A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND MARCH 2015 – MARCH 2017

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Confidentiality Public

Preface

The Finnish Defence Force Logistics Command, Joint System Centre (FINLOGCOM JSC) initiated and supported this work. The editors are indebted to the following individuals who helped in the preparation of the review (organizations and individuals in alphabetical order – the reference list refers to paragraph-specific contributions):

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Editors

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1 Introduction

Finland became an independent state on 6 December 1917, so in 2017 Finland celebrates its centenary year. The theme of Finland 100 Jubilee Year is “Together” - theme which has over decades also reflected to the in-country ASIP activities for the Finnish Air Force (FINAF). Finns as a relatively small nationality are team players with very genuine problem solving mindset: always looking for the practical solutions for common good. We cannot afford to disperse our skilled workforce and brainpower for contradictory research.

The year 2017 marks also the 99th anniversary of the Finnish Air Force (FINAF) – one of the oldest independent air forces in the world. It was founded as an independent service on the 6th March 1918. Today, the objective of the Air Force is to monitor and secure Finland’s territorial integrity. This task requires continuous maintenance and development of air defence capabilities. The fixed wing aircraft inventory of the FINAF at the time of writing this review is summarized in Figure 1.

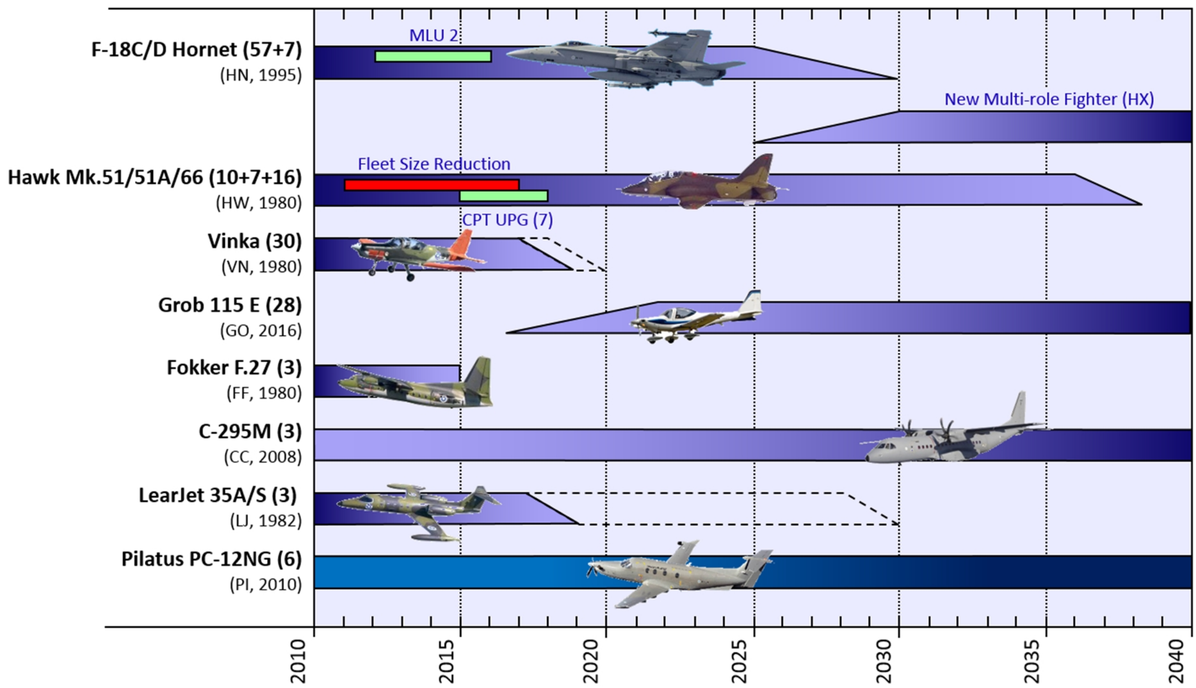

Figure 1: An overview of the fixed wing aircraft inventory of the Finnish Air Force (FINAF). Picture courtesy of the Joint Systems Centre.

The 20 TTH/SAR NH90 helicopters purchased earlier by the Finnish Defence Forces (FDF) are being retrofitted (by Patria Aviation) to modify/update the Initial Operational Condition (IOC) and IOC+ up to the Full Operational Condition (FOC). The retrofits (including the platform and various systems therein) started in 2014 and the process will be completed in 2018. The helicopters of the FDF at the time of writing this review are summarized in Figure 2.

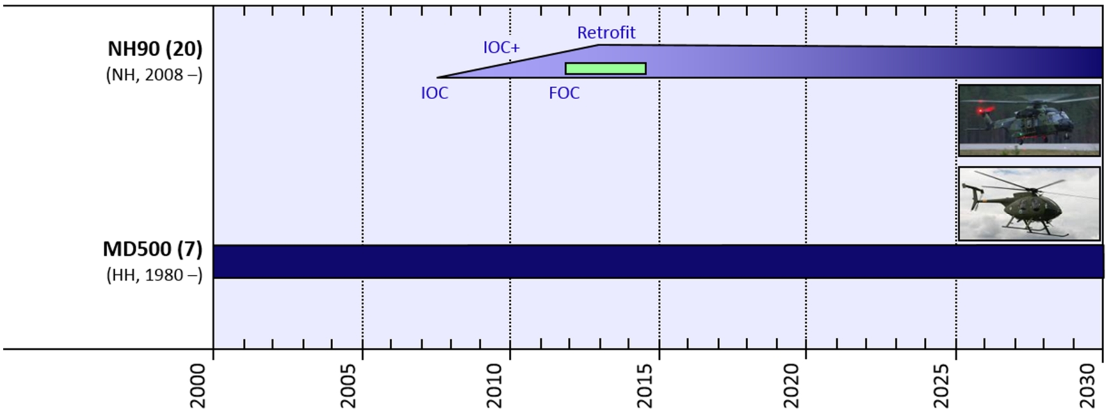

Figure 2: An overview of the rotary wing aircraft inventory of the Finnish Defence Forces (FDF). Picture by courtesy of the Joint Systems Centre.

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

1.1 Valmet L-70 Vinka

The Valmet L-70 Vinka is a three-seat piston-engine aircraft of Finnish design and manufacture (Figure 3). The Vinka is used by the FINAF in a primary training role since 1980 to teach basic flying skills to military pilots. Due to its long service life the Vinka has undergone several minor structural reinforcements and other modifications. 27 of the original 30 Vinkas remain in service with the FINAF. The German Grob G 115E will replace the Vinka aircraft in the primary and basic training role (Ref. Chapter 1.2). According to the FINAF's current plans the Vinkas planned withdrawal date is 2018. [1]

Figure 3: Valmet L-70 Vinka primary trainer aircraft. Figure by courtesy of the FINAF.

Previous activities related to the Valmet Vinka primary trainer of the FINAF were outlined in e.g. [2] Chapter 13.1.1. During the Life Extension Program (LEP) of the Vinka primary trainer fleet, each aircraft was equipped with a g counter. The structural life consumption and severity of the usage is monitored by Patria Aviation by using the g counter data. Patria also issues recommendations on a yearly basis regarding the rotation of the Vinka fleet as well as its fleet leaders. This is to obtain a more even rate of structural life expended and to keep the fleet leaders reasonably ahead of the rest of fleet in flight hours.

Based on the g counter information, the aircraft are in good structural condition with regard to the flight hours. The severity of usage in view of the g counter status is more benign than that used as the basis of LEP analyses and tests, see Figure 4.

The first fleet leader was removed from operation in September 2015 after logging 7100 FH (it was given 100 FH extension to the official 7000 FH limit). After that the aircraft was disassembled for structural inspections. The majority of the inspections were done visually, but the most critical locations were inspected using NDT. No cracks were found. As Vinka will be replaced by Grob G 115E fleet in 2018, the other two fleet leaders are not planned to be operated differently compared to the rest of the fleet any more.

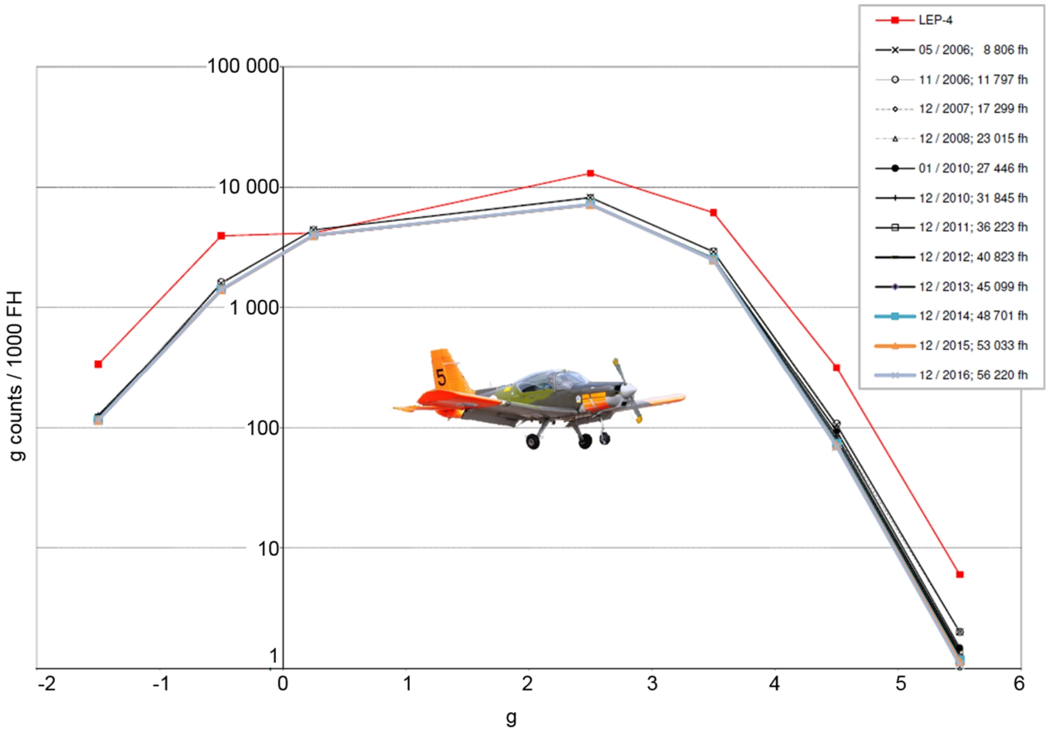

Figure 4: *The g counts per 1000 FH of the Valmet Vinka. From top to bottom: The spectrum representing the LEP design assumptions (LEP-4); the post LEP g counter spectrum as of May 2006; as of November 2006; as of December 2007; as of December 2008; as of January 2010; as of December 2010; as of December 2011; as of December 2012; as of December 2013; as of December 2014; and the updates from the previous review: as of December 2015; as of December 2016 including a total of 56 220 FH. All curves (excluding the red LEP-4) represent the fleet average from all Vinkas, as ranked according to the aircraft center of gravity normal acceleration. Figure by courtesy of Patria Aviation.*

1.2 Grob G 115E

The Grob G 115E is a small, lightweight, two-seat piston-engine aircraft built in Germany by Grob Aircraft. In October 2016, the FINAF procured 28 pre-owned Grob G 115Es for the Defence Forces to supersede Valmet L-70 Vinkas in primary and basic training roles. The aircraft were purchased from civilian company Babcock Aerospace Limited which had previously operated them as a training platform for the Royal Air Force. [1]

Before handover to the customer, the Grob fleet will receive an avionic and communication systems upgrade. State-of-the-art digital displays will be fitted in order to bring the cockpit layout compatible with the other aircraft operated by the Defence Forces.

On the contrary to its successors (Vinkas), the structure of Grob G 115E is manufactured of composite materials. It is constructed predominantly from carbon fiber reinforced composites, has a tapered low wing, a 180 hp engine with a 3-bladed variable-pitch propeller, a fixed tricycle undercarriage, fixed horizontal and vertical stabilizers and conventional flight control surfaces (Figure 5)

Figure 5: Grob G 115E primary trainer aircraft. Figure by courtesy of the FINAF.

1.3 Hawk Mk.51/51A and Mk.66

The BAE Systems Hawk is a British single-engine two-seat jet trainer which is operated in Finland by the Air Force Academy in advanced and tactical training roles. The first Hawks, Mk.51s, entered Finnish service in 1980-1985. In 1993, the FINAF ordered an additional batch of seven Hawk Mk.51As that contain minor improvements in structure and avionics compared with the Hawk Mk.51. Finland augmented its Hawk fleet in 2007 by sourcing 18 low-hour Hawk Mk.66s from Switzerland. Externally, the former Swiss Hawks stand out from the grey legacy Hawks owing to their red-and-white paint scheme (see Figure 6). [1]

Due to increasing signs of metal fatigue, a major structural reinforcement program (SRP) was performed to extend the operational life of Finland's Hawks. The Hawk SRP was completed during the late 1990s. Finnish Mk.51s and Mk.66s underwent an extensive series of upgrades carried out by Patria Aviation, completing in 2011-2013. The upgrades made the Hawk an updated and effective training platform. The glass cockpit upgrade program included the replacement of analogue cockpit instruments with modern displays which narrows the gap between the instrument layout of the Hawk and F/A-18C/D Hornet (see Chapter 1.4). 18 modernized aircraft were delivered to the FINAF by January 2014. The aircraft, which were not modernized, will be retired due to lifespan limitations by the end of 2017. Because of the changes in the Hawk life cycle plans and the loss of two already modernized Mk.66 aircraft, a new avionics upgrade project takes place between 2016-2018. Additional seven Mk.51 aircraft will also be modernized by then. Thus, the 2019 fleet will consist of 31 modernized Hawks: 8 Mk.51s, 7 Mk.51As and 16 Mk.66s. They are expected to remain in service until the mid-2030s. [1]

Figure 6: BAE Systems Hawk Mk.51A (left), and Mk.66 (right) advanced jet trainer. Figures by courtesy of the FINAF.

The usage profile of the Finnish Hawk fleet is shown in Figure 7.

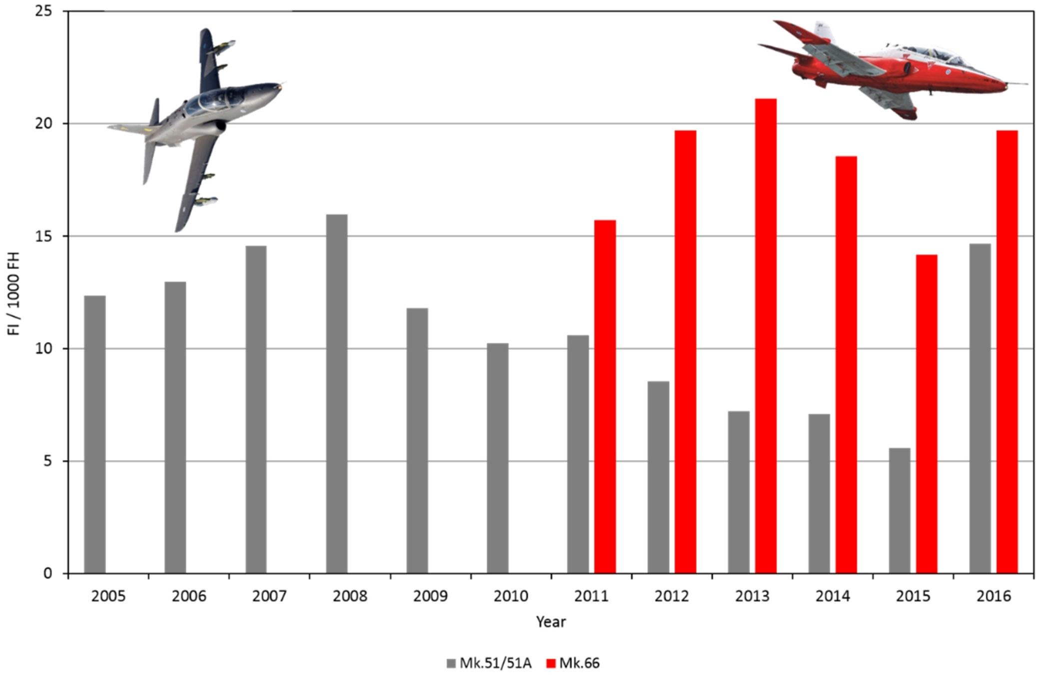

Figure 7: Annual Fatigue Index (FI) development of the FINAF Hawks (Mk.51/51A in grey; Mk.66 in red) at the end of September 2016. Figure by courtesy of the FINAF.

