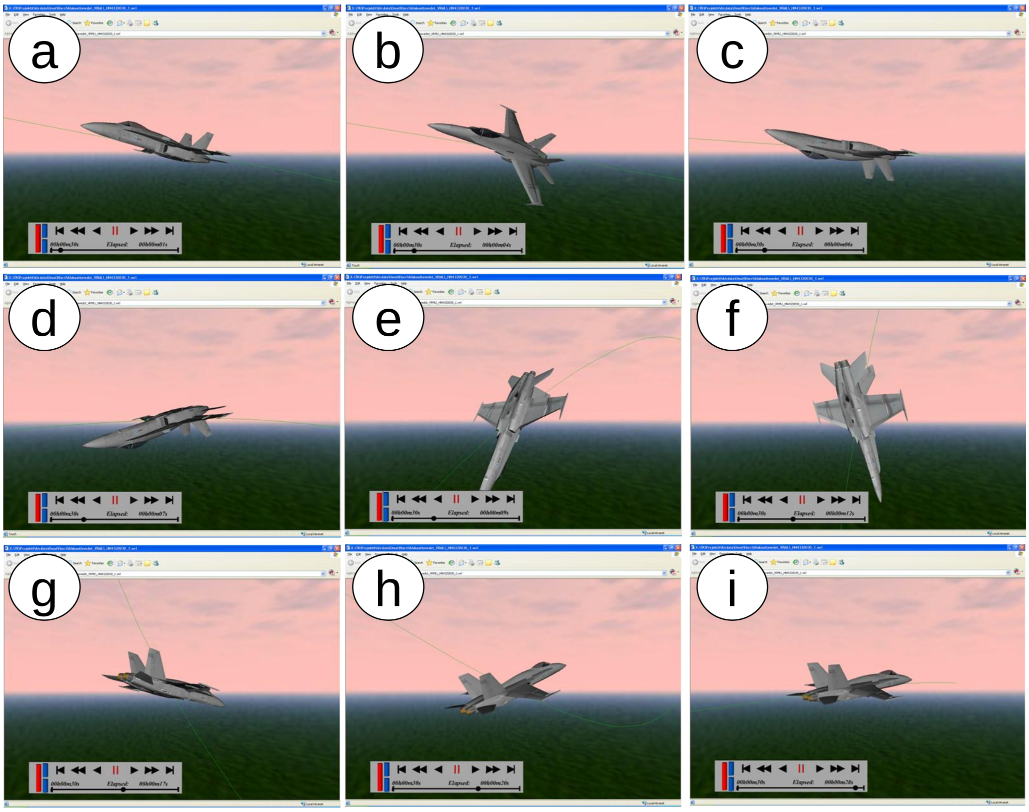

Figure 12: *An overview of a flight manoeuvre identification using the Mini-HOLM I data of a FIAF F-18 Hornet. Each frame shown is a snapshot of a "split S" manoeuvre:* ***a)*** *start …* ***i)*** *end. Courtesy of VTT.*

13.4.4 Wing version and stressing of the aft fuselage regions

The FIAF Hawk Mk.51 and Mk.51A have different type wings, namely pre-mod 999 and post-mod 999, respectively. There are no significant structural differences within the aft fuselage regions between the Mk.51 and Mk.51A. Initial estimates on the basis of statistical data of the FIAF squadron usage, collected and analysed from the two OLM aircraft (HW-348 with the pre-mod 999 wing and HW-319 with the post-mod 999 wing) indicated systematic differences in the predicted structural life consumption – the Fatigue Index (FI) consumption – for aft fuselage regions [ICAF 2005 Chapter 3.4.3]. The FI consumption for the aft fuselage regions appeared to be faster for those jets having the post-mod 999 wing, ***Fig. 13***.

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[3] The development of the visualisation tool was started at TKK/LAD and it is further being developed at VTT.

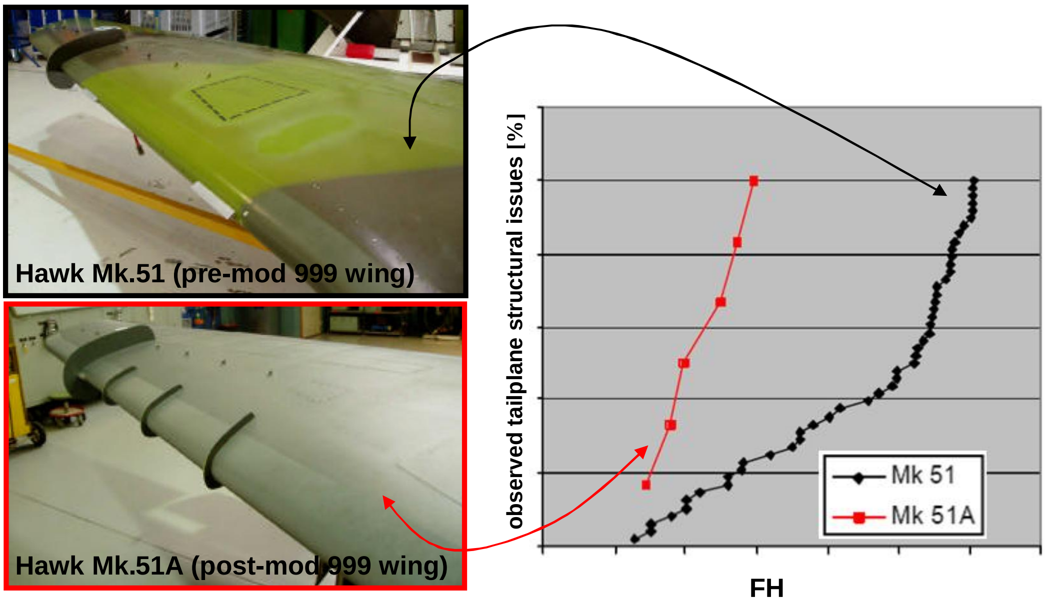


Figure 13: *An overview of the observed and wing configuration related tailplane structural issues requiring repair actions. Courtesy of Patria Aviation Oy.*

The structural repair and inspection methods embodiments of the FIAF Hawks, implemented fleet-wide [ICAF 2005 Chapter 3.1], are based on experience gained with the pre-mod 999 wing configuration. These embodiments have been approved to meet the planned withdrawal date of the FIAF Hawks. If the structural life consumption of aft fuselage regions indeed is faster for the post-mod 999 configuration, the structural repair and particularly the inspection methods developed and implemented may need to be readjusted.

13.4.4.1 Analyses based on dedicated test flights

To better try and isolate the observed differences and structural phenomena (aft fuselage region) related to the differences in the wing configuration, detailed test flights were designed by Patria and the FIAF Flight Test Centre and then flown by the FIAFFTC. Patria analysed the OLM data [Tikka 2005] downloaded by VTT.

The test flights were flown as planned. On the basis of the analyses, the more severe stressing of the aft fuselage region due to the post-mod 999 wing was indeed manifested for some manoeuvres, ***Fig. 14***. It appears that the majority of calculated damage is caused by tailplane's structural vibrations of relatively high frequencies superimposed on a low frequency component with a strong dependency on dynamic pressure. The observations indicate the Postmod 999 wing's detrimental effect on the calculated life of the tailplane location throughout the dynamic pressure (speed) range investigated.

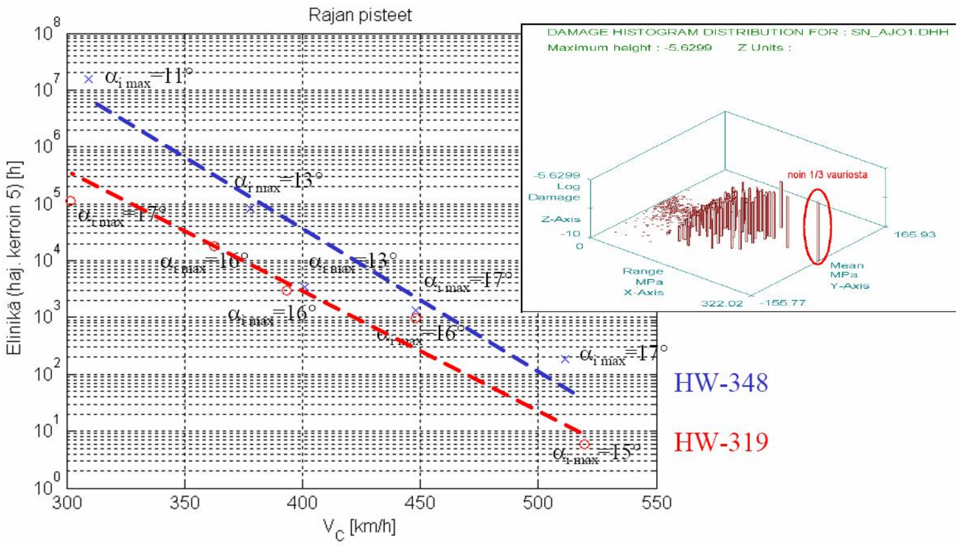


Figure 14: *Estimated structural life (scatter factor 5) for a tailplane location for selected manoeuvres. Blue line HW-348: Premod 999 wing; Red line HW-319: Postmod 999 wing [Tikka 2005]. Courtesy of Patria Aviation Oy.*

Recommendations (i.e. what flight parameter combinations for a given point in the sky to avoid) to the pilots could be made [Tikka 2005]. Additional analyses, should they become necessary, should be based on the data mining of the OLM flights database. Unfortunately, the analyses above had to be done using limited data, as some vital parts of the test flight data were lost due to the unsatisfactory data capture rate of the onboard OLM system's storage media (data tape) – a feature experienced before [ICAF 2005 Chapter 3.4.2] and as highlighted in ***Fig. 11***. Efforts to replace the current onboard data storage unit with a solid state recorder have not realised as of writing of this review.

13.4.4.2 Analyses based on the OLM database

The efforts to screen and find "comparable" flights continue. Although the OLM data from the two OLM jets (HW-348 and HW-319) contain good data from over 1 300 squadron flights (approximately 50/50 between the two OLM jets) as of writing this review, the data mining e.g. to screen and find "comparable" flights between the two aircraft is a challenge. First analyses of this kind have been completed at VTT [Janhunen 2006a].

From the OLM database [Viitanen et al 2005; ICAF 2005 Chapter 3.4.1.2], various selection criteria were used for the selection of flights. Among the selection criteria was *"for the two jets, find same sortie flights such that differences in aft fuselage structural life consumption (in view of the FI - Fatigue Index) result"*. The analyses for over 100 selected flights were made on the basis of the data OLM from tailplane strain gauges and all flight parameters. On the basis of these preliminary analyses it appeared that the structural life consumption depends more on the combination of IAS (speed) + TPA (tailplane angle) rather than NAC (normal acceleration) + IAS + AOA (angle of attack). The preliminary analyses clearly pointed out that in view of the aft fuselage stressing, the highly damaging flight conditions seldom – if ever – depend on one flight parameter value alone.

A new analysis tool – Flight Analyzer – was developed at VTT to be able to better focus the aft fuselage's "multiple aircraft parameter dependency" analysis activities [Janhunen 2006b; Bäckström *et al* 2005]. The following can be summarised: In view of the aft fuselage stressing, the way how the pilot handles the stick (rough or smooth TPA rate) – particularly near stalling –

together with IAS and AOA seems to cause the majority of damage (FI) for both wing types, ***Fig. 15***. The main focus of the investigation – i.e. to find reasons why the aft fuselage's FI consumption is higher for the post-mod 999 wing configuration – remains to be solved. The investigations are on-going, although the main efforts have shifted from the FIAF Hawk applications to those of the FIAF F-18 Hornets.

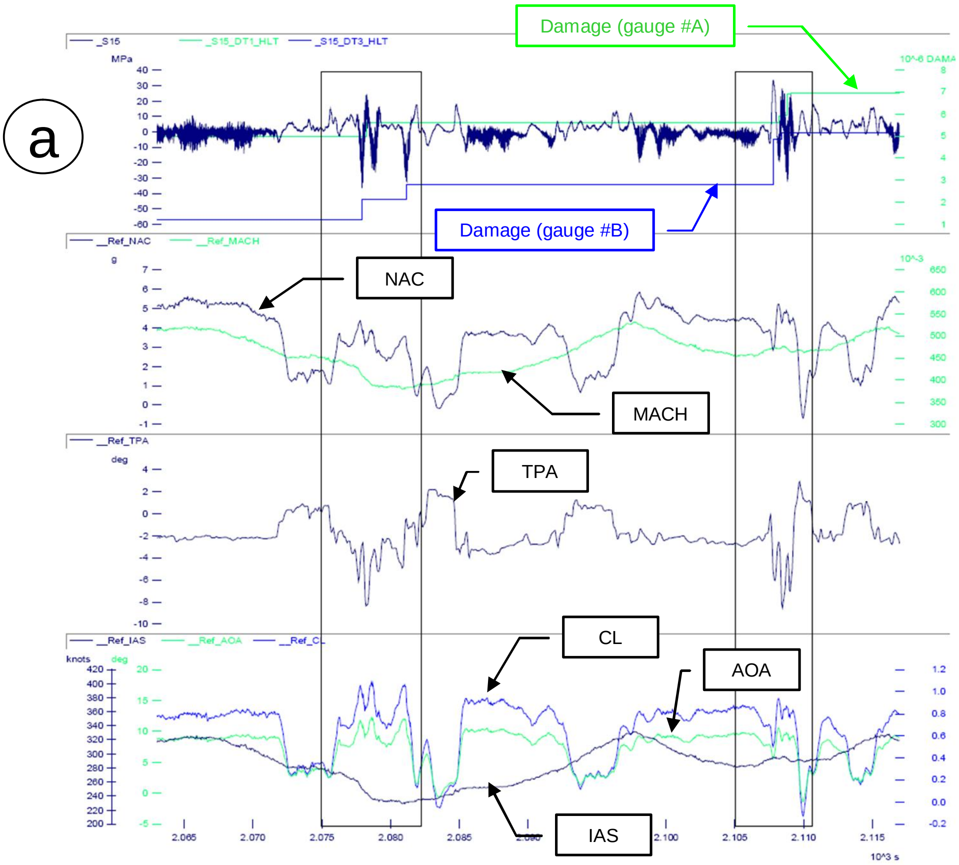


Figure 15a: *An overview of the effect of rapid control surface (TPA) deflection rate (rough stick handling) on the calculated damage for two strain gauge locations within the aft fuselage – see inside the black boxes. Courtesy of VTT.*