1.4 F/A-18C/D Hornet

The Boeing F/A-18C (single seat) and F/A-18D (two seat) Hornet are twin-engine, mid-wing, carrier-capable, multirole jet fighters (see Figure 8), that form the nucleus of the Finnish air defence. The late-production Lot 17 aircraft entered Finnish service between 1995-2000. The Finnish two-seaters were built in the United States by McDonnell Douglas which later merged with Boeing, while the single-seat aircraft were assembled at the Patria Aviation facility in Finland. [1]

It was recognized already in the initial stage of the Hornet program that technology of the 1990s would be obsolete way before the planned withdrawal date of the type, 2025-2030 time frame. Therefore, in order to keep the Hornet fleet at their highest level of performance, the fleet would be subjected to continuous and systematic development over its life cycle. The Hornet fleet's capabilities have been improved through midlife upgrades, and its relative performance will peak at the end of the 2010s. The partners in the upgrades were Boeing, Naval Air Systems Command as an upgrade design organization and equipment supplier, and Patria Aviation as a life cycle support service provider for the aircraft. The Finnish Hornets have undergone two mid-life upgrades, designated as Mid Life Update 1 (MLU 1) and Mid Life Update 2 (MLU 2) which were incorporated between 2004-2010, and 2010-2016 respectively.

Figure 8: The Boeing F/A-18C Hornet multirole jet fighter. Figure by courtesy of the FINAF.

The focus in MLU 1 was to improve the Hornet's air-to-air capability. The aircraft were fitted with provisions for a helmet-mounted sighting system to improve close-range combat capability and the AIM-9X Sidewinder missile. [3]

The primary objective in MLU 2 was to enable the FINAF Hornets' air-to-surface capability by integrating various types of weapons, and self-protection, communication, navigation and information distributions systems which make the aircraft more interoperable in joint operations. Along with the MLU 2 upgrade, the FINAF Hornets have also gained the ability to perform air-to-ground operations. This will reflect on training programs and the use of the aircraft. The Finnish pilots are enabled to exercise the full potential of the Hornet in joint and combined operations with a wide range of air-to-air and air-to-ground capabilities.

Other significant MLU 2 upgrades are, for example, the cockpit upgrade with new displays and the BOL countermeasures dispensers. There are special arrangements to manage the C and D model differences between the USN and the FINAF in the MLU 2 induced configurations: The software testing will be done in Finland by the FINAFSAC ACC (Satakunta Air Command, Air Combat Centre, Flight Test Section) and Patria Aviation's STIC laboratory (Software Test and Integration Centre). For the first time in the history of the Hornet, there is a foreign (Finnish) organization approved as a part of the approval process of the US software.

From structural point of view, the MLU 2 upgrade included structural strengthening and a purchase of Line Replaceable Units (LRU) and other spares to ensure the safe and reliable performance until the sundown of the aircraft type. All structural MLU 2 modifications were carried out by Patria Aviation, and the MLU 2 preparation work was done in cooperation with the Swiss Air Force. However, the combined effect of MLU 1 and MLU 2 will not extend the airframe's service life from late 2020s. According to the structural analysis, and verified by the recorded measurement data from operational conditions, Finnish Hornets will reach their expected 4500 FH service life without a need for further airframe work as planned. Summary of the wing root fatigue life expended (FLE) of the FINAF F/A-18C/D fleet is presented in Figure 9.

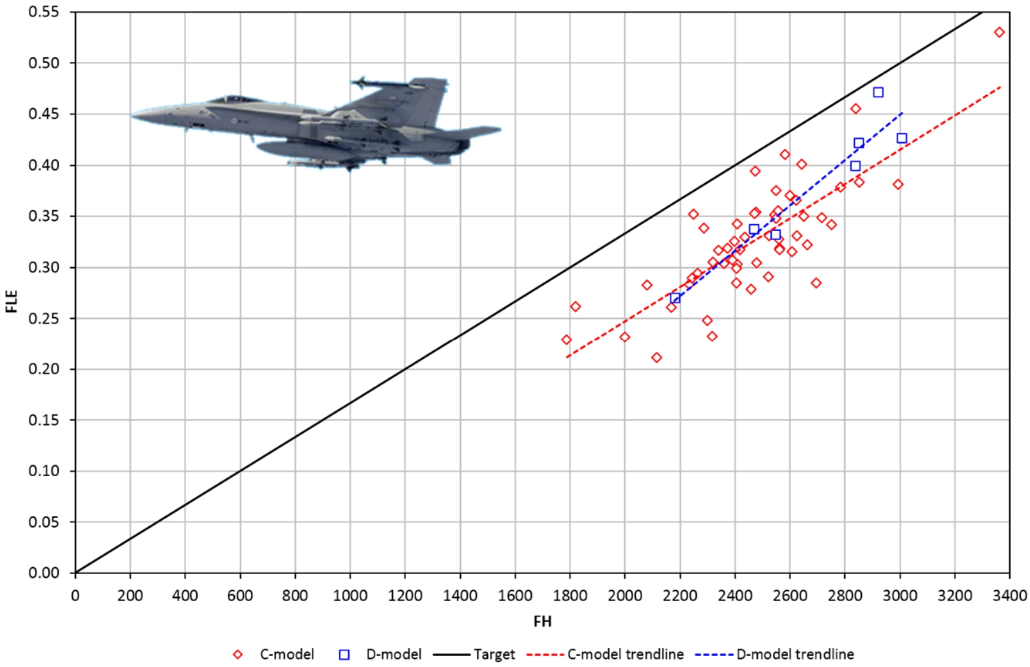

Figure 9: Summary of the left wing root fatigue life expended (LWR FLE) of the FINAF F/A-18C/D fleet at the end of 2016. The data is from all 62 aircraft included. The target is 4500 FH and 0.75 FLE simultaneously. Figure by courtesy of the Joint Systems Centre.

There will be no post-MLU 2 upgrades; the Hornet will not be given any new capabilities. Only updates and modifications that are essential for the maintenance of flight safety and operational performance will be carried out. The Hornet is capable of accomplishing its operations safely and reliably until the mid-2020s. The decommissioning of the Hornet fleet will start in 2025. Phasing out the aircraft becomes a reality when they are about to reach their structural flight hour limits between 2025 and 2030. Then new multi-role fighters to be purchased through the HX Program will replace an obsolescent fleet (see Chapter 1.5). [1], [4]

1.5 HX Multi-role Fighter Program

The planned service life of the Finnish Hornet fleet will end by 2025–2030 as the aircraft reach the end of their 30 year service life. In parallel, the replaced capabilities must be phased in and be in full operational service in 2030. There are three major factors that limit the service life of the fleet: weakening comparative capabilities, structural fatigue and challenges in obtaining system support for the aircraft. Substantial additional costs would be incurred in case of the service life of the Hornet fleet would be extended. Moreover, this would not provide additional options for replacing its capabilities: it is not possible to replace the operational capability of the Hornet fleet with anti-aircraft weapons or unmanned aircraft alone since both systems would only cover a part of the capabilities of the Hornet aircraft. [5], [6]

Extending the lifespan of the F/A-18 Hornet into the 2030s, contrary to the present plans, would increase expenses in life-cycle management and increase the cost risks of system support. The relative capabilities of the Hornet fleet will degrade in the 2020s and the most significant degradation falls on its interdiction capability. Extending its structural life and implementing a new, sizeable midlife upgrade would make it possible to delay the decision to replace the Hornet capabilities by five years, at most. It is estimated that the capability would be fully available no earlier than eight years after the financial decision is taken. As a result, extending the service life of the Hornet fleet is neither a cost-effective solution nor would it be sufficient in terms of Finland's defence.

The aim of the HX Fighter Program is to replace the operational capability of the Finnish Air Force F/A-18C/D fleet in the most cost-effective manner to Finland's state economy. The capability, which will be created through the procurement, must be viable for at least 30 years, and it must be constantly sustained and developed. The HX Multirole Fighter Program will take about 15 years to complete as presented in Figure 10. A Request for Information (RFI) and Request for Quotation (RFQ) precede the actual procurement. After sending RFIs to the aircraft manufacturers or to the authorities administering the defence industries in their countries in February 2016, the procurement will proceed as follows:

- Responses to RFIs[1] 10/2016
- Promulgation of RFQs[2] 02/2018
- Tenders 02/2019
- Contracts 02/2021

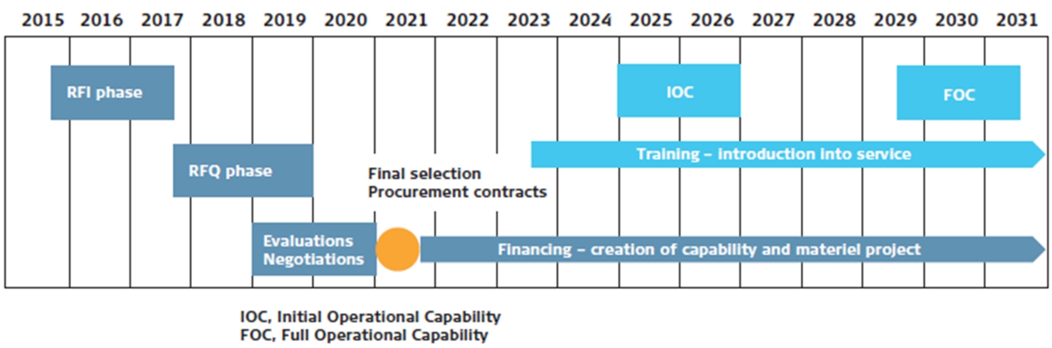

Figure 10: HX programme schedule. [6]

The final selection, i.e. the procurement decision, must be made in such a timetable that the preconditions for signing the procurement contract are in place at the beginning of 2020s.

1 RFI: Request for Information
2 RFQ: Request for Quotation

1.6 Scope of the review

This national review on aeronautical fatigue concentrates on the fixed wing aircraft inventory of the FINAF related to fighter aircraft and associated pilot training aircraft. Today, the FINAF inventory ncludes 62 F/A-18C/D Hornet fighters, 8 Hawk Mk.51, 7 Mk.51A and 16 Mk.66 jet trainers, and 27 Valmet Vinka primary trainers. During the writing of this review, approximately 158 000 FH have been flown with the Hornets, 255 000 FH with the Hawks, and 179 000 FH with the Vinkas.

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

The severity of the Finnish usage in view of structural fatigue with the aircraft of noteworthy maneuvering capability can be seen in Figure 9 (Hornet). Figure 9 clearly demonstrates the need to maintain, further develop and apply concrete and systematic efforts to cope with the structural deterioration effects of these two aircraft types.

During 2005, the International Committee on Aeronautical Fatigue and Structural Integrity (ICAF) formally welcomed Finland as a full member of the ICAF, making Finland the 13th full member. This Finnish national review of current aeronautical fatigue investigations up to March 2017 – although the 9th review but the 7th review as a full member – was compiled by Tomi Viitanen, Piritta Varis and Aslak Siljander (VTT).

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Patria	Patria Aviation Oy, Lentokonetehtaantie 3, FI-35600 Halli, Finland (http://www.patria.fi/).
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TUT	Tampere University of Technology, Mechanical Engineering and Industrial Systems, P. O. Box 527, FI-33101 Tampere, Finland (http://www.tut.fi/en/home).
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2 Current activities: ASIMP 2013-2016 and ASIMP 2017-2020

The Aircraft Structural Integrity Management Program (ASIMP) 2013-2016 with its various sub-programs [2] has progressed according to the plans. An attempt is provided below to provide highlights of the ASIMP 2013-2016 achievements, including those from the parallel research programs.

2.1 Loads and stresses

2.1.1 Developments in helicopter flow simulations at Patria Aviation

This section describes the CFD work done at Patria Aviation in co-operation with Finflo Ltd. In the ICAF 2015 report (Chapter 13.2.1.1.1 of Ref. [2]), helicopter CFD work aimed at modelling the flowfield around NH90 fuselage was described. The basic helicopter model created at Patria consists of 99 structured grid blocks and around 17 million cells covering the fuselage, and the main and tail rotors are modelled as actuator disks using additional overset blocks. By 2015, the interactive actuator disk modelling based on momentum and blade element theories was completed and partially validated against published data from the EU research project GOAHEAD.

During 2015, the NH90 flow simulation capability was expanded by creating three additional versions of the helicopter model, because NH90 often flies with open doors. The first of the new versions represents the helicopter with a removed rear ramp, the second one includes open sliding doors on both sides, and in the third version just the right side door is open and the winch fairing is added above it [7]. All of these models include an approximate fuselage interior to enable air flow through it. The extra features increased the number of grid blocks at most by 24 and the number of cells by 1.5 million. The new versions were tested with the FINFLO RANS solver in different flight conditions to verify their applicability. An example of the NH90 in fast cruise with both side doors open is shown in Figure 11.

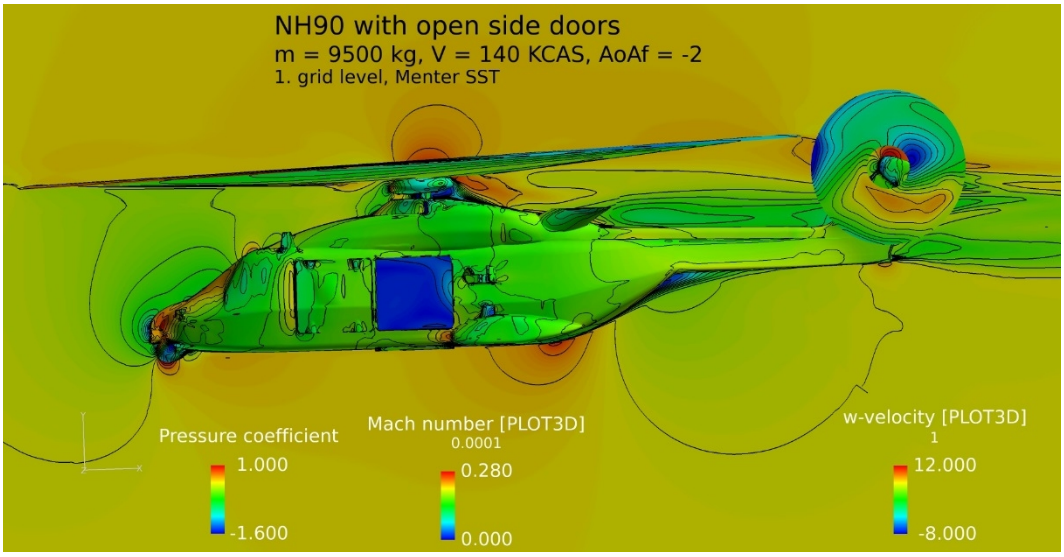


Figure 11: Flowfield around NH90 at fast cruise with both side doors open as computed by FINFLO applying its current actuator disk rotor modelling. Figure by courtesy of Patria Aviation.

In addition to the work concentrating on fuselage flowfield, detailed time-accurate NH90 rotor flow simulations were also recently pursued after a lull of several years. In this work [8], a completely new grid system utilizing overset blocks was created. Each individual blade hinged at its root is modelled by a limited-volume block combination featuring 4 million cells. The large background grid having 11 million cells contains a simplified fuselage model to cover the interference phenomena which affect the rotor flow conditions. In addition, a simple rotating rotor hub and mast stub are included to produce the related flow blockage and wake. In creating the background grid cell distribution, special emphasis was laid on enabling the capture and maintenance of blade tip vortices to model the blade-vortex interactions. The blades are considered as rigid bodies, but they are connected to each other by lag dampers, and the collective and cyclic blade control angles are dynamically adjustable.

The new model for main rotor simulations, shown in the top left corner of Figure 12, was initially tested with FINFLO in a fast cruise condition. The physical time steps of 0.001 s applied in the second-order accurate dual-time stepping simulation correspond to rotor rotational steps of 1.54 degrees, and the rotor thrust averaged over a blade cycle is around 100 kN. The model was proven applicable and the results agree with expectations. An example of an instantaneous flowfield is given in Figure 12 that shows the blade tip vortices in the rotor wake on the symmetry plane of the truncated fuselage. However, the simulations with the 27-million grid system covering several rotor revolutions to reach a steady operational state are quite slow even applying parallelization to 22 processes. For the future work, several items were identified for potential improvements to shorten the time required for such computations.

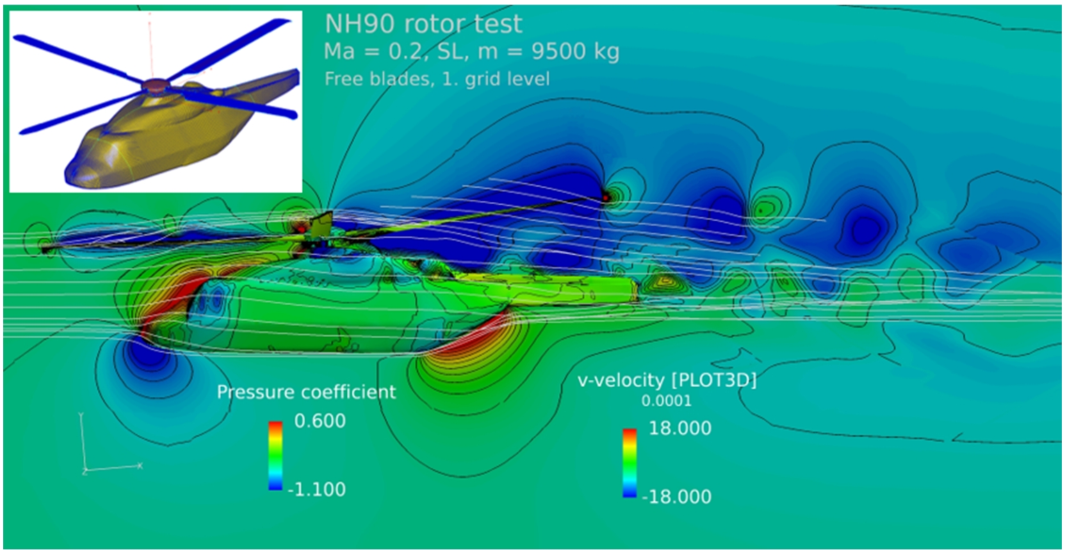


Figure 12: Instantaneous vertical flow speed components in the fuselage model symmetry plane as computed by FINFLO applying the new NH90 rotor modelling. Figure by courtesy of Patria Aviation.

2.1.2 Flow simulation model and computations for Hawk Mk.66

After several years of inaction, a need emerged for applying numerical flow simulations to BAe Hawk of the FINAF. The aim was to predict aerodynamic load distributions for the tailplane in different flight conditions to be utilized in a planned domestic fatigue test of the component. Since the existing CFD model for the Hawk was quite outdated and not applicable to studies with variable tailplane deflection angles, a completely new model was created at Patria Aviation in 2016. In the work, an iges geometry model and the available official drawing set were utilized.

The new Hawk model to be employed in the RANS-type flow solver FINFLO represents the current Mk.66 configuration with its local wing modifications, like the leading-edge fences, vortex generators and the single stall strip per side. The surface grid of the half model and a zoomed view of the wing leading edge area are shown in Figure 13. Currently, only the deflection of the tailplane modelled using overset grid blocks can be easily changed with the other control surfaces fixed at their neutral positions, but a grid improvement to enable straightforward deflections of all control surfaces, including the airbrake, is planned. The new Hawk grid system consists of 98 blocks and about 9 million cells for the half aircraft model that can be applied in symmetric flight conditions. [9]

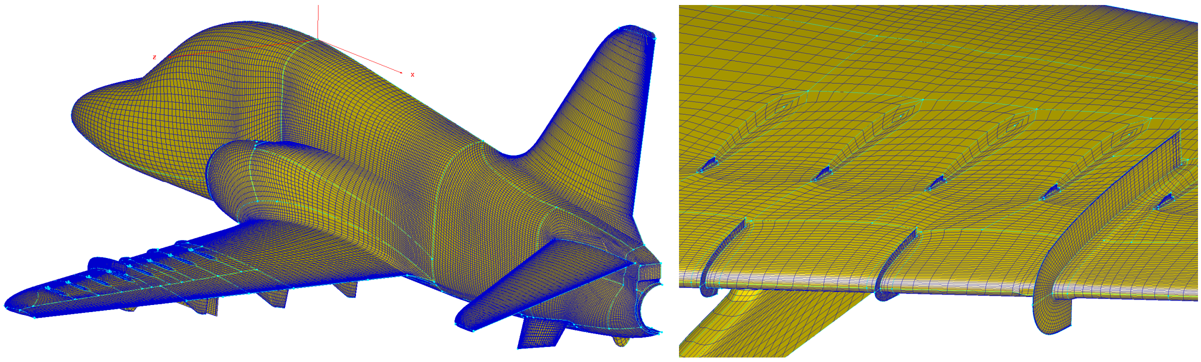


Figure 13: Surface grid of Hawk Mk.66 and a related wing detail. Figures by courtesy of Patria Aviation.

The idea of the related steady-state FINFLO computations was to cover maneuvering at different load factors and Mach numbers. Some of the conditions were to represent flight close to the stall boundary with known fatigue-inducing tailplane buffet and some were more benign steady cases. In all cases, the curvature of the flight path had to be taken into account. The results were to give the time-averaged tailplane load distributions and the location of the wing wake to be able to formulate the dynamic loadings for the fatigue testing with some additional data about the buffet severity.

The actual conditions for the FINFLO studies were determined on the basis of flight test measurements from a specially instrumented aircraft, but the data did not contain the essential tailplane deflections. Therefore, the tailplane deflection was dynamically adjusted during the evolution of each flow solution to obtain zero pitching moment about the selected aircraft center of gravity. The iterative process applied for the first time at Patria eventually gave the required deflection angle as a result along with all the aerodynamic loads. It is appreciated that the applied method contains uncertainties, especially in the transonic flow cases involving flow separation, but at this stage the overall results appear realistic.

An example of the results is shown in Figure 14, where the flow over the wing is illustrated by the pressure coefficient on the wing, a Mach number distribution at a chordwise plane and a total pressure distribution in a plane perpendicular to the aircraft longitudinal axis. The mildly transonic pull-up represents a situation, where the separating wake from the mid-wing behind the stall strip hits the tip of the tailplane, as expected. In addition to the blue flow loss area, the small wakes of the outer vortex generators can be seen in the total pressure distribution. In all the cases studied, the wing wake trajectories predicted by FINFLO seemed to correspond to the knowledge about the occurrence of tailplane buffet which gives some credibility to the numerical studies.

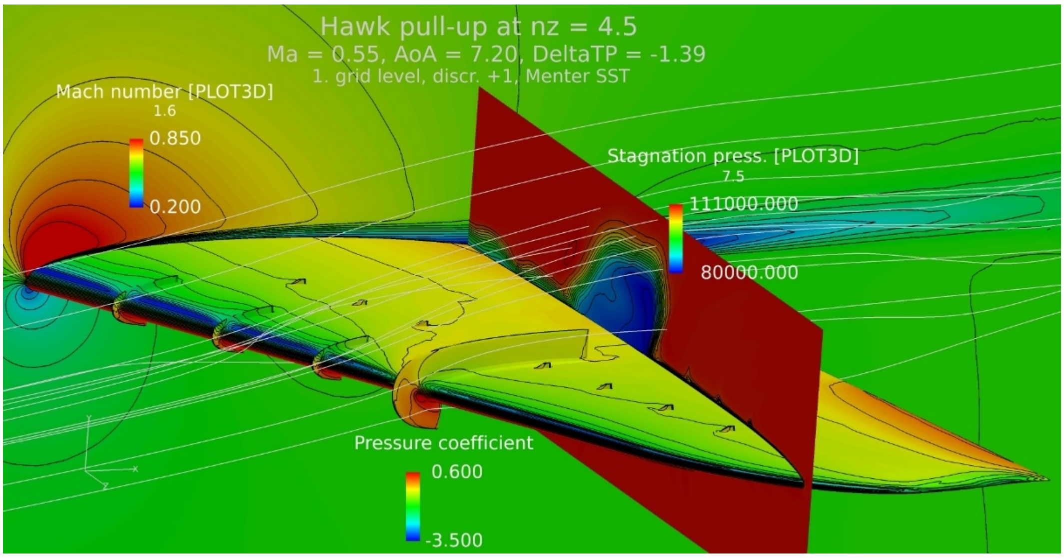


Figure 14: Flow over the Hawk wing in a 4.5 g pull-up involving tail buffet as computed by FINFLO. Figure by courtesy of Patria Aviation.

2.1.3 Computational Fluid Dynamics activities at Finflo Ltd.

Computational fluid dynamics (CFD) research at Finflo Ltd. is based on the in-house flow solver FINFLO. FINFLO is based only on a structured-grid approach, but the interfaces between neighboring blocks can be non-matching or the blocks can overlap each other (Chimera). The Chimera method perfectly suits for describing movable control surfaces and external loads of an F/A-18C Hornet aircraft. Furthermore, a whole moving aircraft can be described using a group of Chimera blocks. [10]

In 2015 and 2016 time-accurate CFD simulations of the F/A-18C Hornet were continued and a renewed simulation procedure was developed. In the new approach the trajectory of the aircraft is described by changing its location and attitude angles. In other words the aircraft is moving along a predefined flight path. The aircraft is connected to the stationary background grid using the Chimera method and a motion of the aircraft generates the flow field. Deflection angles of the control surfaces are also changing during the simulations. The deflection angles are defined along with the trajectory data. Aircraft engines are modelled using appropriate inlet and outlet boundary conditions. A new procedure was also developed for taking into account the grid movement on the inlet and outlet boundaries. In the simulations performed flight conditions were based on measured operational data from actual flights. Data for the trajectories was produced by VTT Technical Research Centre of Finland Ltd and Trano Ltd (see Chapter 2.2.1). A time-accurate simulation with the SST k-ω DDES turbulence model was applied. The time step in the simulation was 0.15 ms (≈ 6667 Hz).

The goal of the CFD simulations is to provide loads for subsequent fatigue analysis. The FINFLO flow solver allows very flexible definition of the force groups on different parts of the aircraft. The time history from these entities can be presented as a function of time or Fourier transforms can be done. As an example of the frequency domain analysis, the Fourier transformation for the aerodynamic force of the vertical tail in the particle body coordinate system (y-direction) is presented in Figure 15.

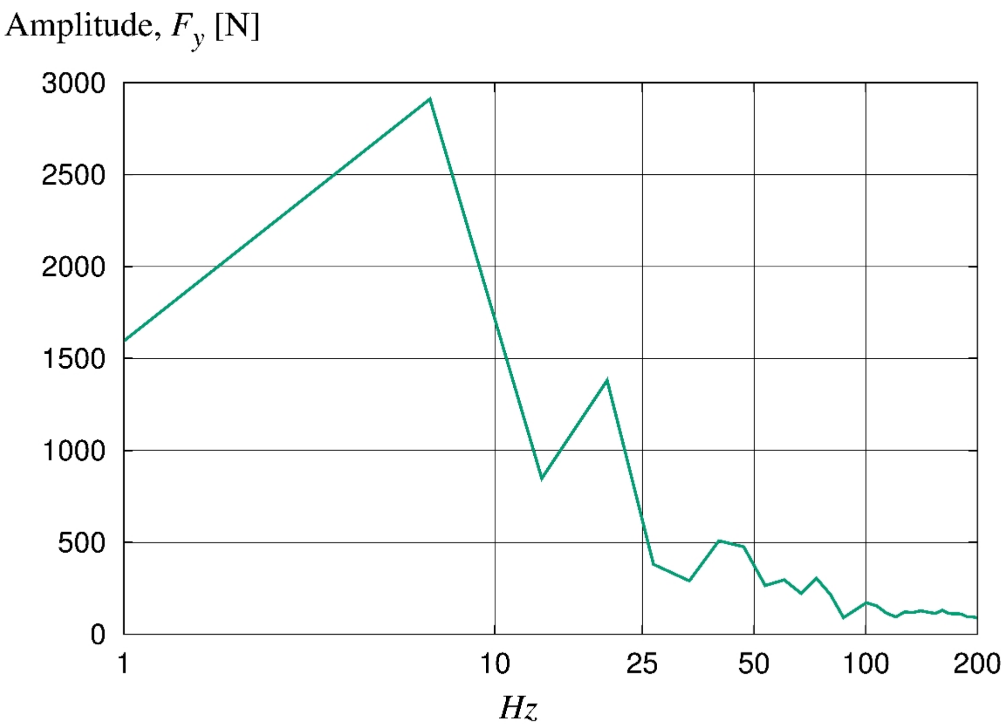


Figure 15: Fourier transformation for the aerodynamic force of the vertical tail in a pull-up case. Flight parameters are Ma=0.64, α=15.7° and n_z=5.9. Figure by courtesy of Finflo Ltd.

Another visualization in Figure 16 depicts the vorticity structure in the proximity of the airplane. In the future, aerodynamic forces and moments will be compared to the measured flight test data. At the moment deformations of the structures have been ignored and this incompleteness will also be corrected in the future.

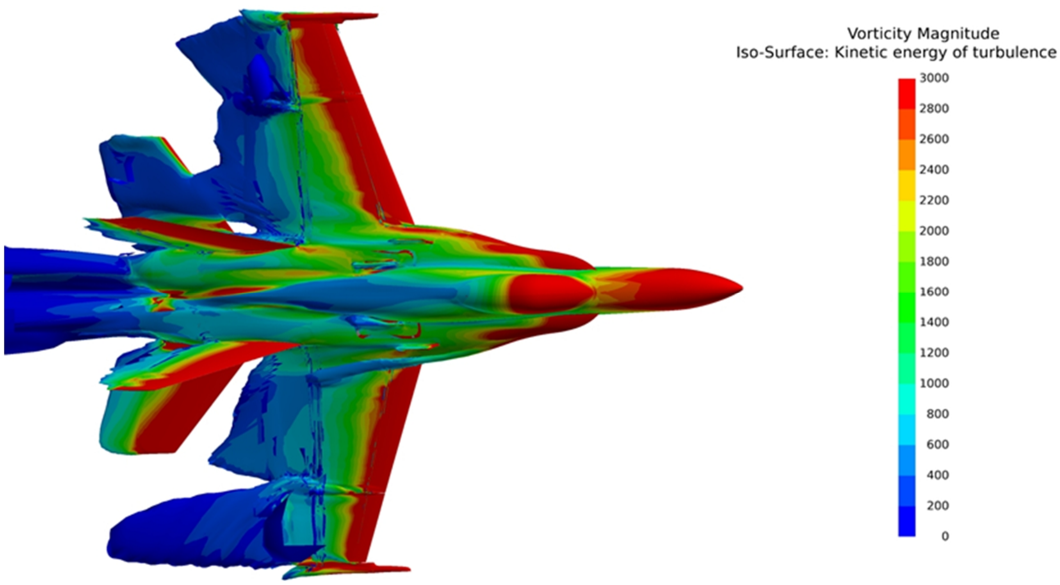


Figure 16: An iso-surface of the kinetic energy of turbulence colored by the vorticity magnitude in a roll case. Flight parameters are Ma=0.58, α=2.1° and p=220°/s. Figure by courtesy of Finflo Ltd.

2.1.4 Hornet FE modeling - update

Previous development phases of the global and detailed finite element (FE) modeling of the FINAF F/A-18C Hornet have been outlined in [2] Chapter 13.2.1.2. Since then no new FE models have been prepared, but some re-analyses with the existing FE models were performed to determine the effects of the structural modifications in the FINAF F/A-18 Structural Refurbishment Program (SRP) on the HOLM strain gage transfer functions used for life estimation [11]. These structural locations were: Bulkhead Y488 MLG Well Area and Engine Door Frame Y657 (with Boron fiber composite patches, Figure 17), and Upper Outboard (steel strap) and Upper Inboard (enlarged critical radius) Longerons. In addition to transfer function changes, the effects of the SRP modifications on the Life Improvement Factors (LIF) due to the Ion Vapor Deposition (IVD) removal, polishing, shot peening, cold working and interference fit fastener, and the effectivity of removal of damaged material (e.g. due to oversize fasteners) were considered for all fatigue tracking locations. The life estimation effects of SRP modifications are taken into account in the Parameter based fatigue tracking system for each aircraft and each tracking location according to actual date of enforcement of modifications (see Chapter 2.2.6).

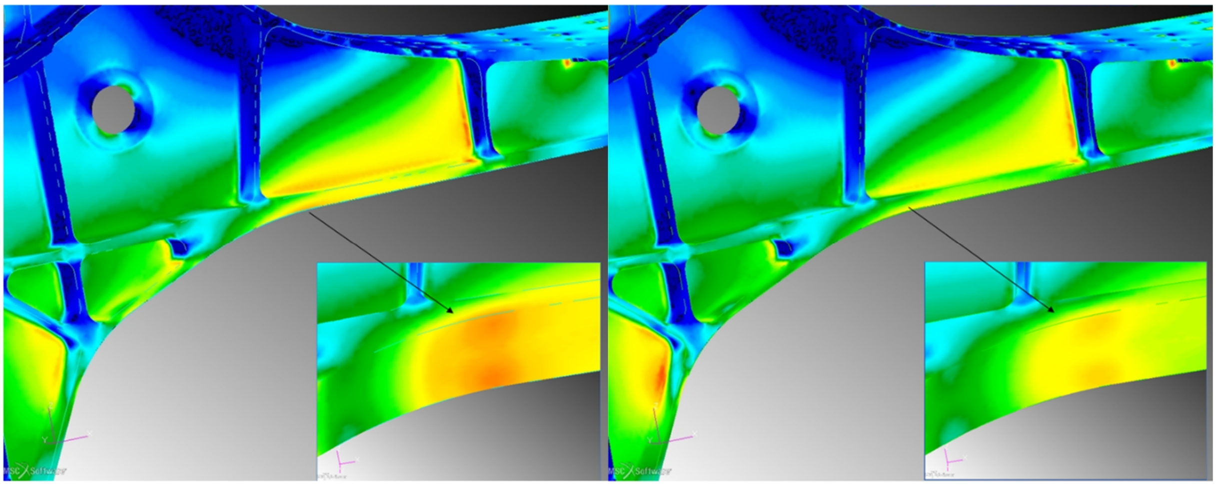


Figure 17: Bulkead Y488 max principal stresses at 6 g steady state pull-up (SSPU) with original structure (left), and with boron fiber reinforcement (right) . Figure by courtesy of Patria Aviation.