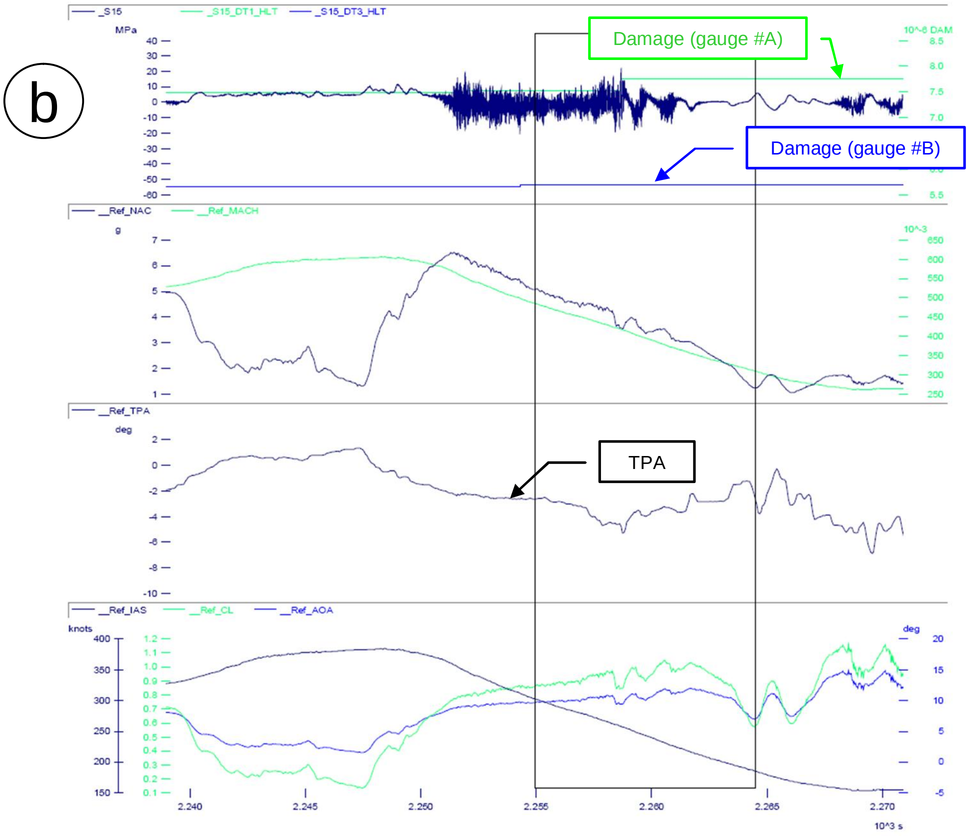


Figure 15b: *An overview of the effect of smooth (determined, not phlegmatic) control surface (TPA) deflection rate on the calculated damage for two strain gauge locations within the aft fuselage – see inside the black box. Courtesy of VTT.*

13.5 F-18C/D HORNET

The FIAF F-18C/D Hornets reached their 10 year FIAF service life in November 2005. During the intended 30-year life cycle of the Hornet the FIAF will undertake two upgrades to maintain its capabilities up-to-date and to ensure that functional and structural lifespan requirements will be met. The first of these upgrades will take place during 2009. The second upgrade, planned for incorporation between 2012 and 2014, will include a study of giving the aircraft air-to-ground capability, among other matters [FIAF 2007]. It is worthwhile to note that while the Vinka primary trainers have been concentrated in Tikkakoski and the Hawk jet trainers in Kauhava, the Hornet fighters are not, see ***Fig. 16***.

An overview of the structural integrity research activities, also related to the above upgrades, is provided below.

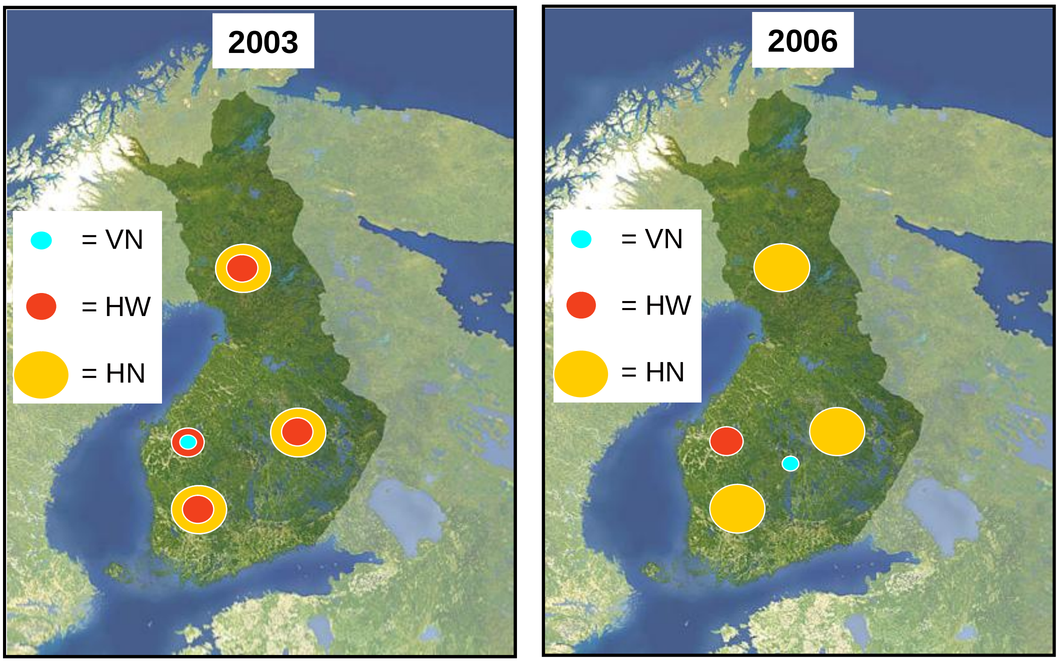


Figure 16: *An overview of the operational bases of the FIAF.* ***Left*** *(2003): Prior to concentrating the Vinkas (VN) and Hawks (HW);* ***Right*** *(2006): The Vinkas (VN) in Tikkakoski, Hawks (HW) in Kauhava and Hornets (HN) in Satakunta Air Command (Tampere), Karelia Air Command (Kuopio) and Lapland Air Command (Rovaniemi). Courtesy of the FIAF.*

13.5.1 The HOLM program

The Hornet Operational Loads Measurement (HOLM) program has progressed according to the plans [e.g. ICAF 2005 Fig. 6]. Both HOLM aircraft have been delivered to the FIAF. The first one – HN-432 – was delivered to Lapland Air Command in September 2006. The other – HN-416 – was delivered to Satakunta Air Command in April 2007.

13.5.1.1 Hornet FE modelling – an update

The development phases of the global (coarse) Finite Element (FE) model of the FIAF F18C Hornet have been outlined previously [ICAF 2005 Chapter 4.2]. Since then, the Hornet global FE model has been revised and verified by comparisons with Mini-HOLM I ground and flight test measurements [Miettinen & Malmi 2006] and to results calculated with OEM FE models. The FE analyses of the flight test manoeuvres were made using FINFLO CFD loads on the FE model, and served also as verification for the CFD loads [Malmi 2006].

Based on the assessment of the fatigue critical structural locations of the FIAF Hornets ([ICAF 2005 Chapter 4.7] and Chapter 13.5.1.3.4), several detailed FE models have been prepared by Patria [Kettunen, Keinonen, Orpana 2007; Lähteenmäki & Malmi 2007; Tikka & Malmi 2007; Liius & Malmi 2007; Salonen 2006; Aittolahti 2006; Linna 2006; Lähteenmäki 2006; Lähteenmäki 2007; Salonen 2007; Liius 2007]. Examples of the detailed FE models are provided in ***Fig. 17***.

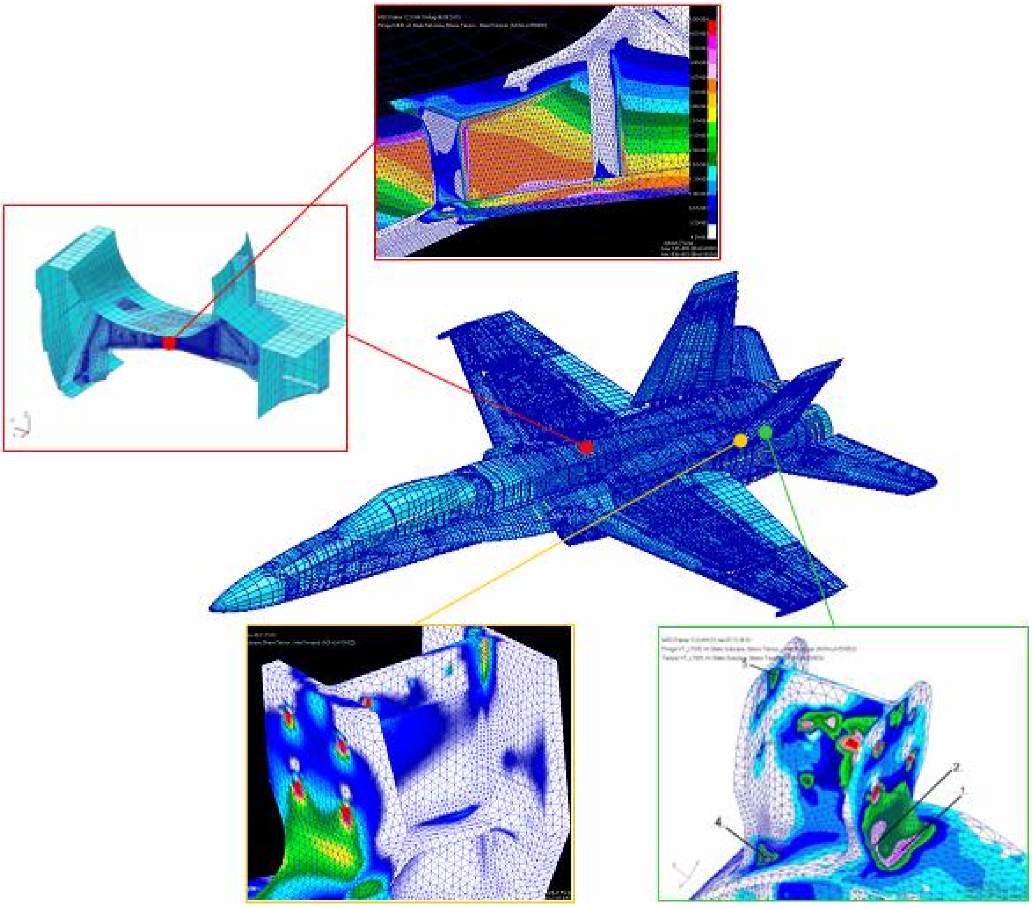


Figure 17: *Examples of the FIAF F-18 Hornet's FE models. Courtesy of Patria Aviation Oy.*

The fatigue life estimates for these structural locations have been determined using the load spectra (strain gauge data) of a selection of the Mini-HOLM I test flights representing the FIAF's average usage. Due to the quite severe aircraft usage by the FIAF, the life estimates show that these structural locations require careful fatigue tracking – i.e. the IAT (individual aircraft tracking). Most of these structural locations will also require at least some pre-emptive treatment (polishing, reaming of fastener holes, shot peening, strengthening by bonded patches). Some structural parts probably need to be replaced, at an appropriate phase of the aircraft usage.

For some locations, unreasonably low fatigue life estimates have been obtained using simple transfer functions (constant factors for strain gauges). In the wing area the internal stresses (included in the strain gauge readings) caused by different temperature expansion coefficients of aluminium spars and composite skins disturb the fatigue life results, too. In addition, some Mini-HOLM I strain gauge channels suffered from warm-up drift of the measurement devices. Attempts to enhance the transfer functions and dealing with the temperature and warm-up drift effects will be made during the next years.

International co-operation with other F/A-18 users under the auspices of FISIF (F/A-18 International Structural Integrity Forum) will provide full scale test data to support the analysis verification efforts.

13.5.1.2 Computational fluid dynamics (CFD) of the FIAF F-18C

The main purpose of the flow simulations is to obtain structural loads to be used as inputs for other analyses (i.e. structural analyses – FEA). The CFD work has been done in the FINFLO environment [Siikonen 2000]. Since the completion of the new CFD model [ICAF 2005 Chapter 4.4; Salminen 2004], a number of CFD analyses with analysis-specific aircraft and stores configurations (e.g. ***Fig. 18a***) have been run.

So far all computations have been based on Reynolds-averaged (RANS) turbulence modelling and a steady-state assumption. For certain time-dependent situations the approximative approach described in [Siikonen 2000] is being applied. This technique has been applied for a simulation of pull-up (***Fig. 18b***). There are plans for the near future to apply also time-accurate simulations.

As a new application, fluid-structure interaction (FSI) is taken into account [Salminen 2005]. This is accomplished by linking the flow solution and the structural analysis code Nastran together. The iterative process is explicit, i.e. the flow and structure are handled separately. For the flow solution the surface displacements are interpolated into the CFD model. Then the volume grid is stretched according to the surface displacement. A novel technique has been developed for the grid stretching. As an example of FSI a series of surface positions are shown in ***Fig 18c***. In the computation of an elastic F-18C, six fluid-structure-coupling iterations were taken in order to achieve a converged deformed state.

The first steps towards international CFD co-operation focused to the Hornet have been taken, together between Finflo Oy (Finland) and CFS Engineering (Switzerland). The CFD codes FINFLO and NSMB maintained by CFS Engineering have been compared. Meetings have been arranged to handle technical aspects and general CFD development.