2.2 Fatigue tracking systems

2.2.1 The FINAF HOLM aircraft in routine squadron service

The Finnish Air Force (FINAF) has routinely been running the Hornet Operational Loads Measurement (HOLM) program since 2006 [12]. The goal in this program is to quantify the effects of operational usage on the structure of the F/A-18 Hornet aircraft and thus support the national aircraft structural integrity efforts. The idea is that the recorded structural response information from a couple extensively instrumented aircraft can be merged with data obtained from Neural Network (see Chapter 2.2.6) such that it will be possible to evaluate the structural life consumption of the whole Hornet fleet with adequate reliability. The HOLM program employs two Boeing F/A-18C Hornet aircraft (HN-416 and HN-432) with originally identical, but recently diverged onboard data acquisition systems and instrumentation (see Chapters 2.2.2, 2.2.4). Strain sensors have been fitted on globally important locations as well as in the vicinity of structural locations addressed to be fatigue critical. The optimized sampling rates of the strains vary from 1280 Hz in the highly vibrating locations (Vertical Tail) to 640 Hz elsewhere. The sampling rate of the acceleration transducers is 2560 Hz.

The onboard HOLM instrumentation is periodically calibrated by VTT. The annual electrical calibrations of HN-416 and HN-432 reveals if any changes in the measuring chain have occurred or if the calibration coefficients need to be adjusted. Based on the calibration results, the quality of the system has remained outstanding: the quality of the strain signals is good and all the recordable strain data has been captured (minimal missing data). This all forms a solid base for all the analyses that are made based on the HOLM data. [13], [14], [15]

To date, VTT has analyzed data from over 2500 recorded flights of the two HOLM aircraft [16], [17]. The extensively covered measurement data is utilized in in-country CFD [18] and FEA activities (see Chapters 2.1.1, 2.1.2, 2.1.3, and 2.1.4), but also as a part of the international F/A-18 cooperation (FISIF): the FINAF have assigned VTT to prepare a HOLM data set i.e. the specific collection of measured data excluding the fatigue analysis results that have been supplied to the FISIF partners and to be used as they see fit.

Since the previous National Review (Ref. [2]), there are neither new nor updated transfer functions within the HOLM damage analysis system at VTT. Compared with the unfinished situation in summer 2015, the system is now up to date [19], but is expecting some updated Bootstrap transfer functions later this year to be implemented to the system (see Chapter 2.2.4).

The strain life analysis consists of thirteen different structural areas including altogether 39 separate transfer functions and fatigue critical locations. The latest considered areas are Stub Y590.500 (updated), Shear Tie Y508.000 (updated twice), and Wing Root Intercostals Y453.000, Y470.500, and Y488.000 (all new). The implementation results have been available to the damage analysis since autumn 2015.

Within the implementation process, almost all of these critical locations can today have benefit from the specific Basic Operational Spectrum (BOS) flight set. This predefined data can be used e.g. to calculate preliminary and indicative fatigue lives prior to the actual flight-specific fatigue analyses including typically all the recorded flights.

In addition to the strain life method, the stress life analysis is also used, but directly at the strain gage instrumentation locations [20]. To achieve more usable results in the future, the commissioning of the damage tolerance analysis methods is ongoing.

The HOLM fatigue analysis database has been updated [21]. The database works seamlessly with the data from the HOLM ground analysis environment. In addition to data from the fatigue tracking system the database includes all the needed information from the data analysis process. Also, the calculation of the center of gravity location of the HOLM aircraft has been taken in use in the HOLM ground analysis environment [22].

2.2.2 Strain and acceleration survey after MLU 2

The instrumentation of both HOLM aircraft, HN-416 and HN-432, was extended during the MLU 2 modification. Both HN-416 and HN-432 got 8 new strain sensors and 4 acceleration transducers. In addition, two of HN-432 strain sensors were relocated. The accumulated data from the newest channel additions of the HOLM system was checked in the end of year 2016 by VTT. Especially the channel ranges were checked with respect to the current calibration limits to see if the set limits would still be valid for the measured data that had been stored since June 2013 (HN-416) and October 2014 (HN-432) when these new channels started accumulate data.

It was concluded that the calibration limits were sufficient with respect to the occurred min/max values during the flights. It was also noted that the applied structural reinforcements (composite reinforcements) during MLU 2 were functional as the strain gages measuring these fatigue critical structural details showed principally decreased strain values, as expected. [2], [23], [24].

2.2.3 Study of buffeting induced fatigue damage

Buffeting is an unsteady aero-elastic phenomenon caused by a separated flow on the aircraft at high incidences. The unsteady vortices in the separated flow originates from the front details of the aircraft hitting the center/aft section of the airframe excite the elastic vibration modes of the structural components therein. The resulted high-frequency excitation loads can induce airframe fatigue problems.

As a part of the HOLM measurement data utilization the FINAF assigned VTT to determine how much the calculated fatigue damage of the dynamic part of the strain signal contributes to the overall fatigue damage in the Center Fuselage of the F/A-18C aircraft in the Finnish usage. The results will be reviewed against the findings in the OEM's Fatigue Test ST16 in which the loading did not include the high-frequency components. The high enough sampling rate of the HOLM instrumentation made this kind of study possible. The idea was to differentiate the low-frequency (deterministic, maneuver induced) and the high-frequency (stochastic, buffeting induced) signal content from each other, and calculate fatigue damage for the full (raw) signal and the low-pass signal. The fatigue damage of the high-frequency buffet data resulted as a difference between these two. It should be noted, that the purpose was not to evaluate the absolute life estimates from the raw and filtered signals but their relative percentages instead. [25]

The study was realized of the low-pass filtering of the strain signals. The proper cut-off frequency was defined as per the lowest fundamental frequencies evaluated from two distinct flights having notably different stores configuration in order to view the mass effect on the fundamental frequencies.

The flight-by-flight basis fatigue damage calculations were based on the stress-life (SN) method, using Rainflow cycle counting, constant hysteresis value (to reduce the analysis duration), and Palmgren-Miner linear cumulative damage hypothesis. The effect of mean stress was taken into account by log-log interpolation of the used, material-specific, SN-curve. As the quotient-based results were highly sensitive and dependent on the absolute values it was decided to exclude damage values less than $1 \cdot 10^{-6}$ (1 µD, "microdamage").

It was concluded that the rationality of the results were as expected: the calculated buffeting induced fatigue damage of the more flexible structural components (longerons) was greater than that of the stiffer structural parts (bulkheads). The calculated dynamic part of the strain signal contributes on average 10…45 % to the overall fatigue damage in the locations in question. The lowest percentages occurred in the lower section of the main bulkheads. The highest values occurred in the left and right hand side upper outboard longerons in the vicinity of the first attachment formers of the Vertical Tail. This can be thought as a result of separated flow feedback from Vertical Tail back to the fuselage.

2.2.4 Bootstrap instrumentation on HN-416 aircraft

One of the existing fatigue-prone structural area among the international F/A-18A/B/C/D Hornet users is so-called Bootstrap area in the aft fuselage. The Bootstrap supports the horizontal tail actuator unit in between the Formers Y615.000 and Y645.850, and is classified as Fatigue Critical (FC) item. Although the HOLM instrumentation system is quite extensive, it does not cover well this specific area and therefore cannot - in its original form - support the structural integrity of the location.

As a part of international cooperation, the FINAF assigned Patria Aviation and VTT to modify the existing HOLM instrumentation system on HN-416 such that it will cover also the structural area under interest. The objectives of the HOLM instrumentation modification are: 1) to provide in-flight strain data with adequate sampling rate, and 2) to provide static measurement data from ground calibrations for Finite Element Analysis (FEA). The placement of the sensors were selected intentionally to maintain compatibility with the other Hornet users' previous measurements. The modification and calibrations are ongoing and will be completed this spring. The recorded data from new locations will be exploitable later within the international F/A-18 Hornet users' community (FISIF).

The instrumentation modification is related solely to strain sensors. Due to scheduling constraints, only minimal changes to the original HOLM instrumentation were possible. This meant minimal changes to the HOLM wiring and that some of the legacy strain sensors were deactivated and relocated, and some temporary strain sensors were exclusively installed during the mechanical calibrations. The modification resulted a total of 5 permanently installed and 11 temporary installed strain sensors, as illustrated in Figure 18.

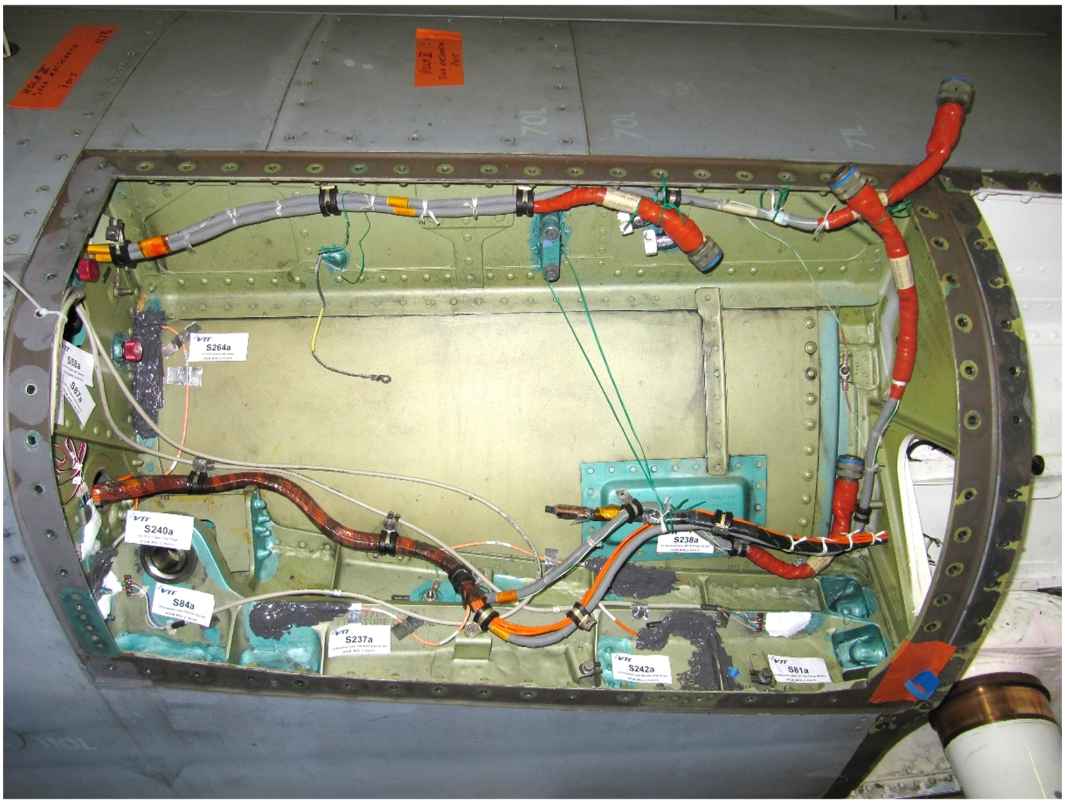


Figure 18: The Bootstrap area instrumentation on left hand side of the HN-416 aircraft. Lower right is shown the horizontal tail spindle assembly. Figure by courtesy of VTT Ltd.

Electrical (shunt) calibrations were performed for the set of permanent and temporary strain sensors before mechanical calibrations. After that, mechanical calibrations were executed for left-hand and right-hand sides with specifically designed tool which can provide bending and torque through the horizontal tail attachment point (i.e. spindle) as shown in Figure 19. Finally, the electrical (shunt) calibrations will be executed before the new HOLM measurement system is ready to fly.

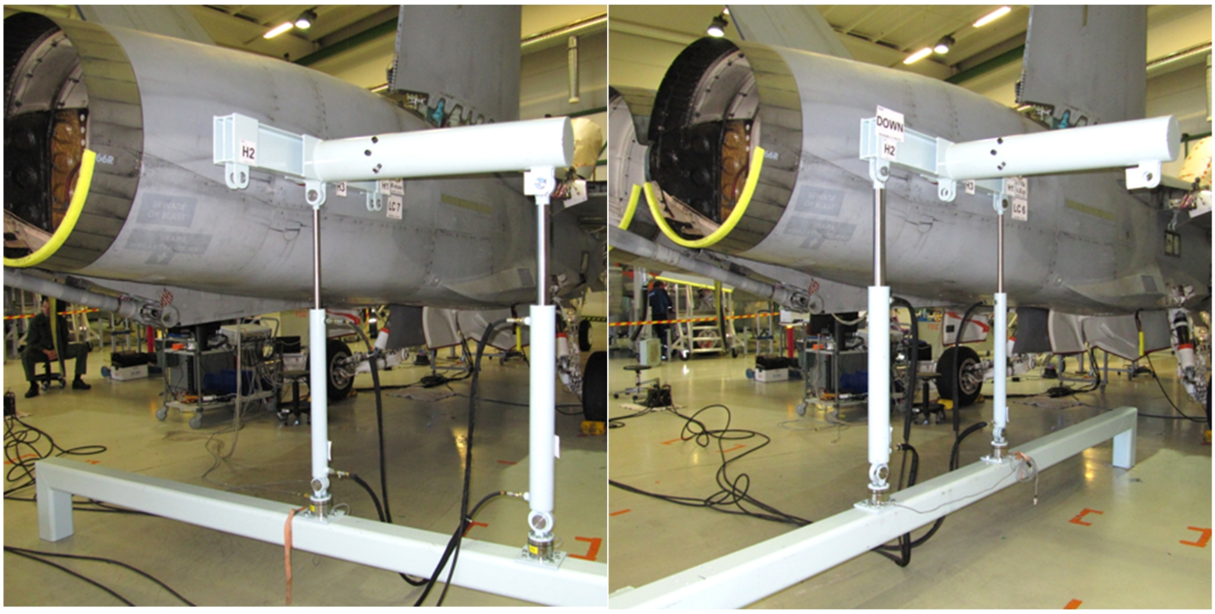


Figure 19: Mechanical calibrations of the HN-416 Bootstrap area. The tool providing bending (left) and torque (right) is manufactured by Patria Aviation. Figure by courtesy of Patria Aviation and VTT Ltd.

2.2.5 Basic Operational Spectrum ver 2 (BOS2)

To support the FINAF F/A-18 fleet ASIP work, a representative FINAF F/A-18 usage spectrum (BOS2) was compiled in co-operation with VTT and Patria during 2016. [26], [27]

When the original BOS version was created, it was noticed that the distribution of flight hours per Flight Purpose Code (i.e. Sortie Profile Code) is well presented if the damage rate is taken into account in three instrumented structural assemblies: Inner Wing Fold (aft spar shear tie), Center Fuselage (lower flange of the Bulkhead Y488.0) and Vertical Tail (stub outer flange of the Former Y590.5).

The aim with the BOS2 spectrum generation was that it would be more representative in terms of both flight loads and flight parameters for the entire Hornet fleet in normal operation than the original BOS version. The recorded flight data of both instrumented HOLM aircraft was utilized in this spectrum update with their newest calculated damage values from the HOLM ground analysis environment. The FINAF reference mission mix remained the same in the BOS and BOS2.

The BOS2 flight set contains 161 selected flights of the HOLM aircraft (64 flights of HN-416, 97 flights of HN-432) resulting a total of 140 FH. During the selection of the BOS2 flights, the content and severity of the candidate flight set was compared with the FINAF F/A-18 fleet whole usage and the last five year's usage (09/2010 - 08/2015). The rationale of the selected BOS2 candidate flights were verified against the flown flight mission distribution of the rest of the FINAF F/A-18 fleet at Patria Aviation by the OEM's fatigue tracking software SAFE (Structural Appraisal of Fatigue Effects). The comparison was executed by the SAFE's reporting feature including aircraft configuration usage, Nz exceedances, flight time in Vertical Tail/Horizontal Tail/Trailing Edge Flap/Aileron buffet areas (time spent in a proper AoA-Q table bin) and Wing Root FLE Rate (FLE: Fatigue Life Expended). Based on the comparisons the compiled BOS2 spectrum was considered as a reasonable representative of FINAF F/A-18 fleet whole usage and noticeably more severe than the last five year's usage.

As the HOLM aircraft records data with high frequency (HOLM strain gages @640/1280 Hz, VT accelerometers @ 2560Hz, and all flight parameters @20 Hz), the BOS2 spectrum HOLM recordings provide extensive data for a variety of studies about the FINAF usage.

The BOS2 spectrum will be further updated to include the MLU 2 instrumentation and the newest flights as well as the mission mix will be updated by the FINAF. [28]

2.2.6 Parameter based fatigue life analysis - update

Previous development phases of the parameter based fatigue life analysis system have been presented in [2] Chapter 13.2.2.2. The technical background of the analysis is comprehensively explained in Ref. [29]. A presentation of the current status, usage and experiences of the monitoring method for FINAF fleet management is found in the Symposium presentation, in Ref. [30].

The parameter based fatigue life analysis is an individual aircraft fatigue life monitoring system developed for the FINAF F/A-18 Hornet fleet by Patria Aviation. The analysis utilizes flight parameter data, stored by standard aircraft systems, and artificial neural networks (ANN) to produce flight-specific fatigue damage estimates. The fatigue damage estimates are calculated for 17 structural locations, each consisting of 1-3 features (e.g. 3 fastener holes in the same structure). The findings give a general view of Fatigue Life Expenditure (FLE) in the fuselage, wing and tail areas and, also provide FLEs of the structural details for each aircraft. This enables arranging tail numbers into FLE order (ascending/descending) for any structural location for scheduling repairs, inspections and structural part replacements. The method is illustrated in Figure 20.

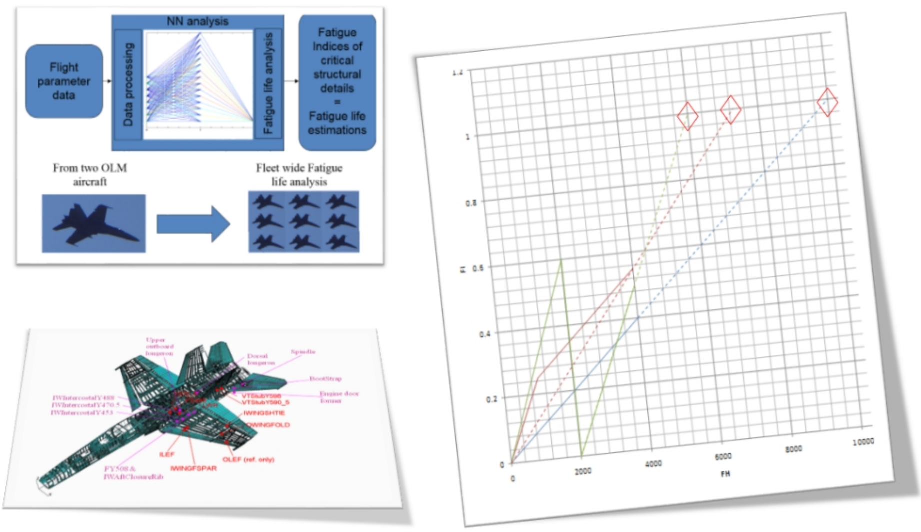


Figure 20: Schematic of the applied monitoring method. Figure by courtesy of Patria Aviation.

Since ICAF 2015 [2] the coverage of the Parameter based analysis has been improved by running the analysis for FINAF F/A-18 fleet flights between 2008-2014 [31], so the analysis now covers flights for years 2000-2014. Also, early flights from 1995 to 1999 are planned to be analyzed in the future. The coverage of the structural locations (17) is already extensive but new needs might always emerge. In 2015 the capabilities of the analysis system were also extended to take into account the effects in life estimation due to the FINAF SRP modifications (changes in transfer function values and LIFs and removal of damage) for each aircraft and each tracking location according to actual date of enforcement of the FINAF F/A-18 SRP modifications (see Chapter 2.3.1) [32], [33].

2.2.7 Research efforts towards Hawk structural integrity management

2.2.7.1 Hawk Mk.66 mini OLM activities

The FINAF flight training syllabi have changed significantly in the past years. For example, glass cockpit modification (see Chapter 1.3) enables practising some training flights with the Hawk aircraft which earlier were flown solely by the Hornet. These changes may reduce the life of some critical structural components or locations well known from the older FINAF Hawk Mk 51/51A fleet.

To study the fatigue behavior and to estimate the structural life of the FINAF's Mk.66 jet trainer fleet, a decision was made by the FINAF to instrument one Mk.66 jet trainer (HW-368) with temporary onboard measurement system, as reported in Chapter 13.2.2.3.2 of Ref. [2]. The purpose of the onboard measurement system was to provide information about structural loads in different flight conditions, and to provide data for the creation of an average usage spectrum of the FINAF's Hawk fleet. In spring 2015 one Mk.66 jet trainer was instrumented by VTT and Patria Aviation with a mini OLM (Operational Loads Measurement) system. The system consisted of ten strain gauges. Three strain sensors were installed in the tailplane, one sensor in the vertical fin root and two sensors in the rear fuselage frame to measure tail loads. Two strain sensors were installed in the centre fuselage to measure loads induced by fuel tank pressure and fuselage bending. Two strain sensors were installed in the wing root to measure wing bending.

The test flight measurements were carried out during autumn 2015 as a collaboration of the FINAF, Patria Aviation, and VTT. A total of 14 test flights were flown. Fatigue damage estimates were calculated by VTT for each of the mini OLM flights. The flight test programme was successful and reached its goals: Time schedule for the structural repair works needed for the FINAF Mk.66 fleet was created based on the fatigue analyses with the measured data. Also initial data for neural network was obtained.

After the mini OLM flights were flown, the FINAF decided to continue the recording of flight data on the instrumented HW-368 aircraft. From the end of the year 2015, the FINAF has delivered flight data continuously to VTT for basic data analysis. The basic data analysis consists of downloading the measured data into the ground analysis environment, data format conversions, supplementing the data with flight report information, data quality checks, and storing the data for further analysis. To date over 200 flights have been recorded and analyzed. The collected flight data has been used e.g. to create the fatigue spectrum for the tailplane fatigue tests (Chapter 2.3.3.2).

The recording of the Hawk Mk.66 flight data continues, and total count of the analyzed flights is planned to be over 350 by the end of year 2017. In addition, VTT is also prepared for updating the OLM fatigue analyses database and developing tools for converting OLM flight parameter and strain gage data into Matlab data structures that can be utilized in the Mk.66 tail neural network training. [44], [45], [47]

2.2.7.2 Hawk Mk.66 Structural Health Monitoring update

Activities related to the FINAF Hawk Structural Health Monitoring (SHM) investigations were highlighted in the ICAF 2015 report (Chapter 13.2.2.3 of Ref. [2]). The Mk.66's obsolete ESDA (Electronic Structural Data Acquisition) onboard monitoring system was replaced by Emmecon's SHM system prototype (Figure 21) which has an ability not only to measure and store strain gauge data from the structure but also to process the obtained stress data and store it in a Rainflow matrix form in a flight-by-flight basis. The stored Rainflow data can be downloaded directly from the monitoring unit with a laptop computer e.g. during aircraft maintenance.

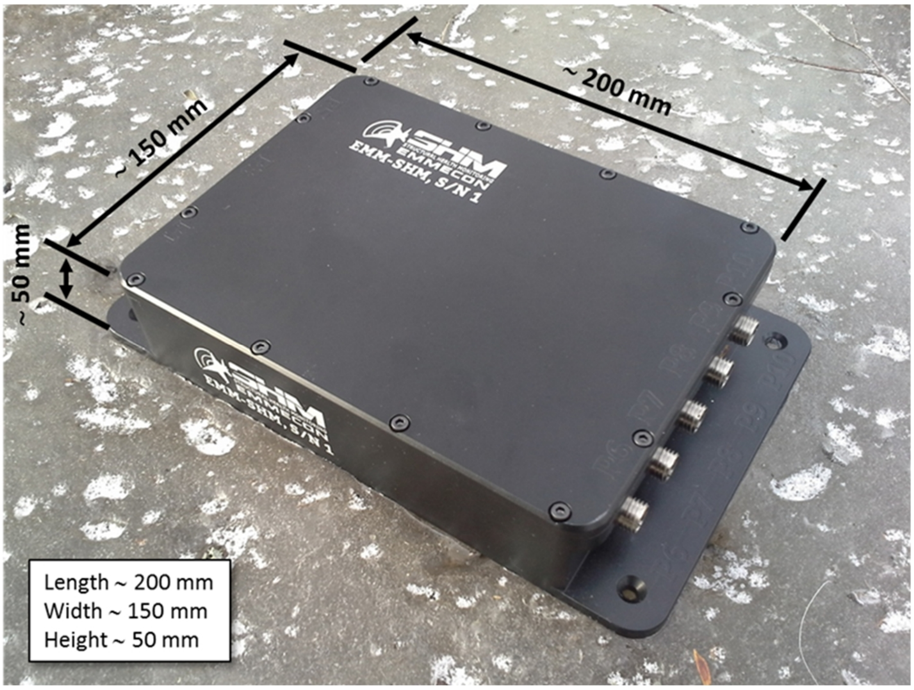


Figure 21: An overview of Emmecon's onboard SHM system. Figure by courtesy of Emmecon Ltd.

In the near future the FINAF Hawks' tail structural integrity shall be tracked by neural network application which uses flight parameter data as an input. The input data will be recorded by the mission data recorder of each individual aircraft. The first neural network was generated during 2016. It will be further developed with flight parameter and strain gauge recordings from two aircraft which shall be instrumented with a EMM-SHM unit, a production version of Emmecon's SHM monitoring unit.

The first EMM-SHM monitoring unit was installed to the FINAF Hawk Mk.66 aircraft HW-360 in autumn 2016 (see Figure 22) and the next two aircraft shall be under installation in the end of 2017 and beginning of 2018. The system monitors three strain gauges in the tailplane and one strain gauge in the vertical fin. One more strain gauge is monitored in the fuselage top longeron to get the aircraft g-load time history which helps synchronise the strain gauge data recorded on the SHM unit and the flight parameter data recorded by the mission data recorder. [44], [45], [46]

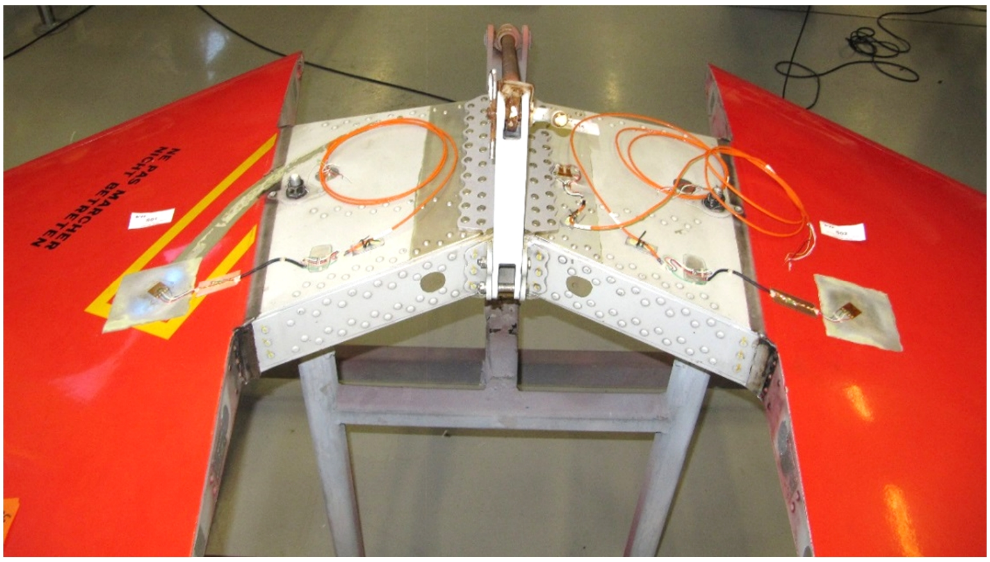


Figure 22: Instrumented tailplane of the Hawk Mk.66 (HW-360), prior to applying wear protection. Figure by courtesy of VTT Ltd.

2.3 Structural integrity of metallic materials

2.3.1 FINAF F/A-18C/D Hornet Structural Modifications

The FINAF F/A-18C/D Hornet fleet structural integrity is managed using an Aircraft Structural Integrity Program (ASIP) which is based on MIL-STD-1530 standard. To achieve the usage life target, several structural modifications must be done. The first Structural Refurbishment Program (SRP1) including 29 modifications was performed between years 2009-2014. Later the SRP1 was supplemented with 11 additional modifications and the new program was nominated as SRP1+ which started 2015 and will be finished during 2018. The SRP1 and SRP1+ modifications have been typical crack preventive modifications which have been performed before reaching analytical Crack Initiation (CI) life. The responsible for ASIP management, modification analysis and modification design has been Patria Aviation delegated by the FINAF.

Based on the ASIP group work, more modifications are needed for the F/A-18 fleet safe usage up to 2030. The Structure Sustainment Program (SSP) was established during years 2014-2016. The SSP includes 40 modifications, 17 On Condition repairs and almost 100 new inspections. At the moment, the first two prototype aircraft are in the modification line in Patria Aviation’s facilities. The whole fleet will be in the SSP configuration at the end of 2021.

Typical for the SSP-modifications is that CI-life for the fatigue critical structural location has been reached before modification. That naturally causes some crack indications and leads to deeper material removals and larger oversize fastener installations than what has been done during the SRP1/1+. The Confidence Cut policy will be obeyed and because of that, Probability of Detection (POD) study (Ref Chapter 2.3.2) for typical SSP flaws has been performed in collaboration with Patria Aviation, VTT, RUAG, FINAF and Trueflaw. The overview of the SRP1, SRP1+ and SSP modification locations is presented in Figure 23 and Figure 24. [34], [35]

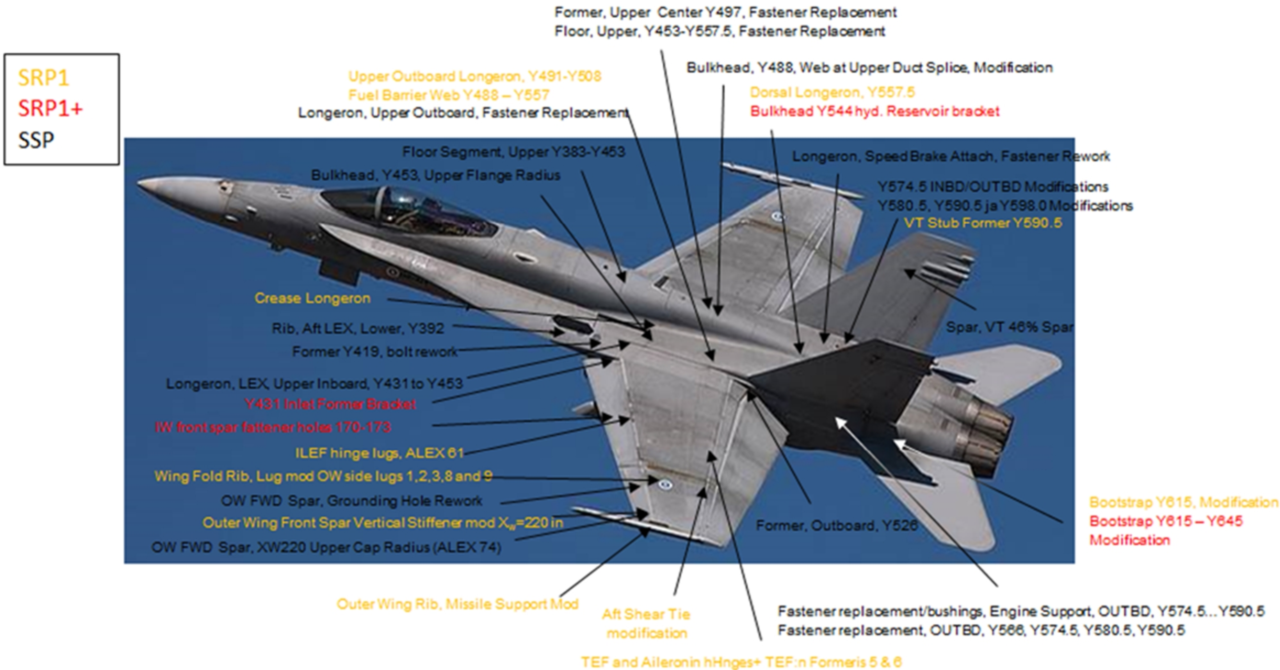


Figure 23: The overview of the SRP1, SRP1+ and SSP modification locations. Figure by courtesy of Patria Aviation.

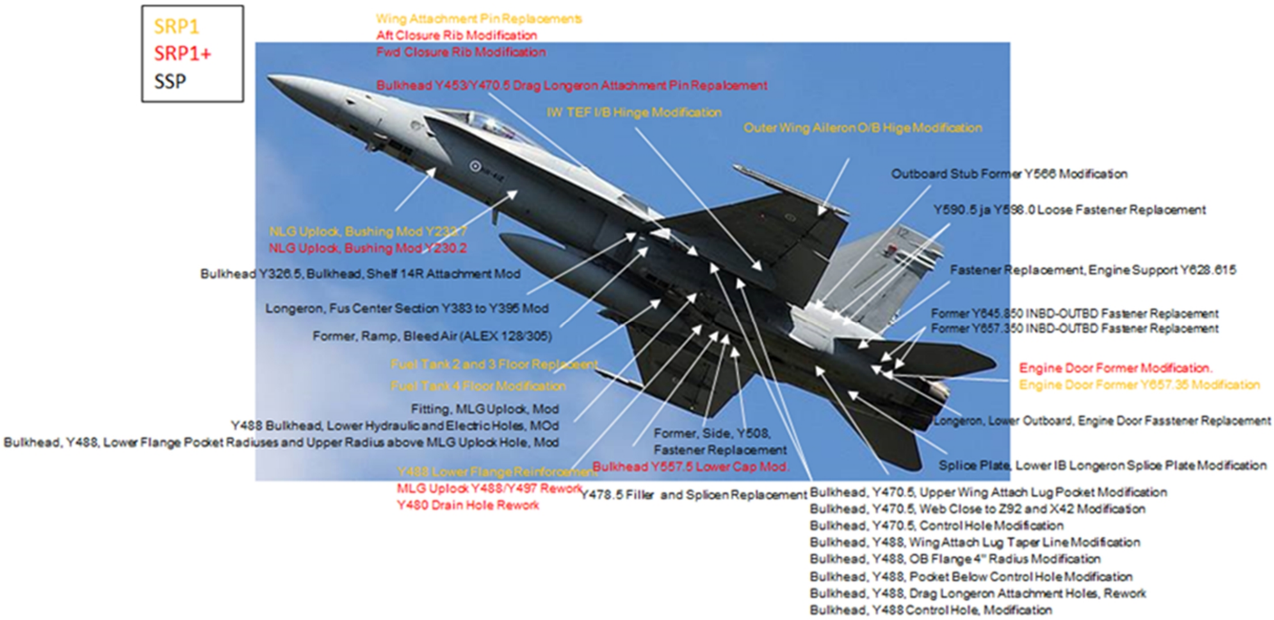


Figure 24: The overview of the SRP1, SRP1+ and SSP modification locations. Figure by courtesy of Patria Aviation.