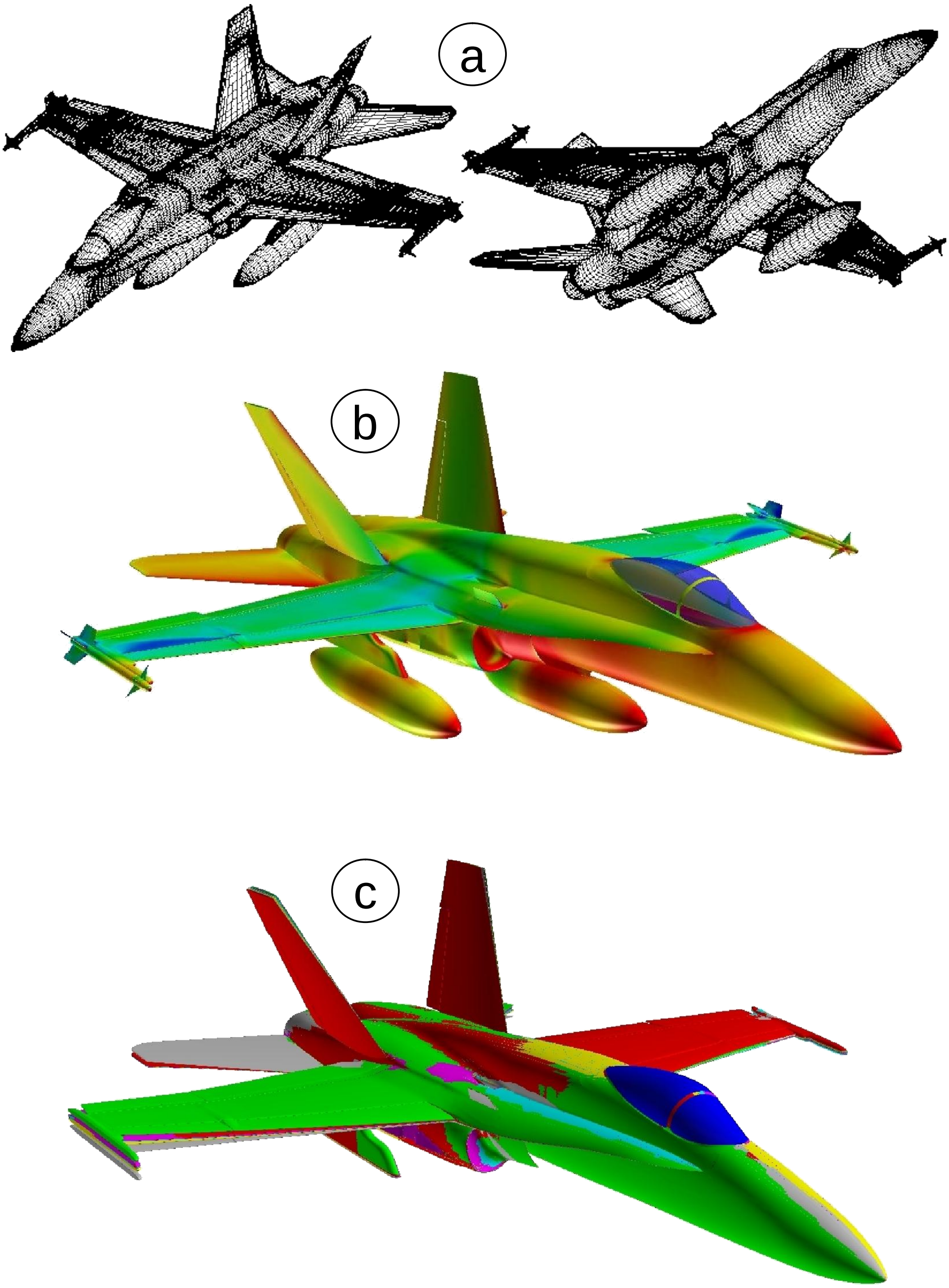


Figure 18: *An overview of the computational fluid dynamics (CFD) of the FIAF F-18C.* ***a)*** *An overview of the surface grid with a selection of stores;* ***b)*** *Pressure distribution on an F-18C Hornet performing a 6.0g pull-up at Ma= 0.9;* ***c)*** *A series of the fluid-structure interaction (FSI) solutions showing a deformation of the F-18C aircraft – note the displacements at the tips of the control surfaces. Courtesy of Finflo Oy.*

13.5.1.3 HOLM flight test activities

As a part of the HOLM research programme between the FIAF, Patria Aviation and VTT, a series of dedicated test flights (Mini-HOLM 1 flights) were conducted during 2005. The purpose of the flight measurements was to get detailed information about the structural behaviour of the F-18 in FIAF specific use, and also to screen potential strain gauge locations for the permanent HOLM system – a.k.a. the proto-HOLM modification – installed later in two FIAF F-18 aircraft. Also to gain practical experience from the prototype HOLM measuring system was one of the main goals of these measurements. The following summarises these efforts.

13.5.1.3.1 Mini-HOLM I national research needs

The onboard Mini-HOLM I instrumentation suite as described in more detail in [ICAF 2005 Chapter 4.6; Liukkonen & Teittinen 2005] was successfully used for a series of test flights. A selection of 25 test flights were designed by Patria and the FIAF Flight Test Centre [Orpana 2005] and flown by the FIAFFTC. These flights consisted of flights representative of the FIAF squadron usage (e.g. “typical FIAF”, “extreme FIAF”), specific tailored flights including flight manoeuvre calibrations, service flights and some ground fuelling events. The correspondence between the realised "FIAF representative" test flights and the real FIAF average squadron usage was assessed using the data gathered by the OEM Fatigue Tracking System: A set of ten flights were chosen to comprise the FIAF representative spectrum to be used for the life estimation analyses [Orpana 2005b].

Delightfully, nearly 100% of the recorded and synchronised data (strains, accelerations and the MIL-1553 bus parameters) were successfully stored for later analyses. Important lessons were learned in view of e.g. temperature drifts and signal-to-noise ratio in view of the on-board hardware configuration and cable routing details for subsequent proto-HOLM modifications [Liukkonen, Bäckström, Teittinen 2005]. Once these experiences were converted into modification requirements, the HOLM system elements were tailored for the proto-HOLM modifications.

13.5.1.3.2 Mini-HOLM I international flights

As the instrumentation suite of the Mini-HOLM I [ICAF 2005 Chapter 4.6] was specific to the FIAF needs, some strain channels specific to and previously recorded by (using their own jets) the FISIF partners were added to the “international flights’” onboard the Mini-HOLM I configuration. Additionally, some national Mini-HOLM I strain channels were replaced by FISIF partner specific acceleration measurement channels, of which the FISIF partners had previous measurement results from their own flight test programs [Miettinen 2006; Liukkonen & Teittinen 2005b; Liukkonen & Bäckström 2006]. Additional 3 flights – the “international flights” – were flown by the FIAFFTC to support the ASIMP needs of the international FISIF community [FIAFFTC 2006]. These flights consisted of specific manoeuvres suggested by the FISIF partners for defined aircraft conditions (clean aircraft vs. stores configurations) at given points in the sky (PITS) e.g. Mach – Altitude – Weight. All data from the three “international flights” were successfully captured and stored. All data were provided to the FIAFHQ for the release to the FISIF partners to allow each partner carry out own analyses and comparisons to their own aircraft use.

13.5.1.3.3 HOLM prototype 1 & 2

The demarcation line between the “research” and “prototype” of a new fatigue tracking system is somewhat vague. In this review, the Mini-HOLM I is considered as “research” while the following is deemed “prototype”. Based on the experiences of the temporary (“research”) Mini-HOLM 1 installation (55 strain channels) and 28 test flights in 2005, the permanent (“prototype”) HOLM system with 36 strain channels was designed in summer 2005 [Liukkonen & Teittinen 2005c; Miettinen 2006b]. It is worthwhile to note that the data from all instrumented sensors of the “research” instrumentation suite were collected at high enough sampling rate. On the basis of the analyses afterwards, each channel selected to the “prototype” modification has been optimised in view of the sampling characteristics such that the accuracy in the structural damage assessments in the years to come is not compromised [Liukkonen, Bäckström 2007].

Prototype 1: The temporary Mini-HOLM I "research" instrumentation of the HN-432 jet were stripped and replaced with a HOLM modification (permanent installation). The Prototype 1 modification work was finished in May 2006. Overall, the onboard KAM-500 COTS system [Acracontrol 2006] is configured to monitor 36 strains and two MIL-STD-1553 data buses, and the data is stored on removable 4GB CF cards. From the two data buses, over 200 aircraft parameters are monitored and stored [Liukkonen 2006a; Miettinen 2006b], such that the research needs of other projects are also satisfied. It is worthwhile to note that the strain data from the seven (7) OEM production strain gauges are included in the aircraft parameter list.

Prototype 2: The onboard instrumentation suite applied to the HN-432 aircraft was duplicated to another Hornet, the HN-416 [Liukkonen 2006b; Liukkonen & Teittinen 2006d]. The prototype 2 modification work was finished in December 2006 [Liukkonen & Teittinen 2007].

Ground calibration tests (similar to the Mini-HOLM I tests - [Liukkonen & Teittinen 2005d]) were performed [Miettinen 2007; Miettinen 2007b; Liukkonen & Teittinen 2006; Liukkonen & Teittinen 2006b; Liukkonen & Teittinen 2006c; Liukkonen & Teittinen 2007b] and two calibration test flights were flown with both installations. The two HOLM aircraft are now in routine fleet usage of the FIAF. In view of the limited scope flight tests (the mini-HOLMs), statistically reliable data are being acquired with the two HOLM prototypes in real FIAF usage, thus improving the fleet management aspects – i.e. the reliability of the fatigue life estimates – in the future. An overview of the Proto-HOLM hardware location is shown in ***Fig. 19***.

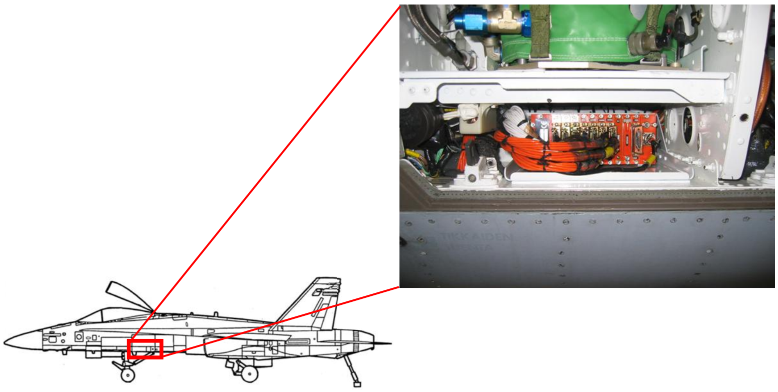


Figure 19: *An overview of the HOLM Prototype hardware location onboard the aircraft. Courtesy of the FIAF.*

These HOLM data will also be used for teaching the neural networks within the national technology program on the flight parameter based fatigue life analysis of aircraft structures (see "related activities") to calculate the HOLM strain gauge histories from the flight parameter histories stored by the standard OEM fatigue tracking system (permanently onboard each aircraft). The neural network calculation routines aim at performing fatigue life analysis of the whole fleet from the maiden flight of each individual aircraft (the OEM fatigue tracking data of all flights are stored).

13.5.1.3.4 Fatigue critical structural location database updated

The F/A-18C/D structure's stand-alone fatigue cracks database has been updated twice since previous review [ICAF 2005 Chapter 4.7]. The 5th update (v3.0) containing the information in SLB008, data obtained from FISIF as well as the FIAF fleet findings was completed in 2005 [Viitanen 2005a]. The 6th update (v3.5) was completed in 2006 [Viitanen 2005b]. The database has been used e.g. in screening the fatigue critical structural locations of the FIAF F-18C/D configurations and to help focusing the proactive maintenance planning activities.

13.6 RELATED ACTIVITIES

13.6.1 Aircraft structural fatigue training package – update

An overview of a modular training package on aircraft structural fatigue to teach various "target groups" was overviewed in [ICAF 2005 Chapter 5.1]. Since then, the package has been used internally within the FIAF.

13.6.2 Structural health monitoring activities – update

13.6.2.1 Prototype demonstration of modular SHMS for military platforms (AHMOS II)

The background and motivation for the joint European research and technology program *"Prototype Demonstration of Modular Structural Health Monitoring (SHM) System for Military Platforms"* was provided in [ICAF 2005 Chapter 5.2.1]. As a part of the project, SHM systems are tested in actual military aviation environment. The goal is partly to get experience of the operation of the SHM systems and partly to get feedback from the ground crews who will operate the systems in the future.

Two of the many flying test laboratories of the AHMOS II project are related to research activities in Finland. The first flying test bench – planned for squadron usage with F-18 Hornet fighters for a given FH – has been designed and developed by Patria Aviation. The other flying test laboratory – planned for test flights with an aircraft arranged by BAE Systems – has been designed and developed by BAE Systems.

The following contains an update of the project activities biased to those conducted by the Finnish partners.

13.6.2.1.1 Network and communications

In line with the global avionics trends regarding data communications technology, commercial Ethernet network with internet related protocols were implemented to form the backbone of the AHMOS II project. The network and communications were specified by Emmecon Oy [Hedman 2006] for both flying test laboratories.

The Hawk test bed contains the full network implementation with subsystems (each of which provided by the various European project partners): central computer, notebook system and the chosen sensor systems (fibre optics, acoustic emissions, lamb waves and strain gauges). The main on-line communication protocol (by Emmecon Oy) is based on the UDP (User Datagram Protocol), while the TCP (Transmission Control Protocol) is used for the off-line communications. Each subsystem of the network has its own unique identification number, an IP number. Messages are sent from IP to IP; from subsystem to subsystem. Applications to use the message data within the subsystem are identified with an application specific port number. The IP and port numbers are country and partner specific. The central computer, together with a notebook system, controls the operational state of the other subsystems of the network. Four types of messages will be used in the AHMOS II messaging concept: diagnostics, data, maintenance and test. Diagnostic and data messages use customized data format defined for purposes of the AHMOS II. Maintenance and test messages will follow the general internet standards or conventions.

Prior to SHM systems' installation in the two flight test beds, ground tests were performed to minimise risks and ensure the functionality of all SHM system elements. An example of such a ground test was the shared preparational ground tests, in which the performance of the integrated and modular SHM systems in detecting damage from "real test specimens in suitable environment" was assessed [Siljander & Hedman 2006]. The integrated and modular SHMS was formed of software and hardware identical or similar to those to-be-employed in the flight tests, ***Fig. 20***. The test specimens were realistic yet different from those employed in the flight tests.

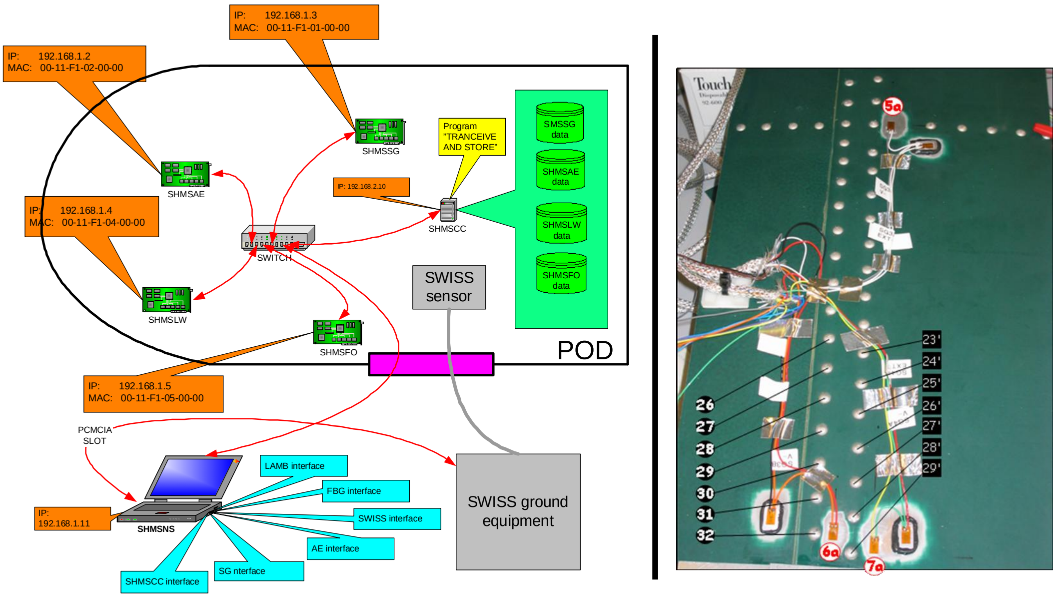


Figure 20: ***Left:*** *The principle of the modular system network environment, a version of which was implemented in the shared preparational ground tests organised by and held at Risoe (Denmark).* ***Right:*** *Strain gauging of one of the realistic laboratory test specimens. Courtesy of Emmecon Oy and VTT.*

13.6.2.1.2 F-18 flying test bed (the AHMOS II pod)

The F-18 test bed, being smaller in diameter than the Hawk test bed, contains only a partial network implementation as shown above. An overview of the flying test laboratory (the AHMOS II pod) was provided in [ICAF 2005 Chapter 5.2.2.1]. The engineering design and implementation activities to fulfil the flying test bed requirements to be flown at the wingtip of FIAF F-18 Hornets within the AHMOS II project were lead, conducted and completed by Patria Aviation [Pirtola & Raunio 2006]. The requirements for actual military aviation environment, based on actual F-18 requirements and measured FIAF's operational data (using e.g. the Mini-HOLM I aircraft), were adjusted for the SHM system components and associated test equipment inside the pod, to take into account the research nature of the AHMOS II project employing many commercially available (COTS) grade elements. The adjustment of the requirements were so conducted that even in harsh events, the possible failure of the SHM components inside the pod would not affect flight safety. The pod is carried at the wingtip weapon station of the FIAF F-18 Hornet, ***Fig. 21***.