2.3.2 Probability of Detection in Non-Destructive Testing

Non-Destructive Inspection (NDI) has evolved as a key element to monitor the integrity of structural components, especially in the age of Damage Tolerance. Along the inspection technology it has emerged essential to quantify the reliability or performance of the used NDI method. Therefore a statistical concept called Probability of Detection (POD) has been developed.

It was recognized in Patria Aviation that the performance of the NDT inspections should be defined using an established method instead of relying on subjective estimations based on earlier experience, so that the design of structural repairs and modifications, and the definition of inspection intervals can be based on as reliable data as possible.

Based on this need a Probability of Detection project was established. During the project three test specimen sets representing typical metallic aircraft structural details were inspected with eddy current. One of the sets was Patria's own design revealing the challenges one encounters when trying to make cracks of a desired length distribution.

The results showed that Patria's performance when inspecting holes with a rotating probe were in the assumed level. However, the performance when inspecting surface cracks with a pencil probe was not at the expected level, thus requiring corrective actions. Possible reasons for the indicated performance have been considered to help select corrective actions.

The project has been useful in increasing understanding of different NDT-performance-related aspects throughout the organization. It seems that there are several things which have been known before but possibly only now fully understood. [36], [37], [38], [39], [40]

Patria's experiences on a Probability of Detection project will be presented at the ICAF2017 Poster Session [41].

Other Finnish refrences in this matter can be found in [42] and [43].

2.3.3 Hawk tailplane fatigue life assessment

2.3.3.1 Introduction

As there was no certainty about the fatigue life of the Hawk Mk.51/51A/66 tailplane (Figure 25) in the FINAF operational usage (see Chapter 2.2.7.1), the FINAF initiated in 2015 a full-scale fatigue tests (FSFT) to be performed on Hawk Mk.51/51A/66 tailplane's centre box buttstraps. The FINAF's main objective is to get conclusive results to determine if the FINAF is required to procure additional tailplanes to keep its fleet operational until the planned withdrawal date of the aircraft type. The tailplane's life is determined by its critical structural components: the upper and lower centre buttstrap plates and the centre spar. The tailplane's fatigue life is going to be verified based on the results of these tests.

Figure 25: The FINAF Hawk Mk.51/51A/66 Tailplane (LYK45). Figure by courtesy of the FINAF and VTT Ltd.

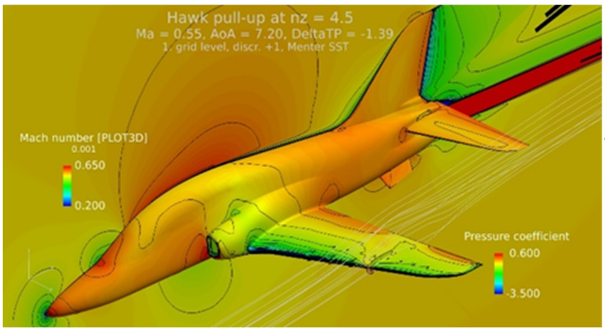
The tailplane fatigue tests will be led by Patria Aviation (prime contractor) and performed by VTT and VTT Expert Services (main subcontractors) during 2016-2017. The tests will be conducted with two tailplane units which both have flown approx. 4 000 FH. The first tailplane has undergone structural repairs during its normal operational cycle and the second item has just been repaired before the test. The tests shall be conducted up to maximum of 10 000 EFH (Equivalent Flight Hours) to be certified for additional 2 000 FH usage with a Scatter Factor, SF = 5. Other ending criteria for the tests is, if a crack, longer than the critical length, appears on the centre buttstraps or the test units are not repairable for other reasons.

The secondary objective is to have data about the crack growth rate which could be utilised to increase the related structural inspection time intervals. This is mainly achieved by means of the periodic NDT inspections during the tests.

2.3.3.2 The current status

The project planning i.e. the design work including strain gauge location drawings, load generation, load distribution and support designs, and manufacturing as well as load spectrum basics were accomplished in 2016.

The aerodynamic resultant load location was analysed with the Hawk CFD and FE models (Figure 26) in four different flight conditions. The aerodynamic loads were transferred to the FE-model and the FSFT loading method was also modelled. The location of the resultant load was selected by criteria of obtaining similar stress distribution in both models. The result corresponded well to the OEM’s determination of the tailplane aerodynamic centre.



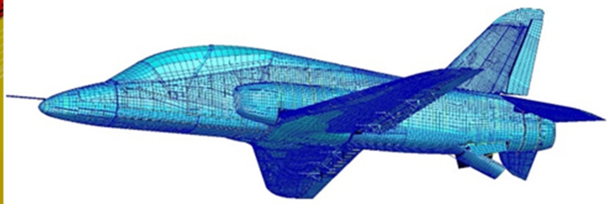


Figure 26: *BAE Systems Hawk Mk.51/Mk.66 CFD (left), and FE (right) models. Figures by courtesy of Patria Aviation.*

The test spectrum is based on i) the strain gauge signal S15 of the two FINAF OLM Hawks: HW-368 (Mk.66) and HW-319 (Mk.51A), and ii) on today's real, flight hour and syllabus based usage spectrum of the FINAF flights. The S15 is located at the top skin of the tailplane centre box.

The Hawk mission mix was received from Patria Aviation and it consisted of distribution of various flight tasks as percentages. The duration of one spectrum block was agreed to be 62.2 FH. As the ground handling time equalled (on average) 10 % of the flight time, the total flight hours were increased to 68.8 FH (as the ground handling would be cut out) and respective hours per each Mission Type were calculated.

The test spectrum was created based mainly on the HW-368 mini-OLM flights. The set was completed with HW-319 flights in case of short-handed or completely missing flight tasks of HW-368. The fatigue damage values were calculated for the selected flights; it was noticed that some of the Mission Types had a fatigue damage effect that was practically zero and these Mission Types (2 flights) were ignored.

Only flights above a certain damage value were taken into account in the final spectrum and of these flights only the part of the flight that had an effect on the damage value was taken in account. In practice that meant that a part was cut out from the beginning and from the end of the recorded flight. The spectrum block is equivalent to approximately 68 FH, and divided to equal number of test blocks determining the accuracy of lifetime of the test article.

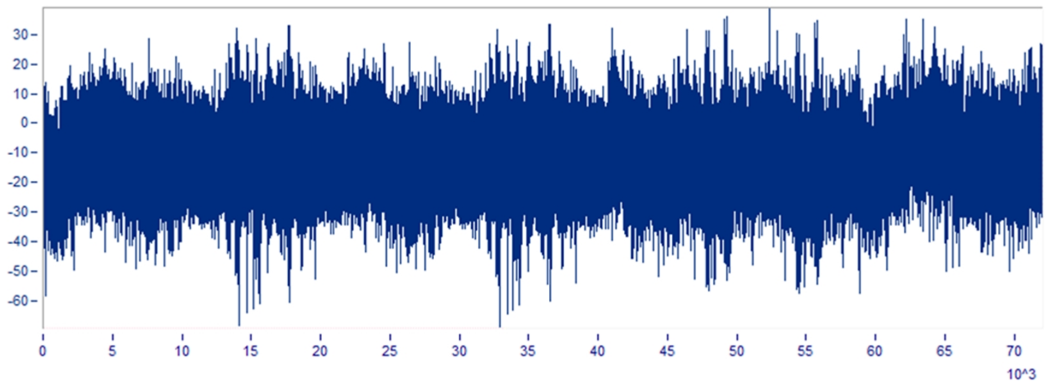


Figure 27: *Starting point for the actual test spectrum generation (turning points, S15 [MPa]). Figure by courtesy of VTT Ltd.*

The developed spectrum is not a general Basic Operational Spectrum (BOS, see Chapter 2.2.5), like e.g. the FINAF's F/A-18 Hornets have. This is, because it is further edited (and calculated with stress life analysis) to match the needs of the FSFT's command system, and to make the iterations and fine tuning of the actuator loads and displacements possible.

The tests are installed under 2 MN portal loading frame, and the tailplanes are attached to the custom made test bench manufactured by KTS-Mekano Ltd. (Figure 28 and Figure 29). This bench is bolted on the structural test floor with anchorage points, whose dynamic capacity is ±400 kN each in the horizontal and vertical direction. The tests have two symmetrically mounted 50 kN servo hydraulic actuators, and also their loads are always kept symmetric.

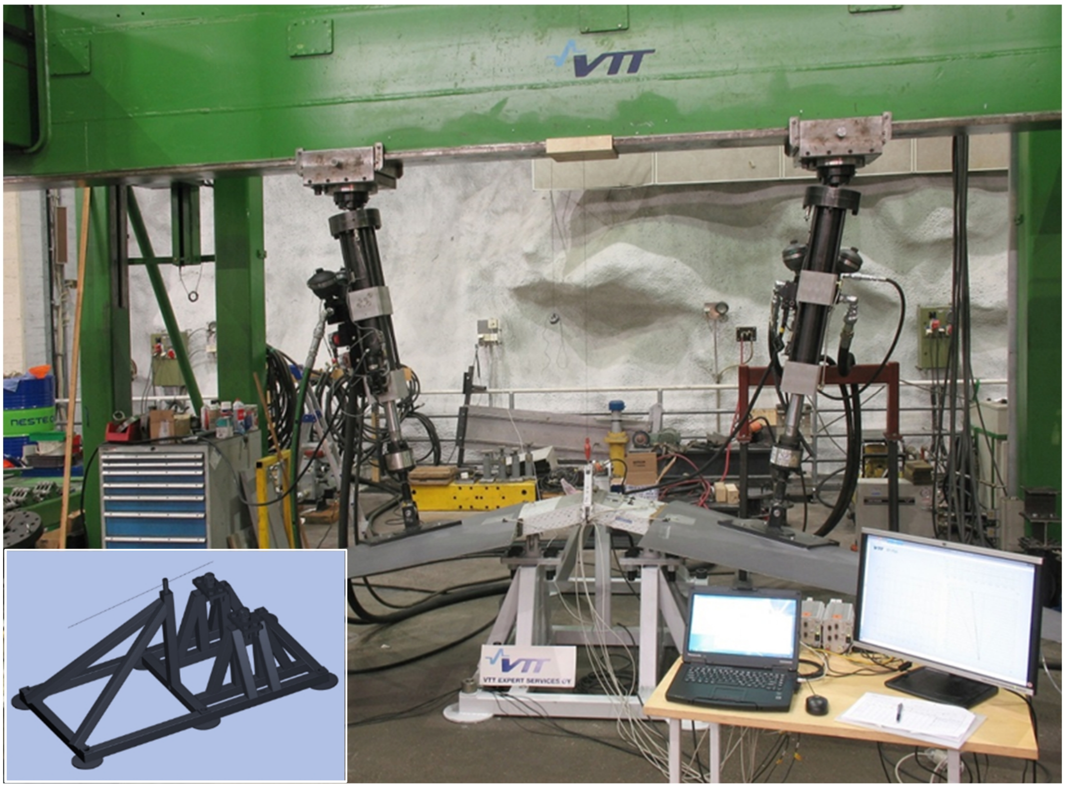


Figure 28: The test bench drawing (KTS-Mekano Ltd.), and the test set-up. Figure by courtesy of VTT.

Figure 29: Aligning the upper attachments of the test bench. Figure by courtesy of VTT Ltd.

The instrumentation is based on the FINAF's Hawk OLM programmes (Ref. [48]), but with fewer strain gauges. Three strain gauges (S15, S01 and S02) are identical to the original instrumentation. Three additional verification and backup strain gauges are fitted to support the primary gauge S15. All actuator forces and displacements, as well as the upper connecting rod forces, are measured.

The first test device instrumentations, all data acquisition setup work, and calibrations were done 03/2017. The monitoring scheme is shown in Figure 30, and instrumentation in Figure 31 and Figure 32.

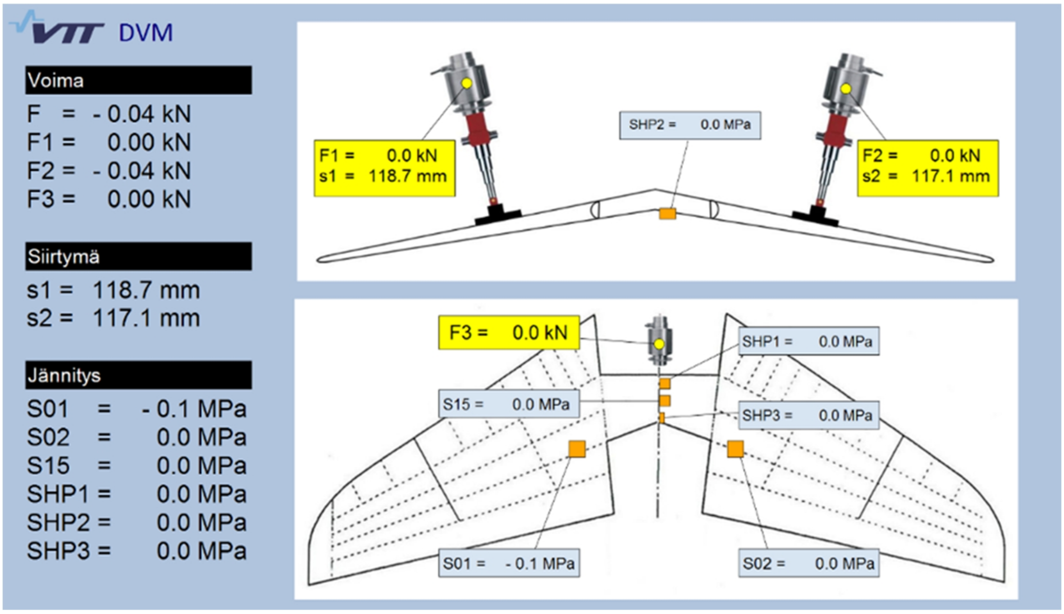


Figure 30: The main monitoring view showing the test set-up and instantaneous measurement values. Figure by courtesy of VTT Ltd.

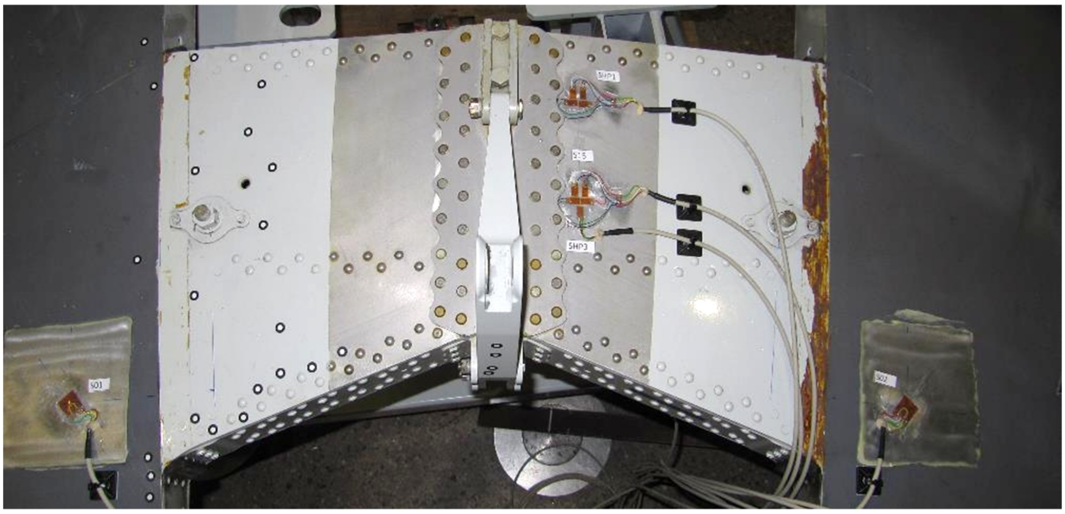


Figure 31: Strain gauges on top of the tailplane. Figure by courtesy of VTT Ltd.

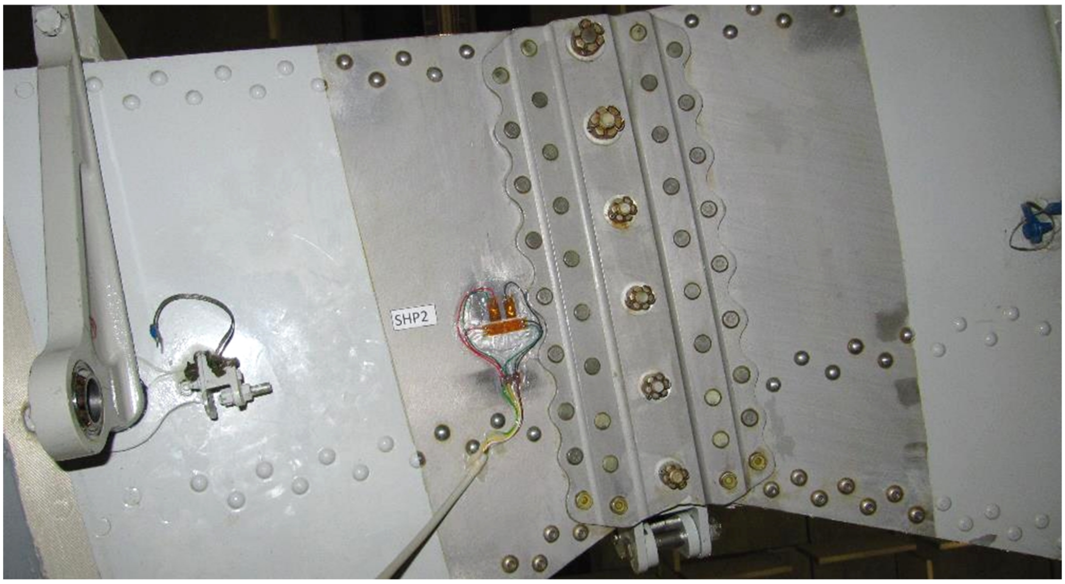


Figure 32: Strain gauges on bottom of the tailplane. Figure by courtesy of VTT.

The tests will be conducted full-time 24/7 with normal monitoring and supervision resource allocations. The test load spectrum frequency is still under review. The work is going to proceed unmanned when out of the working hours, but the operation is always stopped automatically and controlled way, when the next EFH target is reached, or when force or displacement are exceeding the predetermined limit values.

The predetermined critical area inspections will be done after every 250 EFH in a limited extent (Figure 33), and a full inspection is done after every 1000 EFH. The first tests with the first tailplane shall be commenced in March/April 2017, and all the results should be ready and analysed by the end of 2017.

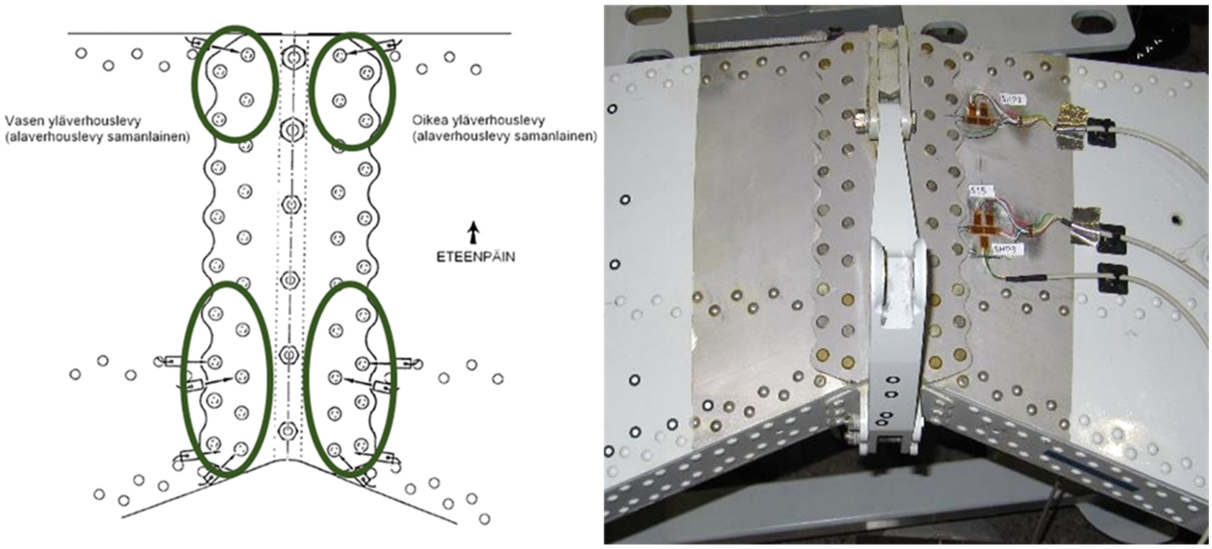


Figure 33: An example of the critical areas to be inspected with NDT. Figure by courtesy of VTT Ltd.

2.3.4 Development of fatigue data for longitudinally loaded lugs in Aluminium-Lithium alloy AA2050-T84 and adaption to a fatigue design method for lugs.

This chapter highlights the international cooperation reseach activities in between Saab Aeronautics (Sweden) and VTT (Finland).

Saab Aeronautics applies an in-house developed calculation method and sizing procedure for the fatigue strength of lug joints, [67]. The method has been used in all aircraft projects since the late 60s together with related fatigue materials data for a number of aluminium alloys and steels. The method handles lugs of basic design and lugs furnished with bushings with or without interference fit. Special parameters account for oblique loaded lugs and specify allowed cumulative damage sums for the application to variable amplitude loading. Scatter reduction factors are specified to meet design practice regarding safe-life design.

Fatigue tests have been made by VTT of longitudinally loaded lug of Aluminium-Lithium alloy AA2050-T84 since the alloy can be a candidate to replace lug joints currently made of alloy AA7050/7010-T7451. The test programme was intended to produce fatigue data necessary for the application of the lug design method to lug made of alloy AA2050-T84.

A total of 44 longitudinal loaded lug specimens were specified for the purpose with some additional specimens kept in spare. A total number of 51 specimens were finally tested. Two lug geometries were defined, A and B, and the B lug configuration consists of variants with and without bushings, net fit and interference fit.

Two orientation of specimens regarding product form directions were included, longitudinal (L) and short transverse (ST). The main number of the specimens were tested under constant amplitude loading and a smaller number under variable amplitude loading for checking purposes. The dimensions of the specimens, pins and bushings are given in Figure 34.

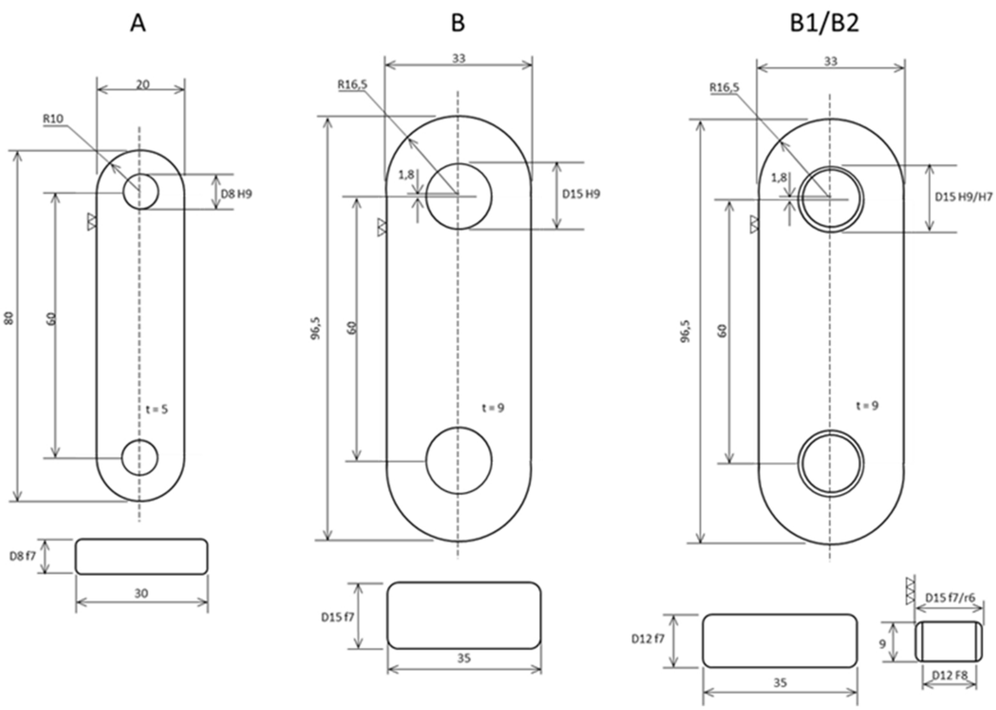


Figure 34: Lug specimens. Figure by courtesy of Saab Aeronautics.

All constant amplitude testing were done at a cyclic minimum stress of 10 MPa. The maximum stress levels were selected in order to obtain relevant SN-curves.

In Figure 35 are some results for lugs of type A (net fit, no bushing) loaded in the longitudinal (L) direction shown together with some previously obtained results for the same type of lugs made in AA7010-T7451. There is a tendency to lower fatigue strength in the high cycle regime for these simple net fit specimens without bushings.

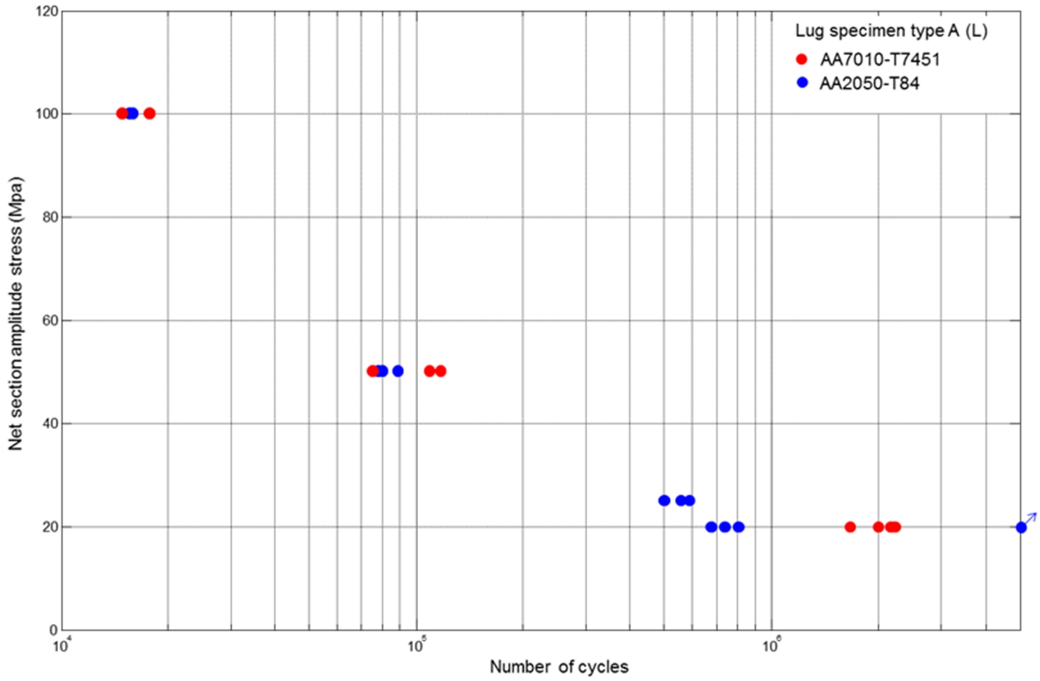


Figure 35: SN test data for type A lug specimens made of AA7010-T7451 and AA2050-T84. Figure by courtesy of Saab Aeronautics.

The variable amplitude testing was done with the type B2 lug configuration installed with a lubricated bushing with interference fit. The loading was based on a fighter wing bending type spectrum. The spectrum has been used for many general materials investigations within Saab Aeronautics, also in the previous lug tests for AA7010-T7451 with a mean life of 30 000 flight hours. The load sequence was truncated from compression load states for use in the longitudinal lug testing. The target mean life was set to 30 000 flight hours for the L-oriented lugs and a peak spectrum stress level of 200 MPa. The actual obtained mean life was 32 000 flight hours for the L-oriented lugs and 13 000 flight hours for the ST-oriented lugs i.e. about a factor of 2.5 shorter life in the ST-direction.

The experimental data are converted to a "reference" lug geometry according to [67]. The influence of bushing and fit are accounted for by application of a cycle dependant adjustment factor ψ. This fitted factor together with the experimental SN-curves for lug of basic geometry are used to derive SN-curves for lugs with special conditions, e.g. bushing, lubrication, interference fit. The SN-curves together with other parameter settings are used to construct complete Haigh-diagrams.

2.4 Structural integrity of composite materials

2.4.1 Fracture mechanics based analysis and tests of delaminations and debonds

The applicability of Virtual Crack Closure Technique (VCCT) continued by performing additional analyses and experimental tests. The primary interest concentrated on debonds in ductile adhesive layer. In addition to mode I loading also analysis and tests were performed in mode II loading. Analysis work included also case studies of a stepped lap joint including debonds. In mode I loading the applicability of the VCCT and experimental results with good correspondence were published in Reference [68]. The numerical parameters used in the simulation play also a significant role and their effect on the results were published in Reference [69]. These parameters do not have a physical meaning and are needed to achieve convergence but they also have an effect on the actual properties obtained from simulations that can be significantly erroneous depending on the parameter selection. The analyses were performed using both 2D and 3D models.

The specimen for mode II loading End Notched Flexure (ENF) was designed is such way that a stable crack growth could be possible without excessive effect of friction. This was accomplished with the use of numerical simulations (Figure 36).

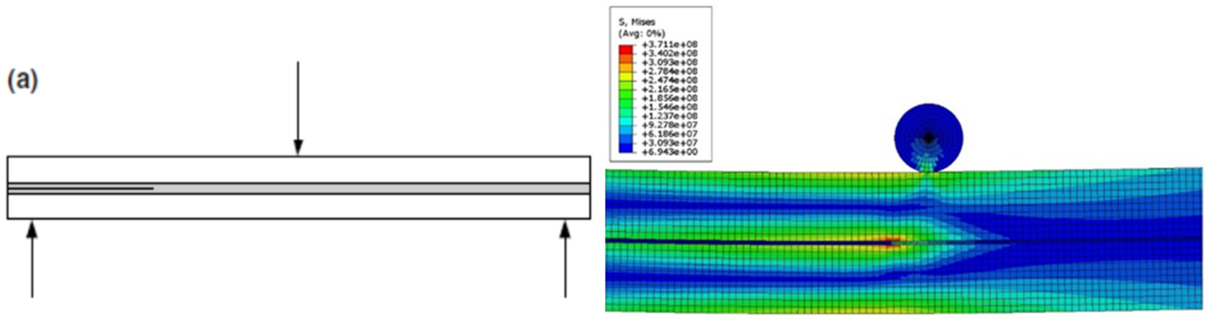


Figure 36: Schematic of the ENF specimen (left) and numerical simulations (right). Figure by courtesy of Aalto University.

An ENF test program including three different configurations was created. The specimen consisted of aluminum adherends and FM 300-2 adhesive film. The three configurations were: 1) specimen with two adhesive films and an insert film (representing debond defect) between the adhesive layers 2) a single adhesive layer with the insert film above the adhesive and 3) a single adhesive layer with the insert film below the adhesive. The three different configurations and the ENF test arrangements are illustrated in Figure 37.

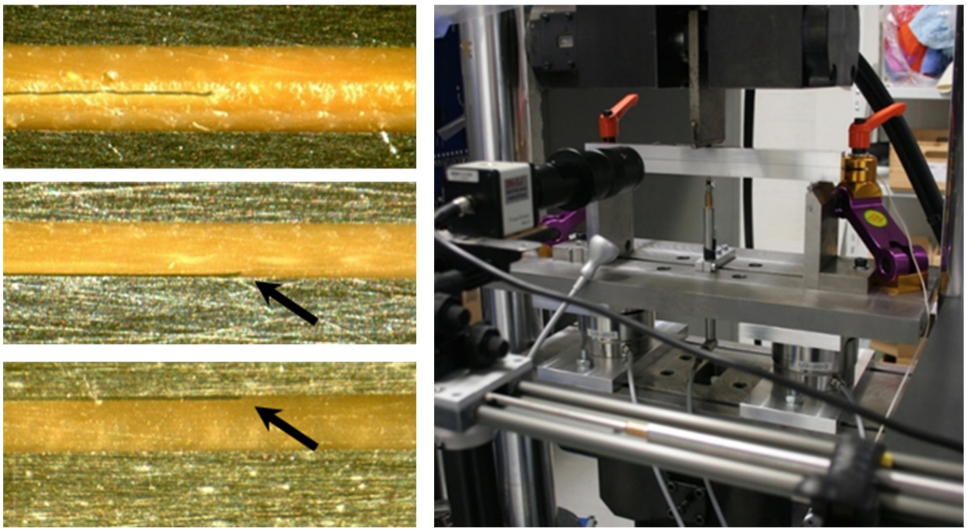


Figure 37: The ENF test configurations (left), in which the position of the insert film pointed with an arrow, and the ENf test arrangements (right). Figure by courtesy of Aalto University.

The load-displacement results for test configurations 1 and 3 are presented in Figure 38 in which the effect of the adhesive layer thickness and the position of the insert film is clearly visible. The results from configuration 2 are between these two graphs. A research paper combining the test results and simulations in a peer review journal is under preparation.