The AHMOS II pod is a look-alike of the AIM-9 CATM missile, which is the training version of the AIM-9 Sidewinder air-to-air missile. The pod's outside geometry, mass, centre of gravity and moments of inertia are identical to the actual missile, but no wings or fins are installed. All mechanical interfaces between the aircraft and the pod are identical to those of the missile. However, the pod's electrical interface is modified such that the aircraft supplies only 28 VDC to the pod. The aircraft's Flight Control Computer (FCC) sees the pod as a missile.

Figure 21: ***Above:*** *An overview of the AHMOS II pod (flying test laboratory) at the wingtip weapon station of the FIAF F-18 Hornet.* ***Below:*** *An overview of the interior of the AHMOS II pod. Courtesy of Patria Aviation Oy.*

The space inside the pod is used for test purposes. The test setup inside the pod consists of fatigue test specimens, an electric motor with associated equipment to generate constant amplitude loading to the specimens and the tested SHM sensors and associated electronics to detect the cracking from the specimens.

In the F-18 tests there are two types of SHM sensors: strain gauges whose data are monitored in real time (i.e. during the flights) and ultrasonic systems whose data are interrogated on ground (i.e. periodically in between selected flights). The strain gauge electronics has been designed and built by Emmecon Oy while the ultrasonic systems come from KT-Systems GmbH.

The ground testing of the AHMOS pod and its equipment were completed in late 2006 and the first flights were flown in early 2007. After the initial flight test program the pod will be transferred to an operational squadron. The goal is to fly about 100 hours with the pod.

13.6.2.2 Integrated Eddy current inspection development activities

Previous review highlighted the development activities at Patria Aviation of a permanently installed SHM system and integrated Eddy current (ET) sensors for the F-18 trailing edge lug [ICAF 2005 Chapter 5.8.1]. The possibilities of low-cost ET sensors and related electronics have further been studied by Patria Aviation and Emmecon in an ongoing work funded by the FIAFHQ [Ylitalo & Hedman 2006].

The aim is to develop an affordable inspection procedure for aircraft locations, which require extensive disassembly to gain access for NDI personnel. The work has three objectives: a) develop low-cost sensors which can be permanently installed onto critical locations; b) prove that the sensors are compatible with existing FIAF NDI equipment; and c) develop a microcontroller based, networked and automated inspection module. Promising results were achieved for different type of sensors in laboratory tests using existing equipment, ***Fig. 22***. Minimum detectable crack lengths were reasonable for representative specimens for geometric stress concentration and for a riveted joint [Ylitalo & Tikka 2006].

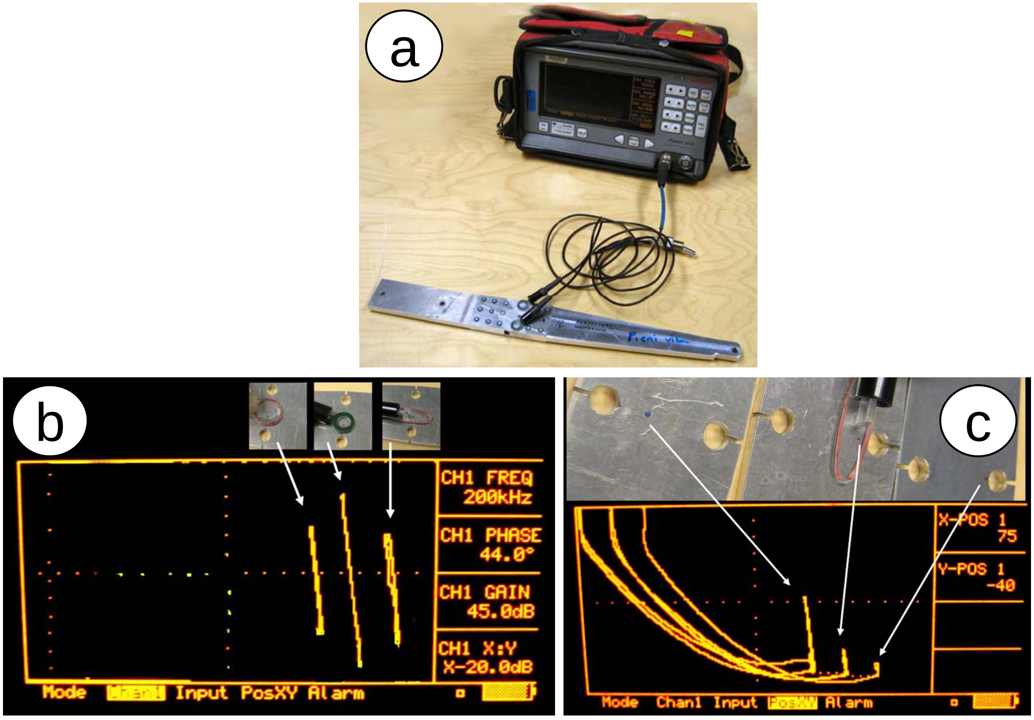


Figure 22: *An overview of the integrated Eddy current (ET) inspection: **a)** Test set-up for a commercial test equipment; **b)** examples of tested sensors and signal responses for geometric stress concentration; **c)** test specimens representing geometric stress concentration with different crack lengths and dynamic indications of the cracks. Courtesy of Patria Aviation Oy and Emmecon Oy.*

A prototype of the microcontroller based inspection module to be used in laboratory tests was developed and tested. Sensor interface of the module was electrically multiplexed allowing sequential use of up to four sensors. The measurement parameters are individually programmable for each sensor. The trends of measuring responses for each sensor can be tracked and the damage initiation and/or growth can be interpreted from the trend.

The performance of developed sensors and electronics in real aircraft structure will be evaluated in 2007 using a retired Hawk centre fuselage section, which will be fatigue tested using fuel tank pressurisation cycling.

13.6.2.3 Smart strain gauge

The FIAF F-18 Hornets are equipped with a selection of production (OEM) strain gauges located in critical locations of the aircraft [ICAF 2003 Fig. 16b]. The signal flow in the original configuration can be seen in ***Fig. 23***. The SDC (signal data computer) amplifies the signals from strain gauge bridge(s) and sends the conversion result through the 1553 network to the MC (mission computer), which checks the conversion result: If the result fulfils certain criteria, the value is then stored to the MU (memory unit).

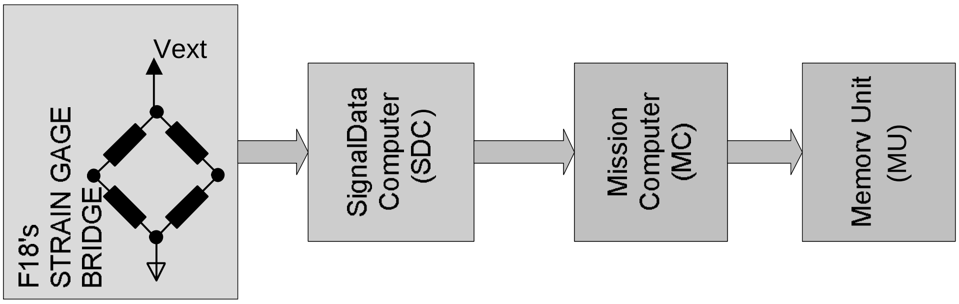


Figure 23: *An overview of the strain signal flow within the original (OEM) strain gauge configuration. Courtesy of the FIAF and Emmecon Oy.*

The SDC multiplexes signals from several strain gauge sensors with signals from several other sensors, and thus the sample rate per strain gauge sensor is moderate in view of structural life assessments dealing with high frequency dynamic content (wide band vibrations) typical to e.g. buffeting. For such events the storage capacity of the MU for each strain gauge sensor is limited and thus the storing criterion of the MC is tight, in terms of allowed number of memory locations / flight / strain gauge sensor.

In order to improve the use the existing OEM strain sensors for life assessment purposes, the FIAF started a “black box” research project with Emmecon Oy aimed at improving the MU storage capacity reviewed above.

An intelligent module was designed and developed by Emmecon Oy. The block diagram is shown in ***Fig. 24***. The module consists of a microcontroller and the necessary peripheral to run Emmecon-specific algorithms (file system, communication, signal acquisition and analysis). The main components and their duties are:

- FLASH memory: file system, storage for parameter, log and other non-volatile files. Files are accessible through serial communication interface;
- Digitator: a combination of amplifier, A/D converter and related components;
- Power supply: an isolated converter to transform 28V to internal voltages of the module;

- RS-232: a standard communication interface to carry PPP protocol (Point-to-Point-Protocol). The PPP is carrying higher internet protocols (IP/TCP/FTP) to access the internal file system of the module and to tune the module (the full protocol ‘stack’ is a product of Emmecon Oy);
- DEVIATOR: An electro-optical device to produce very small deviations to the strain gauge bridge in a software controlled way with a resolution of micro strains (µs) (Emmecon pat. pend.). One unit is for self-diagnostics of the strain gauge bridge and incoming signal processing electronics. The other unit is deviating an internal (to the module) resistor bridge connected to the SDC of the F-18 aircraft.

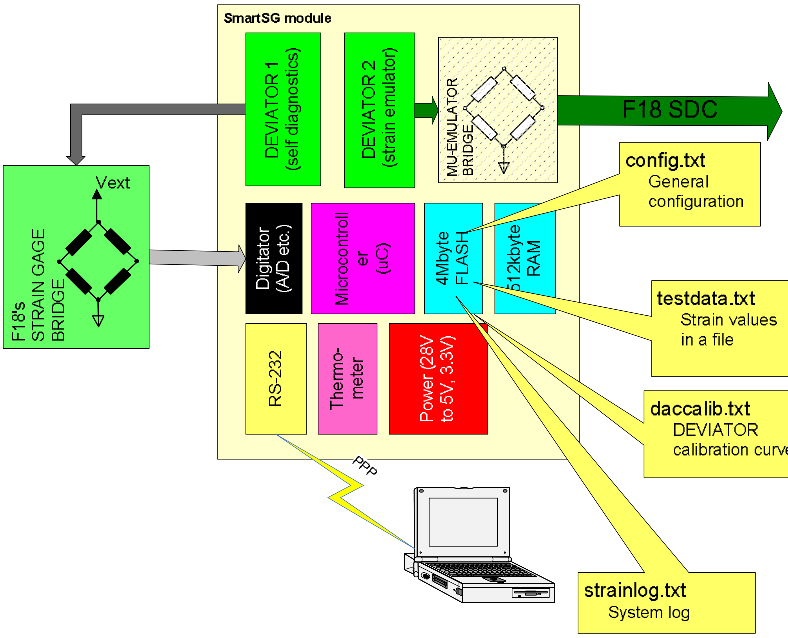


Figure 24: *An overview of the intelligent module designed and developed by Emmecon Oy. Courtesy of Emmecon Oy.*

The module is continuously sampling the strain gauge bridge signals with the frequency of 1kHz and classifying the samples into a rainflow vector. At 5 minute intervals the unit will calculate – with the data collected into the rainflow vector – the structural “wear” of the corresponding structural detail. This amount of “wear” is then coded in a value which can be fed to the SDC/MC/MU as strain: e.g. if this (coded/scaled) value is 1315, the DEVIATOR 2 will deviate the internal resistor bridge to emulate strain of 1315 µs. The SDC/MC/MU will notice this strain and, as it has been calculated by the module to fulfil the storing criteria, it will store it into the MU. Later (i.e. in the ground analysis station) the stored values are encoded and the life history of the detail can be controlled. An overview of the “black box” is provided in ***Fig. 25***.

Figure 25: *An overview of a prototype "black box" developed by Emmecon Oy. The prototype is waiting for a trial installation (in hangar) to test the interface to the SDC. Courtesy of Emmecon Oy.*

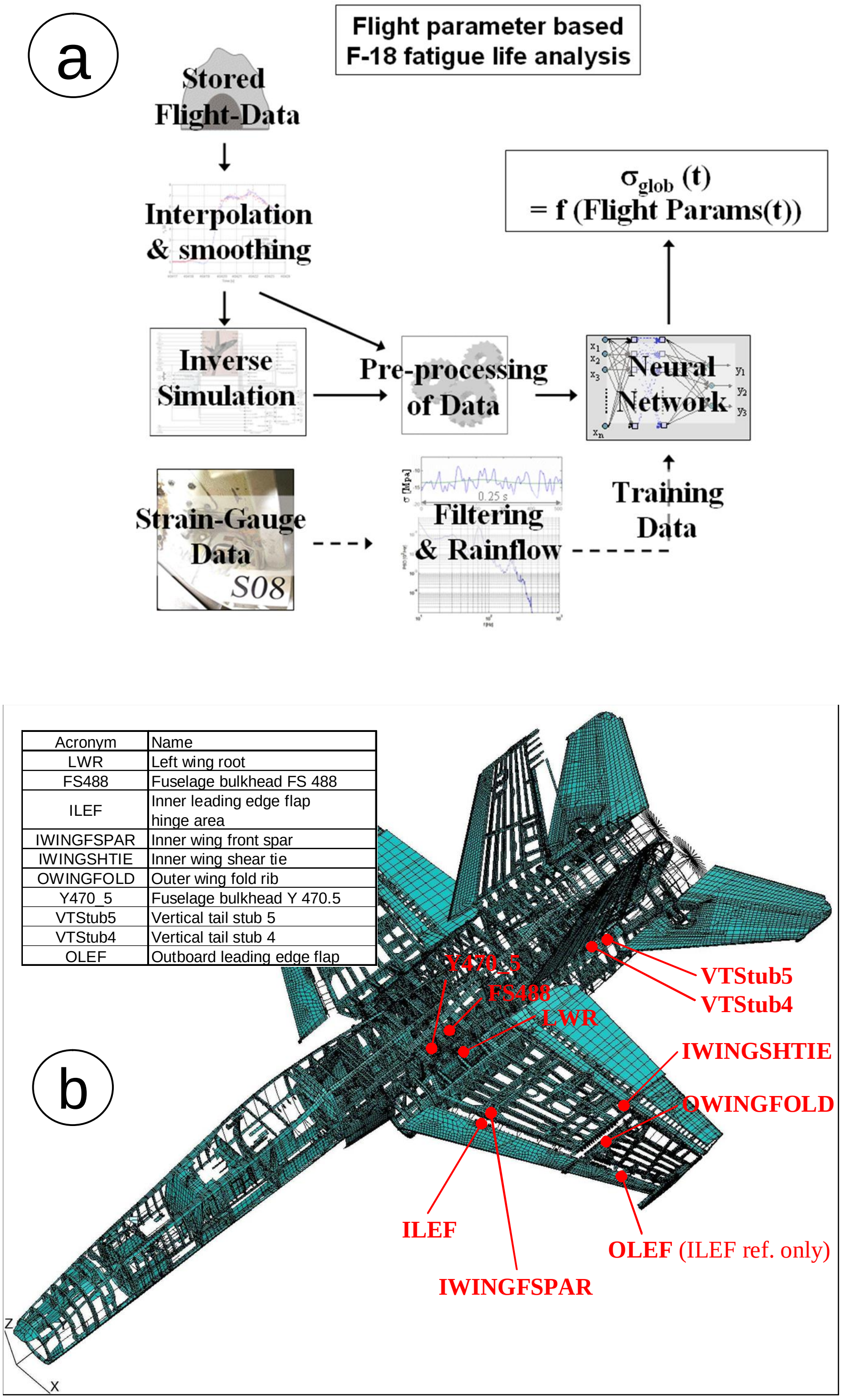
13.6.3 Flight parameter based fatigue life analysis of aircraft structures

13.6.3.1 From proof-of-concept towards production level

The proof-of-concept research phase of the national technology program [ICAF 2005 Chapter 5.3] was applied to two structural locations of the FIAF F-18 aircraft on the basis of the Mini-HOLM I data. A literature review on the subject and number of SOM (self organising map) experiments dealing with the selection criteria of the neural net's (NN) input parameters in order to improve the NN output were included. [Tikka 2006; Laakso, Hiirsalmi, Ahola 2006].

The program, aiming at enhanced individual aircraft fatigue life tracking (IAT) of the FIAF F-18's using flight parameters, has progressed from the proof-of-concept level towards production level.

The analysis environment (***Fig. 26a***) uses stored flight parameter data as an input to predict stress at analysed location. The modelling of stress is done by artificial neural networks, which are trained using strain gauge data from an operational loads measurement aircraft (Mini-HOLM & the HOLM Prototypes). In the production level the analysis environment will be capable to analyse the nine details shown in ***Fig. 26b***. A more detailed description of the programme can be found in [Tikka, Ahola, Hiirsalmi 2006] and in the ICAF 2007 presentation "Parameter Based Fatigue Life Analysis of F-18 Aircraft" [Tikka 2007].



Acronym	Name
LWR	Left wing root
FS488	Fuselage bulkhead FS 488
ILEF	Inner leading edge flap hinge area
IWINGFSPAR	Inner wing front spar
IWINGSHTIE	Inner wing shear tie
OWINGFOLD	Outer wing fold rib
Y470_5	Fuselage bulkhead Y 470.5
VTStub5	Vertical tail stub 5
VTStub4	Vertical tail stub 4
OLEF	Outboard leading edge flap

Figure 26: *An overview of the flight parameter based fatigue life analysis of aircraft structures:* ***a)*** *Analysis procedure, which is used to model stress at critical locations as a function of flight parameters [ICAF 2005 Fig. 11a];* ***b)*** *Structural details being included into the production level analysis environment. Courtesy of Patria Aviation Oy.*

13.6.3.1.1 Improvements in the inverse flight simulation for fatigue life management

Previous activities of the inverse flight simulation for fatigue life management have been outlined in [ICAF 2005 Chapter 4.5]. The applied research efforts, which were initiated and conducted for many years at TKK/LAD and currently continued at VTT, are summarised here in view of the flight parameter based fatigue life analysis of aircraft structures.

Fatigue life usage will be estimated individually for each aircraft and sortie using flight parameters stored routinely in the memory unit (MU) on each FIAF F-18 aircraft. The goal of the inverse simulation work (see ***Fig. 26a***) described here is to develop and validate a reliable way to complete the coarse-resolution MU data before feeding it into a neural network, which then produces the stress time histories of chosen structural details. An integration-based inverse simulation method [Öström 2005] has been devised for a six-degree-of-freedom flight simulation of the F-18 Hornet aircraft [Öström 2004] to determine the control surface deflections, which would produce the recorded flight path, and to complete the parameter data.

This chapter concentrates on enhancements and the validation of the developed inverse simulation algorithm [Öström 2005] as well as integrating the routines into the fatigue life management system for completing the flight parameters. Recent work has involved going through a large set of flight test data in order to validate the inverse simulation results and to pinpoint the problem areas of aircraft simulation model. The aircraft model has been modified on the basis of the results.

The computational rate of the inverse simulation was remarkably improved by modifications in the Matlab code and in the Simulink simulation model. The computational rate was improved from four times slower than real time [Öström 2005] to nearly real time on the same computer.

A total of 26 complete test flights have been inversely simulated using the stored 1Hz MU fight parameter data. The results have been analysed and compared to accurate 20Hz flight parameter data available from the same flights. The paper to be published elsewhere [Öström 2007] will discuss the observed problems of which most were related to the aerodynamic model and occurred either at high angles of attack or at high roll rates at transonic Mach numbers. The effectiveness of the differential control surfaces was altered based on the results. Different angle-of-attack sensor models have also been studied. The iteration time histories of two analyzed flights are presented in ***Fig. 27***. The maximum iterations per each inverse simulation step were limited to 30, and the steps where all the allowed iterations are used usually present a problem. These points are highlighted and explained in ***Fig. 27***.

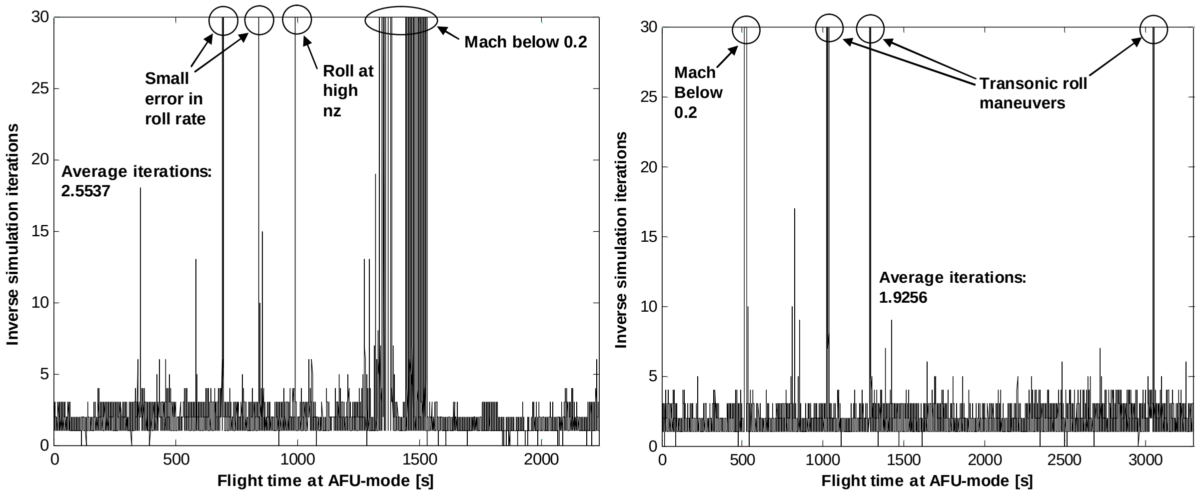


Figure 27: *Inverse simulation iteration histories for two example test flights. Courtesy of VTT.*

In the left frame, the first two highlighted points were generated since the desired roll rate was not achieved. However, the error between the result and the desired roll rate was less than three degrees per second. In the third highlighted point, the desired roll rate was not achieved due to control surface ineffectiveness at high load factors. The rest of the problems were caused by the aircraft manoeuvring in the stall region at very low Mach numbers. In the right frame, the highlighted points are mostly roll manoeuvres at transonic Mach numbers where the rolling moment is produced without ailerons by using differential deflections of leading and trailing edge flaps and stabilators. Their effectiveness had to be adjusted in order to obtain satisfactory results.

The results have been improved due to the new work and are satisfactory apart from the rudder deflections. The rudder deflection does not seem to correspond very well, because the yaw rate is not a triggered parameter in the MU system and this makes its data coarser than that of the other parameters.

The inverse simulation is fully automated to read the MU data and it performs the simulations using batch processing. In the actual fatigue life management system, the inverse simulation is carried out around turning points that are considered to consume the fatigue life. These points are chosen by applying thresholds on certain flight parameters. The inverse simulation of the important turning points in the 26 test flights takes about 5 hours to complete. It can be concluded that after the improvements in execution speed, accuracy and robustness, the inverse simulation method is now a practical element in the fatigue management system [Öström 2007].

13.6.3.1.2 Structural vibrations modelling for automated aircraft fatigue monitoring

As a part of the national technology program (Chapter 13.6.3.1), stress vibrations causing high cycle fatigue (HCF) are being studied. The investigation aims at analysing the HCF of certain problematic structures through the structural strains and flight parameters stored by the Mini HOLM I aircraft. Although the high frequency vibrations have been observed to play a significant role in the aircraft life cycle, the characterisation of these vibrations is not straightforward in view of the automated HCF prediction.

The study considers a strain signal model split in a static and a vibratory component (i.e. low and high frequency bands, respectively). It was noted that the vibrations arise intermittently with varying frequencies. The phenomenon has even some stochastic, noise-like characteristics. Nevertheless, the relevant oscillation having relatively large amplitude occurs locally in a rather narrow frequency band. Due to the non-stationary nature, the signal is analysed with windowing. Two approaches to describe the high frequency part are proposed. In the first approach, short-time Fourier transform is used to extract dominant vibration components. One or more of the strongest samples from the Fourier spectrum are selected, and each is represented by two parameters: frequency and intensity. This approach assumes locally sine-like oscillation (Fourier base functions). In the second approach, pertinent vibration features are obtained based on rainflow stress cycles counting. The rainflow cycle count takes into account only turning points of the signal. Necessary information, such as occurring time, amplitude, and mean value, about the cycles is included. Examining the rainflow count in time window, the approach surveys the local maximum amplitude and vibration rate for certain amplitude bands. There are no limiting assumptions about signal shape.

The suitability of the model is assessed by comparing original signals and model-based reconstructions. In the reconstruction, the vibrations are formed from sinusoidal components, and they are added to the static low-pass component. In this context, the most essential attribute of the model is its capability to convey information about the life cycle. The fatigue life expenditure of both, the original and the reconstructed, is estimated based on standardized design values and related material information available. The stress representation with only the low-pass component is considered as well. Hence the meaning of the vibrations becomes evident for the structures concerned. Here a boundary between the low- and high-frequency bands is set to 5 Hz. ***Fig. 28*** illustrates the quality of the proposed approaches for two structural details.

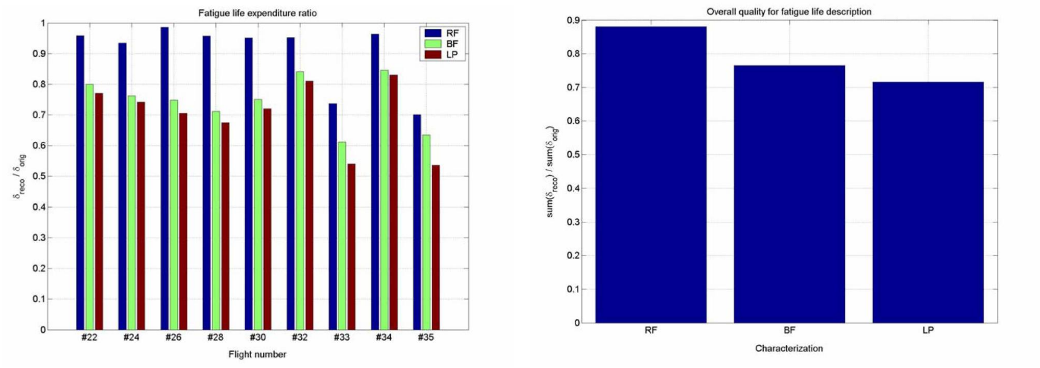


Figure 28a: ***Left:*** *Fatigue life expenditure (δ) ratio between the reconstructed (δ_{reco}) and the original (δ_{orig}) signals for 9 test flights. The original signal is from the strain gauge located in the leading edge flap's hinge area of an F-18.* ***Right:*** *Overall fatigue life expenditure ratio comparisons from the same 9 test flights and the same gauge considered. RF – rainflow approach, BF – Fourier approach (Fourier base function), LP – signal reconstruction with merely the static low-pass component. Courtesy of TUT.*

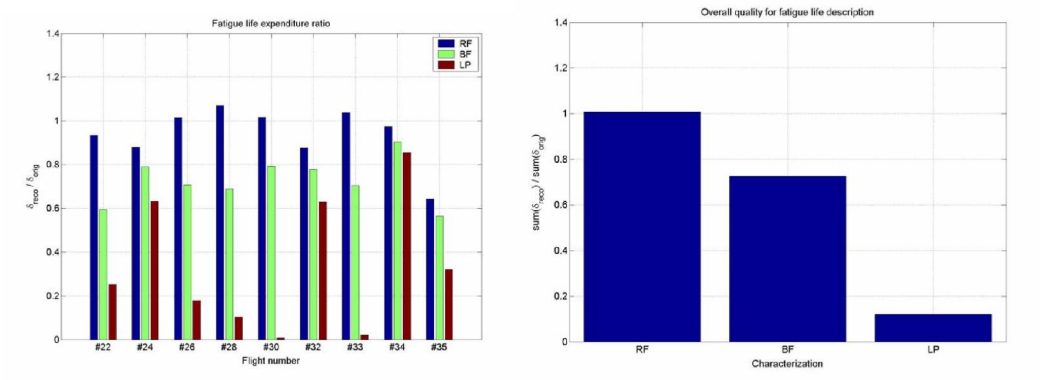


Figure 28b: ***Left:*** *Fatigue life expenditure (δ) ratio between the reconstructed (δ_{reco}) and the original (δ_{orig}) signals for nine (9) test flights. The original signal is from the strain gauge located at the base of the vertical stabilizer of an F-18.* ***Right:*** *Overall fatigue life expenditure ratio comparisons from the same 9 test flights and the same gauge considered. RF – rainflow, BF – Fourier approach (Fourier base function), LP – signal reconstruction with merely the static low-pass component. Courtesy of TUT.*

Several applications of the model exist. In the national technology program on the flight parameter based fatigue life analysis of aircraft structures, essential structural stress content should be predicted. Then the use of the proposed signal model with the vibration characterisation can be regarded as feature extraction. The features include information relevant for fatigue. Neural networks are meant to be employed to return the features via low-frequency flight parameters. Another prospect is strain signal compression. The vibration content can be represented for fatigue life with just a fraction of data samples needed in an ordinary signal.

Based on the results gathered so far, the stress representation with only the static component is insufficient: high frequency vibrations must not be ignored for certain structural details. Instead, the stress model with the static stress and the rainflow-based vibration representation proves to be effective. A more detailed description of the investigation can be found in the ICAF 2007 poster presentation [Jylhä, Vihonen, Ala-Kleemola, Kerminen, Tikka, Visa 2007].

13.6.4 Composite research & engineering activities

13.6.4.1 Carbon fibre heat blank developments – update

Research activities dealing with carbon fibre blankets for bonded repairs were highlighted in [ICAF 2005 Chapter 5.7]. Since then, efforts to come up with a carbon fibre blanket capable of producing more heat to the edges and functioning as a combined heat/vacuum bag have continued.

In the investigation, carbon fibre heat blankets were developed for bonded aircraft repairs. The blanket operates in protective voltage area, is flexible and can produce more heat over local heat sinks. Local heat sinks typically appear when patches are bonded on metallic aircraft structures. The investigations were conducted in several phases.

In phase 2 more carbon fibres were added to the edges of the blanket, thus producing more heat over the edges of the repair area [Aakkula 2005]. The blanket could be used as a combined heat blanket/vacuum bag.

In Phase 3.1 the blanket was constructed from unidirectional narrow strips. Narrow heating elements enabled mode durable and flexible joints between copper input wires and carbon fibres [Aakkula 2005b].

In phase 3.2 the blanket was constructed from 6 x 6 heating strips. Each strip can be heated separately thus producing elevated temperature to the cross section of strips, ***Figs 29, 30*** [Aakkula 2006]. In the phases to come, the improved heat blankets will be finished for production and temperature monitoring and control of the multi-zone blanket will be improved.

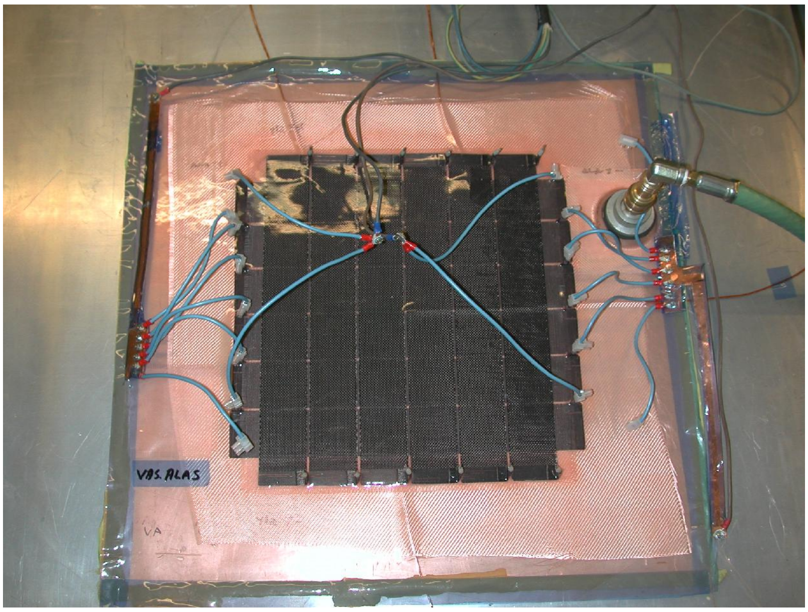


Figure 29: *Multizone (6 x 6) combined carbon fibre heat blanket/vacuum bag over an aluminium test table with heat sinks. Courtesy of TKK / KRT and the FIAF.*

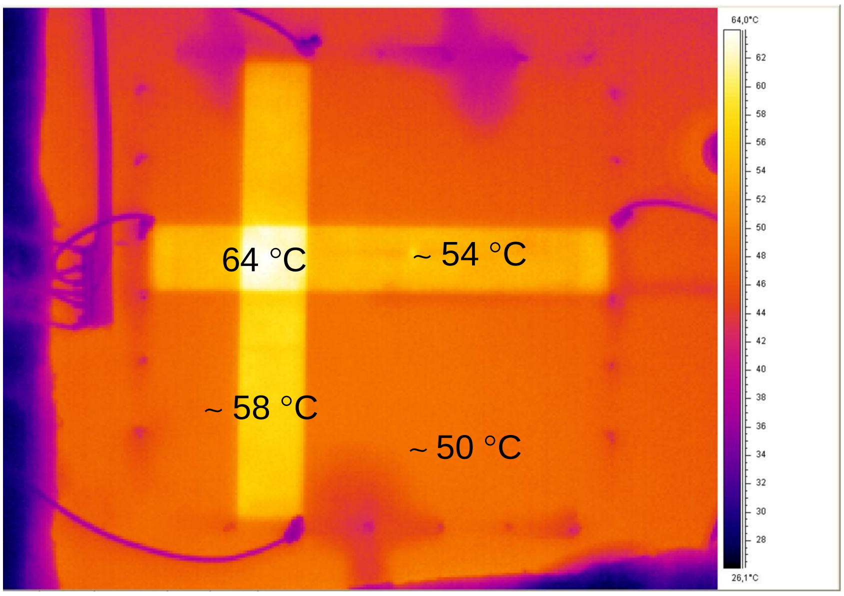


Figure 30: *Thermal image of the multi-zone heat blanket, where two crossing carbon strips were heated. Courtesy of TKK / KRT and VTT.*

13.6.4.2 Hawk wing skin

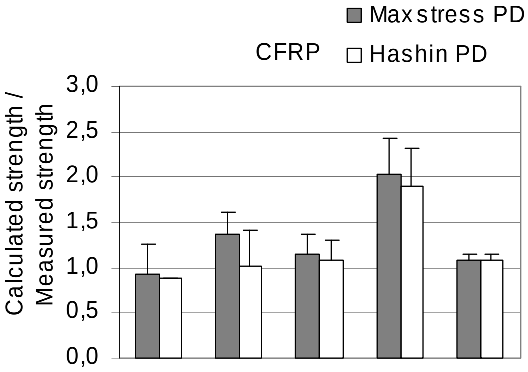
As a follow-on to the previously published service cracking observations of the Hawk Premod 999 upper wing skins [ICAF 2005 Chapter 3.4.3], the associated bonded repair activities have been completed. Composite patches by Patria Aviation have been designed and installed as a pre-emptive measure to the Premod 999 wings. The details have been reported elsewhere [Koski, Tikka, Bäckström, Siljander, Liukkonen, Marquis 2006].

13.6.4.3 Progressive failure analysis of composite laminates

Multidirectional composite structures can carry significantly higher loads after the initial failure (FPF – the first ply failure) of the laminate. To estimate damage propagation and final failure load, a progressive damage model can be used. The so-called traditional progressive analysis method applies layerwise failure criteria and degradation rules. The laminate stresses are computed using classical laminate theory (CLT) and an applicable failure criterion. If failure occurs, the material properties are modified according to the degradation rules. The process is continued until final failure of the laminate. Typically, the structural response is obtained using finite element method using shell elements. Previous research efforts and further background on the topic have been reported previously e.g. in [ICAF 2005 Chapter 5.5].

Since the previous review, the analysis tool is being developed at TKK/KRT using ABAQUS software. The damage in progressive analysis is added to the model with the use of user subroutines and material dependencies. In addition, a commercially available software GENOA is used. The results of the progressive analysis method are compared with those obtained from own static tests. The test cases included two different materials CFRP and GFRP and both un-notched and notched laminates subjected to in-plane loading. The analysis revealed a strong dependency between the failure results and element mesh especially when notched laminates are considered. In addition, the combination of failure criterion and degradation model provides different results with different materials, ***Fig. 31***.

The thickness of the plies affects the damage progression significantly as shown in ***Fig. 32*** for notched GFRP laminate. In Fig. ***32b*** the 90-degree ply cracks are clearly visible as well as the edge delamination that can not be seen in ***Fig. 32a***. In future, the analysis is extended to analyse also fatigue loading. For this purpose, ply-level fatigue tests are performed to provide initial data for further development work. [Wallin 2004; Skyttä 2005; Kosonen 2005; Skyttä, Saarela, Wallin 2006; Kosonen 2006; Wallin & Linna 2005].



Test series	1	2	3	4	5
Max stress PD	647	596	444	444	855
CS	888	698	529	529	905
Hashin PD	624	437	416	416	855
CS	625	608	505	505	337
Measured (MPa)	706	433	386	219	786

Figure 31: *Normalised failure loads for the CFRP laminate in different test cases with different failure criteria and degradation rules (PD – ply discount, CS – constant stress). Courtesy of TKK/KRT.*

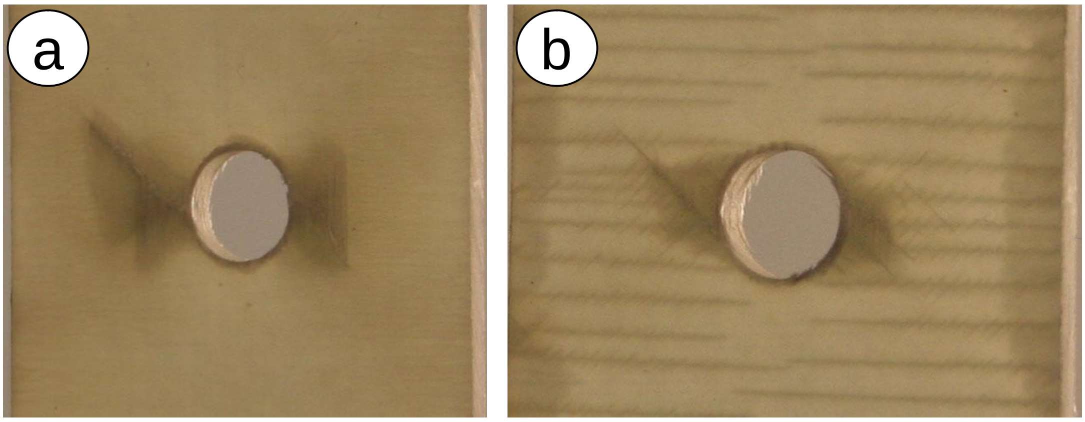


Figure 32: *Tested GFRP laminates prior to failure for **a)** lay-up [0/3(+45/-45/90)]S and **b)** lay-up [0/3(+45)/3(-45)/3(90)]S. Courtesy of TKK/KRT.*

In addition to the traditional progressive analysis method, the fracture mechanics based methods are reviewed. These methods include the Virtual Crack Closure Technique (VCCT) and the Discrete Cohesive Zone Modelling (DCZM – a.k.a cohesive elements). Both methods are finite element based. The principles and basic theories behind both methods are reviewed and simple examples are analysed with 2D structures. In future the analysis will be extended to include 3D structural cases [Kosonen 2006b].

13.6.4.4 Strength prediction of notched and impact damaged laminates in compression

Composite laminates are very sensitive to impact damages. The static residual strength of impacted laminates in compression can be only 30% of the original strength. This behaviour typically determines the damage tolerance criterion and the strain limits for the structure. A new analysis method to estimate the residual strength of open hole or impact damaged laminates was found from open literature. The key elements of the method are: The lay-up independent characteristic distance and a new failure criterion. The analysis method considers only uniaxial compression or tension loading.

The analysis method was reviewed and results compared at TKK/KRT to those obtained from own static tests. The tests were performed for CFRP laminates made of UD-plies. The tests included both open hole and impact damaged laminates. The compression after impact (CAI) test arrangements was used in all testing. The open hole geometries included various round and elliptical holes, ***Fig. 33***. In general, the correspondence between analysis and test results was good. The analysis method somewhat underestimates the residual strength of open elliptical hole but tends to overestimate the round hole, ***Fig. 34***. For impact damaged laminates the analysis curve describes well the average behaviour of test specimens, ***Fig. 35***. In future, the analysis method is extended for other in-plane loading conditions as well as fatigue loading. [Wallin 2005; Wallin 2006].

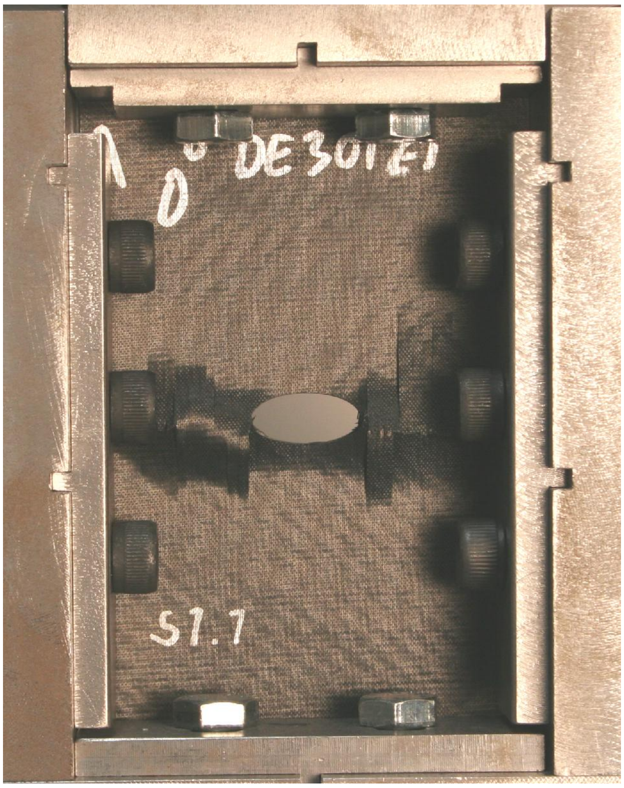


Figure 33: *Typical failure of specimen with elliptical open hole. Courtesy of TKK/KRT.*

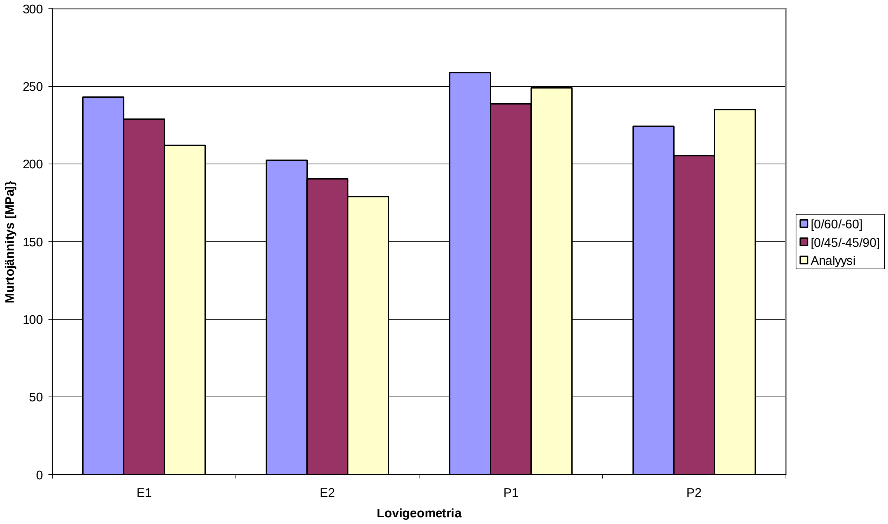


Figure 34: *Analysis results compared with open hole test results (elliptical hole E1 and E2, round hole P1 and P2). Courtesy of TKK/KRT.*

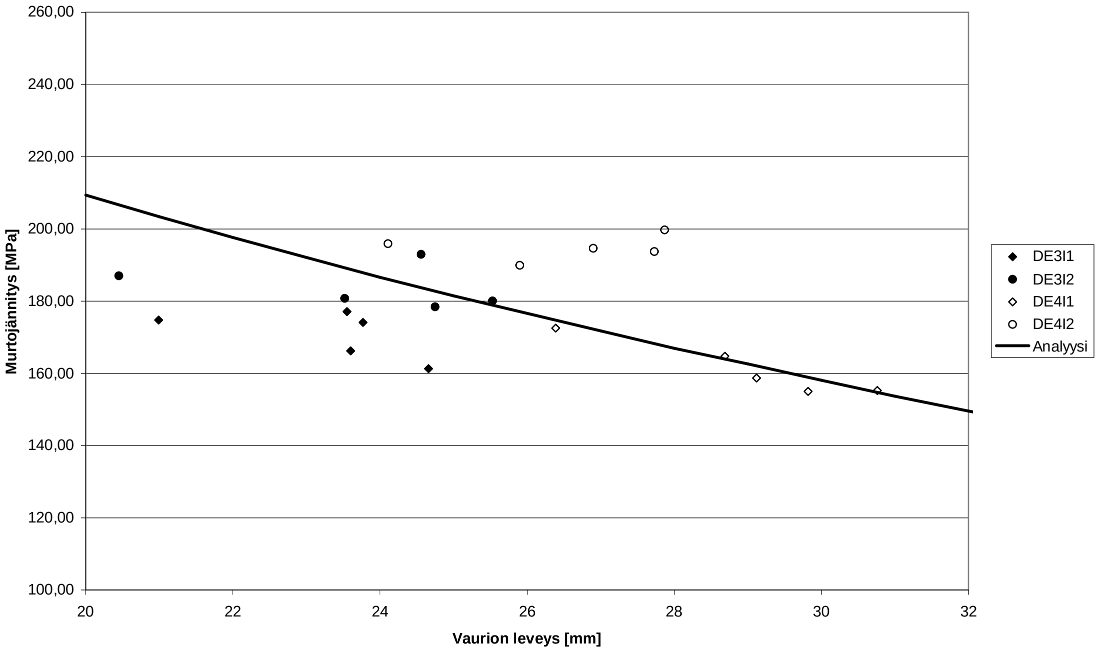


Figure 35: *Analysis results compared with individual test results for impacted laminates as a function of damage width. Courtesy of TKK/KRT.*

13.6.4.5 Thermographic studies

Thermographic research has continued in close cooperation between VTT and the FIAF due to its potential to be used without removing aircraft composite parts from the aircraft and due to the possibility to investigate large areas simultaneously. Using artificial defects it was proven that several types of defect indications can be found with the thermographic inspection. Two thermographic methods have been used in investigations – phase transition thermography and pulse thermography [ICAF 2005 Chapter 5.8.2].

Since the previous review, research efforts (on the thermographic investigation based on phase transition of water at 0 °C) have concentrated on finding the reliable testing conditions and routines for the investigation of real aircraft parts with real defects. The basic inspection routine was developed: The aircraft was first left outside (cold) until possible water inside the structures would freeze, after which the aircraft was towed inside for the inspections during water defrosting. Ten different flight (control) surfaces have been inspected during the same test route (***Fig. 36***). Simultaneous inspections during the one inspection route have been done for both rudder surfaces, both surfaces of trailing edge flaps and bottom surfaces of the horizontal stabilizers.

Figure 36: *Inspected areas in simultaneous thermographic inspection (port and starboard side of the aircraft inspected). Solid red indicates inspection of both surfaces (rudder and trailing edge flap) and dotted red colour indicates inspection from the bottom surface (horizontal stabilizer). Courtesy of the FIAF.*

It was shown that in cold weather conditions (like in Finnish winter) it is possible to cool the whole aircraft outdoors in a reliable manner. Different defrosting conditions showed however that weather and cooling conditions affected strongly to the test results. The best way to cool down the aircraft showed to be a cold hangar with proper ventilation; the hangar prevented the formation of the scrub on the flight surfaces, and ventilation accelerated cooling of the aircraft.

The optimal observation period was consistent with previous studies i.e. within 5 to 10 minutes after the undamaged surface of the structure reached 0 °C (in carbon fibre/epoxide composite). It was noticed that the rate of the temperature change was part specific. Hence, the optimal observation period varies for each structure inspected, ***Fig. 37***. Different testing routes were investigated and optimisation of the optimal testing route is ongoing.

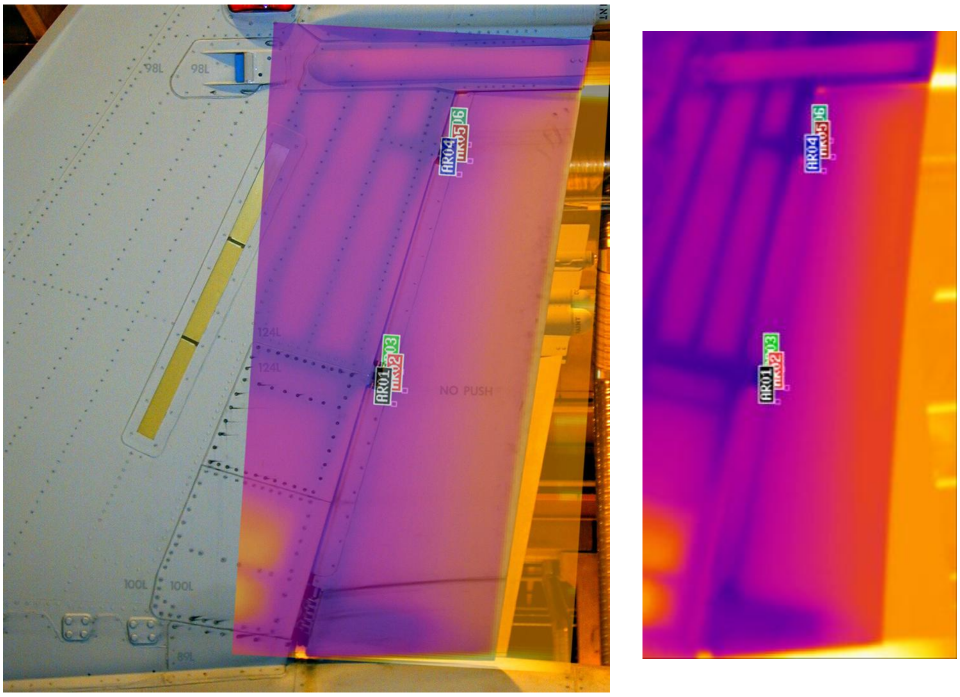


Figure 37: *An example of an undamaged rudder structure. Supporting structures warm up slower compared to the other areas of the surface (blue indicates cold, yellow warm). Courtesy of VTT and the FIAF.*

13.6.4.5.1 Comparison of different NDI methods

In view of thermography, simultaneously inspected area depends on the resolution of the thermographic equipment and heating equipment. Using VTT’s 16 kJ xenon flash lamps, sufficient temperature difference is reached using distances of 0.5…1 m from the surface, typically leading to an inspection area of $30 \cdot 40$ cm^2. Although the pulse thermography has been shown to be a fast method to find multiple types of defect indications simultaneously, the method has no official position in the composite NDI within the FIAF. Ultrasonic NDI is an accepted method for defect inspections in composite structures.

The efficiency of different NDI methods (coin test, ultrasound and thermography) was investigated using a real defect which was formed during the unsuccessful repair of an impact failure in the horizontal stabilizer. The repair of the impact failure was first inspected with the coin test without any indication of unsuccessful repair. Ultrasonic equipment (delay probe and through sensing probe) gave a diverging indication of unsuccessful repair and it was further investigated with thermography (pulse method), ***Fig. 38***. Strong echo indications (ultrasound) were observed in 1 mm with the delay probe. An area of very poor or no ultrasound penetration was found with the through sensing probe. Pulse thermography, however, gave a clear indication of the defected area. The defect was quantified to a depth of 1.1 mm with a tomographic method (time dependence of the defect appearance). These indications together led to the decision of removing the repair. During the removal of the repair, it was observed visually. The defects found were photographed and evaluated. The real defect (porosity / small holes) was compared to the NDI results. The comparison proved that the NDI methods employed complemented each other very well. In this case, ultrasound gave more accurate depth of the defect but thermography showed more reliably the size and shape of the defect.

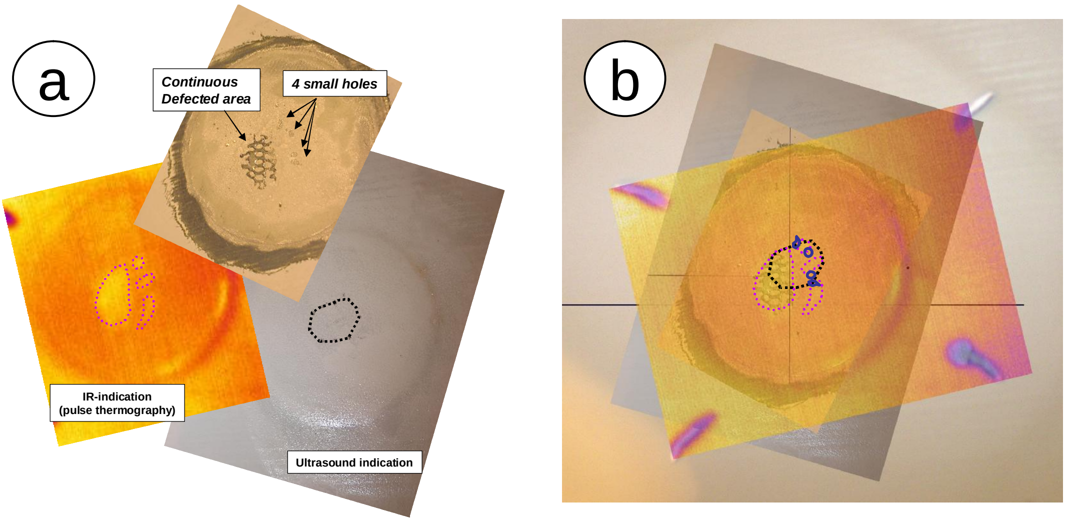


Figure 38: *Comparison of the real defect and NDI results.* ***a)*** Top: *Real defected area (note also the four small holes);* Lower left: *IR inspection result (VTT);* Lower right: *UT inspection result (the FIAF).* ***b)*** *NDI results superimposed on top of the real defect. Pink: IR indication (under which the large real defect); Black: UT indication; Blue: 4 small holes from the real defect. Courtesy of VTT (IR) and the FIAF (UT).*

13.6.5 Risk based approaches – update

The Bayesian based fatigue analysis framework efforts were briefly outlined in [ICAF 2005 Chapter 5.9]. Since that, more details have become available on this study.

13.6.5.1 “Top Down” approach

Fleet management is a sequential multi-criteria decision problem with uncertainties related to both the information at the time of decision-making, and the outcome of the decision. Structural risk and reliability analyses provide a baseline for decision-making, and can be used to provide input information for a higher-level fatigue analysis framework that takes into account decision criteria, reflecting fleet management strategy, in the decision analyses. A ‘top-down’ fatigue analysis framework is introduced, where the framework allows the fleet manager to make ‘what-if’ analyses of the performance of alternative flight task mixes or flight programs. The required measurement data is any fatigue life measures obtained from the fatigue monitoring systems. These are used as evidence in Bayesian inference on fatigue damage parameters needed for higher-level analyses. The framework can be used to assess feasibility and/or rank flight and maintenance programs designed during the flight operations planning phase. The implementation of the fatigue analysis framework requires the development of computer software. The risk based fatigue analysis framework (***Fig. 39***) has been published elsewhere in more detail [Rosqvist, Koski, Siljander 2006].

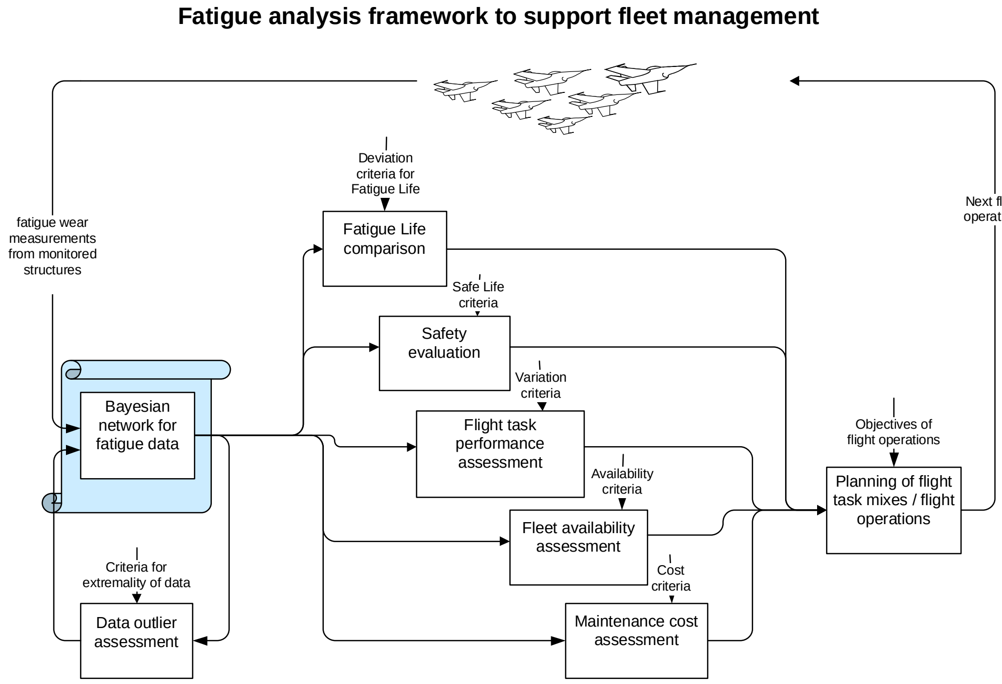


Figure 39: *Fatigue analysis framework supporting the planning of flight operations, as measurement values of fatigue damage from performed flight tasks become available and inferences on fatigue damage can be made. Courtesy of VTT.*

13.6.5.2 “Bottom Up” proof-of-concept experiments

The FIAF Hawks have a number of Premod 999 wings, within which there are 12 jet fuel drain holes in each. Although the OEM design of the Hawk and the wing is based on the safe life, the drain holes are routinely inspected at a certain interval. During one such routine inspection of a wing near the safe life limit, there was a crack indication related to one of the drain holes. In line with the current procedures within the FIAF, the wing was removed from service. According to the structural analyses by Patria Aviation and spectrum fatigue tests by VTT for the wing configuration, the drain hole regions are among the highest stressed structural details possessing significant fatigue crack growth rates. Changes to the periodicity of the NDI have since been implemented.

Although no additional crack indications for other Premod 999 wings of the FIAF Hawks have been observed, there was a concern e.g. on the probability of having such crack observations before the safe life limit of the wing. With the above background and in line with the “top down” approach described above to support decision making on a fleet manager level, a similar “bottom up” approach was applied in a proof-of-concept sense to the Premod 999 wing’s drain hole [Porthin & Koski 2005; Rosqvist & Porthin 2005]. On the basis of one crack indication alone, the verification of the proof-of-concept model could not be completed and decisive conclusions regarding the risk levels of finding additional cracks from the number of similar wings could not be drawn.

13.6.6 Materials testing activities

Various surface renewal activities take place on fleet aircraft to remove incipient cracks arising at structural critical locations in order to make the structure crack-free and more fatigue resistant. Of particular interest in these surface renewal activities are those carried out in regions containing etched surfaces, which – for the FIAF F-18C/D aircraft – are due to e.g. pre-IVD processes during the parts' OEM manufacturing. These surface renewal activities may involve blending or grinding out cracks followed by shot-peening if necessary. As the guidelines describing surface renewal process details/effects (such as depth of surface removal) and expected life improvement factors (LIF) after surface renewal are limited, coupon tests to quantify the LIF of such repair actions are needed. Materials testing activities described here are aimed at serving the ASIMP needs of the FIAF F-18 Hornets.

13.6.6.1 Effect of surface working methods on the fatigue life of two 7000 series Al alloys

The effect of various surface working methods on fatigue life of laboratory specimens made of two common 7000 series alloys was investigated [Linna 2007]. The surface working methods studied were shot peening, polishing and etching. The two tested aluminium alloys were 7050-T7451 and 7175-T7351 in plate form. Thickness of specimens was 6,35 mm and stock material thicknesses were 100 mm and 38 mm. The 7050 specimens were manufactured both in L and LT directions. The total number of specimens was 96 (7050: 72 specimens and 7175: 24 specimens).

Shot peening with Almen intensity of 0,14 mmA was made by using ceramic beads. The surface roughness of the polished specimens was 0,4 μm ≤ R_a ≤ 0,6 μm. Etching was similar to the production pre-IVD coating process. The fatigue tests were performed using three different constant amplitude stress levels (R = -1). The number of test specimens per stress level was four.

The following main test results and *LIF's* (Life Improvement Factors) were obtained:

- $LIF_{polishing}$ is at least 1,86 but $LIF_{shot\ peening}$ can be minimal or less than 1 when the maximum stress level is between $0{,}45 \cdot \sigma_y$ and $0{,}5 \cdot \sigma_y$. Polishing may be useful but shot peening will not give life extension at high stress levels when R = -1.
- $LIF_{polishing}$ is at least 4,87 and $LIF_{shot\ peening}$ at least 1 when the maximum stress level is between $0{,}35 \cdot \sigma_y$ and $0{,}45 \cdot \sigma_y$.
- $LIF_{polishing}$ is at least 4,85 and $LIF_{shot\ peening}$ at least 2,98 when the maximum stress level is below $0{,}35 \cdot \sigma_y$.
- the influence of etching (and IVD coating) on the fatigue life reduction can be significant. ”$LIF_{etching}$ “ is usually 0,5 or less.

13.6.6.2 FISIF Surface Renewal Joint Coupon Program (SRJCP)

The F/A-18 users' FISIF consortium – alphabetically from Australia, Canada (project lead), Finland, Switzerland and the USA – are conducting materials tests to complement the existing data (e.g. [Sharp & Clark 2001]) regarding the LIF due to surface renewal operations to help further substantiating the selected potentially simple and cost-effective solutions for fatigue critical areas. The main objectives of the SRJCP project include [Hajjar 2006]:

- to build experimental data showing the effect of surface renewal/removal operations on the fatigue life of a structural component;
- to provide life improvement factors for several types of surface renewal operations and various parameters;
- to identify the depth of surface renewal required to reset the fatigue life for a given stress level and a given level of expended life;
- to provide data to compare the effect of the IVD finish to anodize surface finishes on the fatigue life

There are over 400 specimens to be tested. The testing responsibilities according to commonly agreed methodologies are shared between each participating nation. Once completed, the test & analysis results will then be shared between the participants. Finland's participation in the SRJCP program includes the creation of a detailed test plan and the constant amplitude fatigue testing of approximately 60 coupon specimens of selected surface finishes [Siljander, Veivo, Arilahti 2006]. An overview of the testing arrangements is provided in ***Fig 40***.

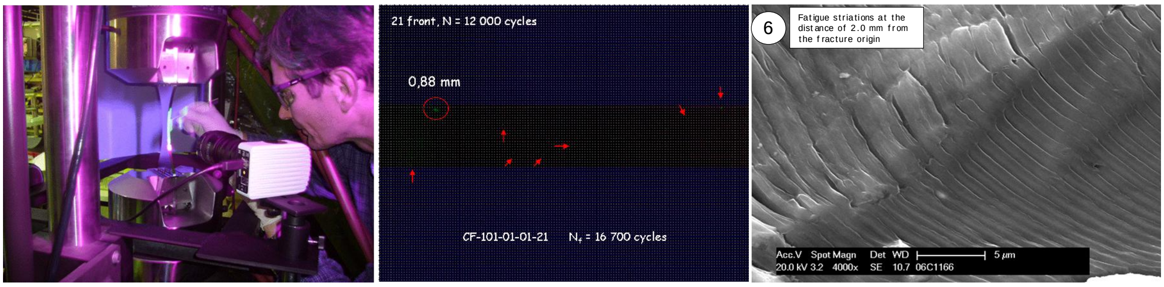


Figure 40: *An overview of the FISIF SRJCP constant amplitude fatigue tests at VTT.* ***Left:*** *The test set-up (NDI in process);* ***Middle:*** *Observed surface crack indications (red arrows & the killer crack circled);* ***Right:*** *Post mortem fractography (SEM) showing striations. Courtesy of VTT.*

13.7 INTERMEDIATE SUMMARY: IT PAYS TO ASIMP

The applied research & development activities associated to the ASIMP (Aircraft Structural Integrity Management Plan) – orchestrated and funded nationally over the years by the FIAF and briefly reviewed herein – have not only markedly improved the in-country capabilities within the FIAF, national industry and academia, but also gained noteworthy savings. According to a recent study by the Finnish Defence Forces' Chief of Staff, estimated savings of the order of 290 million euros (Hawk) and 200 million euros (Hornets) have been saved thus far [FDF 2006].

13.8 FUTURE ACTIVITIES

13.8.1 ASIMP 2007 - 2009

The FIAF have defined a follow-on program to the aircraft structural research activities briefly reported in this review. The finalisation of the contracting activities can be seen during the writing of this review. The follow-on program – which is a sound and logical continuation of the research efforts reported previously – contains 10 sub-programs. Each sub-program contains one or more individual projects. Although the various sub-programs and the projects therein are more or less interconnected, an attempt is provided in the following to try and clarify the brief outlook of the research activities.

13.8.1.1 Loads and stresses

Computational Fluid Dynamics (CFD) and flight simulation tools and techniques will be further developed and applied to the determination of aerodynamic loads. Areas of special interest cover e.g. the inclusion of aeroelastic aspects, as well as the aerodynamic loads due to high angle of attack manoeuvring. Another application area of advanced simulations includes the integration efforts of the aerodynamic model, the finite element model and the flight control system model.

The co-operative efforts between (alphabetically) the FIAF, Finflo Oy, Patria Aviation Oy, TKK/LAD and VTT will ensure the realisation of the overall goal, which is to further improve the aircraft type-specific fatigue tracking capabilities.

13.8.1.2 Fatigue tracking systems

The data collection and analyses of the IAT (individual aircraft tracking) systems (2 OLM Hawks and 2 HOLM Hornets) will continue. Concerning the HOLM systems, the flight parameter based fatigue life analysis methodology will be integrated in existing in-country infrastructure expanded to new (un-instrumented) structural locations. Concerning the Hornets, the fatigue life expenditure (FLE) values will be calculated for a selected structural location fleet wide.

The co-operative efforts between (alphabetically) Emmecon Oy, the FIAF, Finflo Oy, Patria Aviation Oy, TKK/LAD, TUT/ISP and VTT will ensure the realisation of the overall goal, which is to further improve the ways to make use of the data stored by the onboard fatigue tracking systems e.g. FMI (Flight Manoeuvre Identification).

13.8.1.3 Structural integrity of composite materials

The flaw identification, quantification (NDI) and associated repair engineering activities of structural wears, tears and flaws in composite materials are not always as developed as with metallic structures. The capabilities of e.g. these elements will be improved, and means to reduce the aircraft ground time (due to composite integrity activities during e.g. periodic maintenance) will be investigated.

The co-operative efforts between (alphabetically) the FIAF, Patria Aviation Oy, TKK/KRT and VTT will ensure the realisation of the overall goal, which is to further improve the in-country capability in the structural integrity of the composite materials (detect, analyse, design, fix).

13.8.1.4 Structural integrity of metallic materials

The tools and instructions are among the items to-be-developed for the ASIMP documentation (to be published in 2009) for the fatigue life cycle management of the Hawks (meeting the requirements for the remaining post-midlife structural integrity issues) and Hornets (structural lifing policy and damage tolerance aspects). Fatigue tests, NDI methods development and the introduction of a new analysis tool (developed at FOI and) related to the initiation, growth and link-up of small fatigue cracks are among the research efforts associated.

The co-operative efforts between (alphabetically) the FIAF, FOI (Swedish Defence Research Agency), Patria Aviation Oy, TKK/KRT and VTT will ensure the realisation of the overall goal.

13.8.1.5 Repair technologies

As the overall goal, the applicability of existing repair engineering technologies tailored to the FIAF F-18 Hornets will be investigated. The main emphasis is on the metallic primary structures. Selected methods (e.g. the new analysis tool for the initiation, link-up and growth of small fatigue cracks – see Chapter 13.8.1.4) will also be verified experimentally.

The co-operative efforts between (alphabetically) the FIAF, Patria Aviation Oy and VTT will ensure the realisation of the overall goal.

13.8.1.6 Structural health monitoring

The lessons learned from previous structural health monitoring programs will further be tailored. The overall goal is to come up with a SHM system – permanently installed on a selected aircraft type – monitoring the suspected fatigue critical location in an automatic manner and without the need to dismantle the aircraft for the inspections unless the SHM system indicates otherwise.

The co-operative efforts between (alphabetically) the FIAF, Patria Aviation Oy and Emmecon Oy will ensure the realisation of the overall goal.

13.8.1.7 Mechanical systems integrity

Among the overall goals is to validate the simulation model of the hydraulic system of the FIAF F-18 Hornet. Using the simulation model, one goal is to improve understanding of the entire hydraulic system. Another goal is to simulate the functional characteristics of selected (sub-) systems and modification alternatives therein in view of the behaviour and performance of the entire hydraulic system.

The co-operative efforts between (alphabetically) the FIAF and TUT/IHA will ensure the realisation of the overall goals.

13.8.1.8 Engine integrity

The overall goal is to improve the in-country capabilities related to jet engine integrity assessments, before the life limits related to certain FIAF F-18 engine components are at hand. Special emphasis is on experimental methods (e.g. creep tests and associated metallographic investigations) focused on certain turbine blades and the life extension possibilities therein.

The co-operative efforts between (alphabetically) the FIAF, Patria Aviation Oy, TUT/Department of Materials Engineering and VTT will ensure the realisation of the overall goals.

13.8.1.9 Structural integrity of rotary wing aircraft

The overall and long term goal is to create the basic ASIMP infrastructure in-country. The work will also include the first steps in creating capabilities related to repair engineering for selected helicopter components.

The co-operative efforts between (alphabetically) the FIAF, Finflo Oy, Patria Aviation Oy and TKK/KRT will ensure the realisation of the overall goals.

13.8.1.10 Life cycle cost models

The many challenges faced while maintaining the aircraft inventory’s readiness until the planned withdrawal date include e.g. upgrades, obsolete issues, availability of spare parts and associated maintenance strategies – to name a few. The overall goal is to improve the life cycle cost (LCC) analysis capabilities by implementing a mathematical model for the LCC of a selected avionic system component.

The co-operative efforts between (alphabetically) the FIAF, Insta DefSec Oy and VTT will ensure the realisation of the overall goal.

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A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND MAY 2005 – APRIL 2007

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Summary

This document was prepared for the delivery to the 30th Conference of the International Committee on Aeronautical Fatigue scheduled to be held in Naples, Italy on 14-15 May 2007.

A review is given of the aircraft structural fatigue research and associated activities which form part of the programs within the Finnish Air Force headquarters (FIAFHQ), the Finnish Air Force Air Materiel Command (FIAFAMC), Patria Aviation Oy, the Technical Research Centre of Finland (VTT), Helsinki University of Technology (TKK) Laboratory of Lightweight Structures (TKK/KRT), Laboratory of Aerodynamics (TKK/LAD), Tampere University of Technology Institute of Signal Processing (TUT/ISP), Finflo Oy and Emmecon Oy.

The review summarises fatigue related research programs and investigations on specific military fixed wing aircraft since the previous Finnish National Review (tabled in the 29th Conference, ICAF, Hamburg Germany) up to April 2007.

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