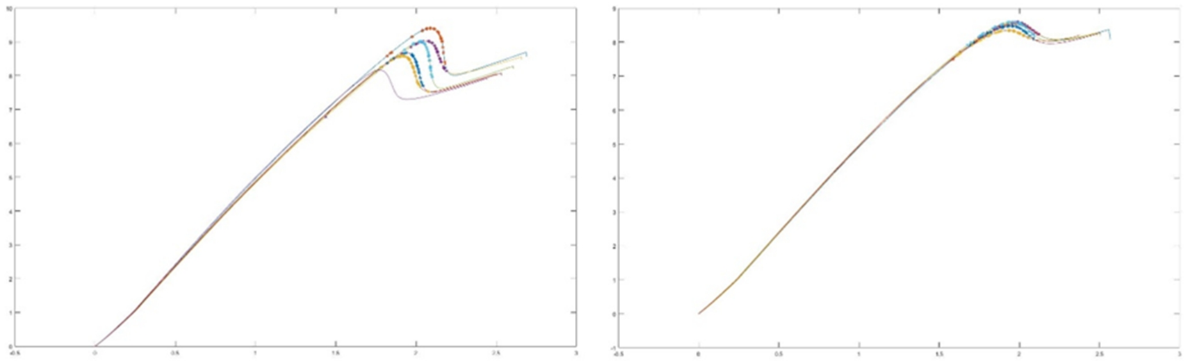


Figure 38: Load responses from the ENF tests, two adhesive layers (left) and one adhesive with insert film on bottom (right). Figure by courtesy of Aalto University.

A simulation model using cohesive elements was used to model the behavior of a butt joint specimen. The effect of cohesive law was investigated with the reference to the test results. The simulation results were published in a conference paper [70]. The simulation model with different cohesive laws is presented in Figure 39 and some reference test results in Figure 40. Additional paper combining the cohesive element with the VCCT-method is under work. Initial part of the study was published in a conference paper [71].

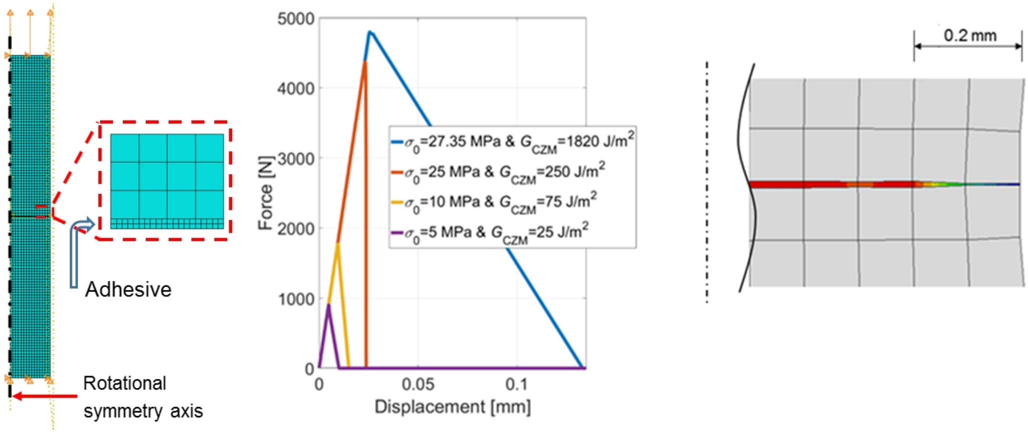


Figure 39: Simulation model for butt joint specimen (left) with cohesive laws (center) and results (right). Figure by courtesy of Aalto University.

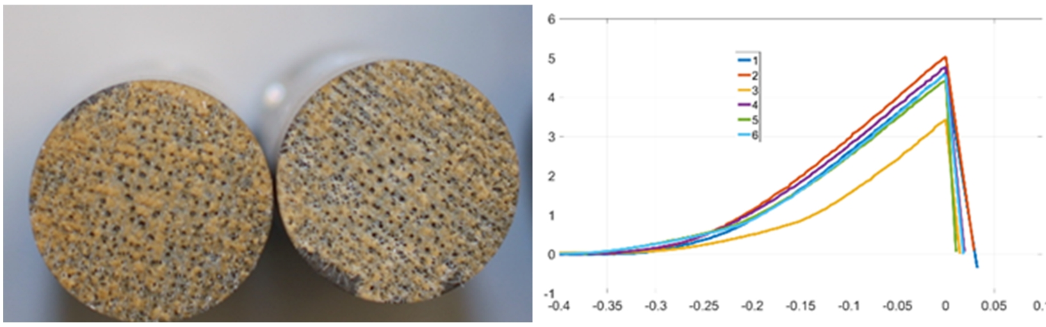


Figure 40: Fracture surface and load-displacement response of the butt joint specimen. Figure by courtesy of Aalto University.

2.4.2 Thermographic studies - update

The number of penetrated water-induced failures within the FINAF F/A-18 Rudders is on the rise. Thus, penetrated water in the composite structures operating in arctic conditions has been a research activity in Finland for several years. VTT and Patria Aviation have been working in close co-operation to develop a method to detect moisture and efficiently remove it from the structures. [72]

Detailed inspection and drying procedure is explained in the ICAF2015 National review [2]. This thermographic inspection method has shown to be the only method that detects small amounts of penetrated water from large areas without removing aircraft composite parts from the aircraft – and the only method within the FINAF, which can detect small amounts of water. The costs of thermography inspection + drying are far less than the costs of repair planning + repair, not to mention the costs of new rudders.

VTT has continued inspecting the water penetration or moisture ingress in the composite sandwich structures. During 2015, 48 Rudders were inspected, of which 8 displayed positive indications of moisture ingress (some of these 8 indications passed the previous X-ray inspections). During 2016, 30 Rudders were inspected, of which 4 displayed positive moisture ingress indications; all these 4 Rudders had passed the previous X-ray inspections. All of the above 78 Rudders had undergone the X-ray inspections prior to the thermographic inspections. Of the 2016 inspections, 3 Rudders of the 30 X-rayed were found to contain moisture ingress and they were subjected to the drying procedure, These three Rudders were later verified as dry using the thermographic inspection.

The chronology of the Rudder inspections has been the following:

1. The selected Rudders are delivered to Patria Aviation's repair shop.
2. Patria Aviation inspects the Rudders using their X-ray method. In case moisture ingress is detected, the Rudder undergoes a drying procedure. The dried Rudder is inspected again using the X-ray method.
3. After the above X-ray inspections, VTT inspects the Rudders using thermography. If moisture is detected, the Rudder undergoes the drying procedure. The dried Rudder is then re-inspected with thermography, but now only from those areas in which moisture was detected.

An overview of the Rudder thermography inspections is provided in Figure 41.

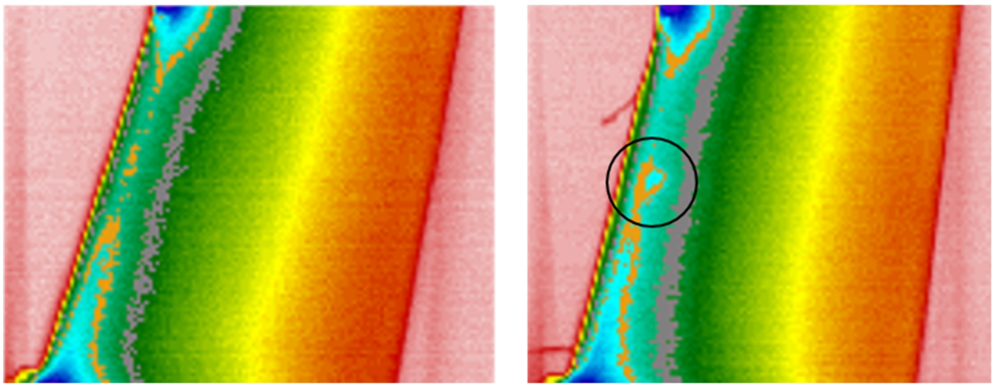


Figure 41: An overview of the Rudder thermography inspections. Left: Normal heating image i.e. no moisture ingress (LYK0127 (U22-2935)). Right: Abnormal heating image, which was verified by analysis as a positive finding of moisture ingress (LYK0119 (U22-2919)). Figure by courtesy of VTT Ltd.

2.5 Repair technologies

2.5.1 DIARC plasma coating activities at Aalto University

Previous metal bonding activities related to DIARC plasma coatings have been reported earlier in [2] Chapter 13.2.5.1.1. The recent achievements are outlined below.

The stability and durability of DIARC vacuum plasma surface treatment was tested for structural bonding with elastic-plastic steel wedge specimens. In the treatment nanostructured DIARC Bindo coating is deposited on the substrates in a vacuum chamber. The DIARC –treated surface is ready for bonding and does not require any additional treatments, chemicals, or primers containing hazardous CrVI chromium. The tests were performed at hot and wet exposure. Virtual Crack Closure Technique (VCCT) was successfully used in the design of test specimens and in the analyses of the results. Five-year-old DIARC coating performed equally with the freshly-bonded DIARC specimens. The results were also comparable with the best results achieved with existing grit-blast silane and grit-blast Sol-Gel primer methods with aluminium and titanium. Due to the copyright restrictions, further in-depth information of the study and the results can be found in [49].

3 Related activities

3.1 EDA Patchbond project

The EDA Patchbond project was broadly introduced in Chapter 13.3.2 of Ref. [2]. The four-year "*Bolt free battle and operational damage repairs of metal and composite primary aircraft structures (PATCHBOND)*" project will be executed in the framework of the European Defence Agency (EDA) R&T Category B projects. The project focuses on the permanent bolt free composite patch repair of damaged composite primary structures on a military rotary wing platform. The primary goal is to specify a certification approach that fulfils the airworthiness requirements for permanent bonded composite patch repair in a highly loaded primary structure of the platform. The secondary goal is to investigate and define materials and repair processes that are capable of repairing the composite structure to comply with the required operational capability.

The project embraces the methods of repairing in-service damages whose size or location falls beyond the ASR/SRM (Aircraft Structural Repair/Structural Repair Manual) limits; i.e. damages in a highly loaded monolithic or sandwich structure and areas therein where drilling of additional fastener holes is prohibited, thus enabling adhesively bonded repair the only feasible repair solution. The project covers the whole spectrum of methods starting from damage assessment, analytical and numerical analysis, repair design procedures, materials and processes, inspection, structural health monitoring and quality control, up to the certification aspects.

The work will be performed by an international consortium consisting of 14 industrial and scientific partners from five European countries enabled to participate in EDA's projects, alphabetically: Finland: Aalto University, Patria Aviation, VTT Technical Research Centre of Finland Ltd.; Germany: Airbus Defence and Space, Bundeswehr Research Institute for Materials, Fuels and Lubricants (WIWeB); the Netherlands: NLR, Fokker Services B.V., KVE Composites Repair; Norway: Norwegian Defence Research Establishment (FFI), Norwegian Defence Logistics Organization (NDLO), DolphiTech, FiReCo, Light Structures; and Spain: Spanish Institute for Aerospace Research (INTA). Project Lead Contractor is NLR (the Netherlands), and Patria Aviation is the Finnish coordinator of the project. The Finnish Defence Force Logistics Command is the national bill paying authority of the project.

The EDA Patchbond project has been divided into nine different Work Packages (WP) which in turn are divided into one or more Work Elements (WE). Some of the recent activities in Finland have been presented in the following subchapters. [50]...[57]

3.1.1 Patria Aviation's activities in EDA Patchbond

Patria Aviation's main interests in the Patchbond project are related to the certification process of bonded repairs as a whole and especially to the analysis methods that can be utilized to support it. [58], [59]

As part of this Patria has concentrated on a "quick and dirty" analysis program with which one could easily check if a repair is feasible in the first place, and if it is, make a preliminary design. In case the load carrying capacity of the damaged part is not critical or, if the results include adequate factor of safety, dimensioning of the repair can be based on the program. In more demanding cases the results would direct the design of the repair and thus hopefully decrease the possible iteration needed with the more time-consuming FE-models. The program is based on the method presented in reference [60] and it can be applied to single lap, double lap, scarf, and stepped lap joints in unidirectional tension.

Related to the development of the analysis methods Patria Aviation has taken part in the testing activities to get first-hand test data.

3.1.2 Aalto University's activities in EDA Patchbond

The work performed at Aalto University in the Patchbond project concentrates on damage tolerance performance of laminated composite structures. An analysis program using analytical method based on open holes was used to estimate the residual strength of notched and impact damaged laminates. A test program consisting of solid laminates with various round open holes and impact damages in compression was accomplished as an international co-operation. Aalto University was responsible of the analysis, test program planning and results interpretation including reporting. Fokker, specimens prepared and tested by NLR, manufactured laminates and Dolphitech performed NDI inspection. The analysis method has been used previously with good correspondence to the impact damaged test results but in this test program the material and the laminate lay-up turned out to be significantly less sensitive to impacts than typically used UD-prepreg laminates. The results are presented in Figure 42. The main conclusion was that in this case conservative results are obtained if the impact damage is modeled as a round hole with equal damage width. Additional test program using same material and laminate lay-up is ongoing. The difference to the previous test specimen is that the specimen includes a scarf joint with paste adhesive using a 1:20 scarf ratio. [61], [62]

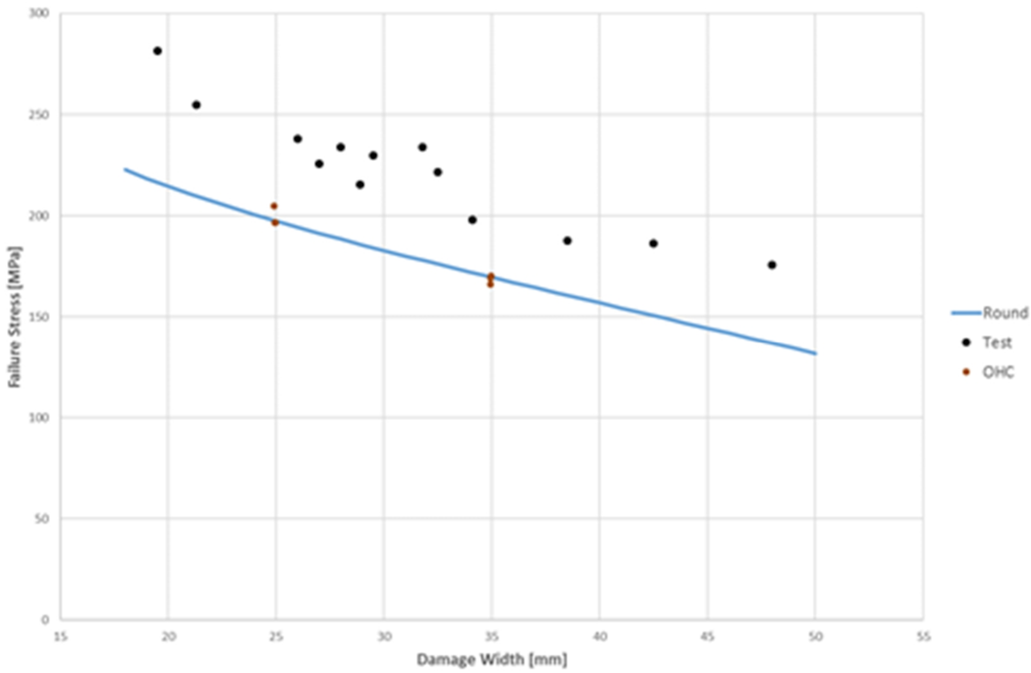


Figure 42: Analysis curve with open hole compression and compression after impact results as function with the damage width. Figure by courtesy of Aalto University.

3.1.3 VTT’s activities in EDA Patchbond

3.1.3.1 Damage tolerance analyses at VTT

VTT’s goal in this subject was to numerically simulate a low-velocity impact damage to a composite sandwich panel and to predict the damage mode and damage size. The simulated structure was a composite sandwich panel corresponding a certain NH90 helicopter sandwich structure. The structure consisted of a top and a bottom face sheet made of carbon fiber/epoxy-prepreg and aramid fiber/phenolic (i.e. Nomex) honeycomb core. The work was done in three phases. First, an Abaqus user material model was created for the sandwich panel face sheets. The user material model took into account the intra-laminar damage. The inter-laminar damage was simulated using cohesive zone model. The user material model was tested by simulating a 30 J impact to a 100 mm x 150 mm 21-ply monolithic laminate made of NH90 base material and comparing the simulation results with test results. According to the results, the user material model was able to simulate the actual dent size well, see Figure 43, but the simulated delamination area was 30-40 % smaller than observed in the tests. Second, a meso-scale FE-model for the Nomex honeycomb core was created and the Nomex paper properties were tested by simulating a core crush test. Two different element mesh sizes were compared: 0.2 mm and 0.4 mm. Again, the simulation results were compared with the test results and they corresponded well with the test results. A better correspondence was obtained with the 0.4 mm mesh size. Finally, an FE-model of a 200x200 mm sandwich panel was created and the low-velocity impact was simulated with 6 J impact energy. [63]

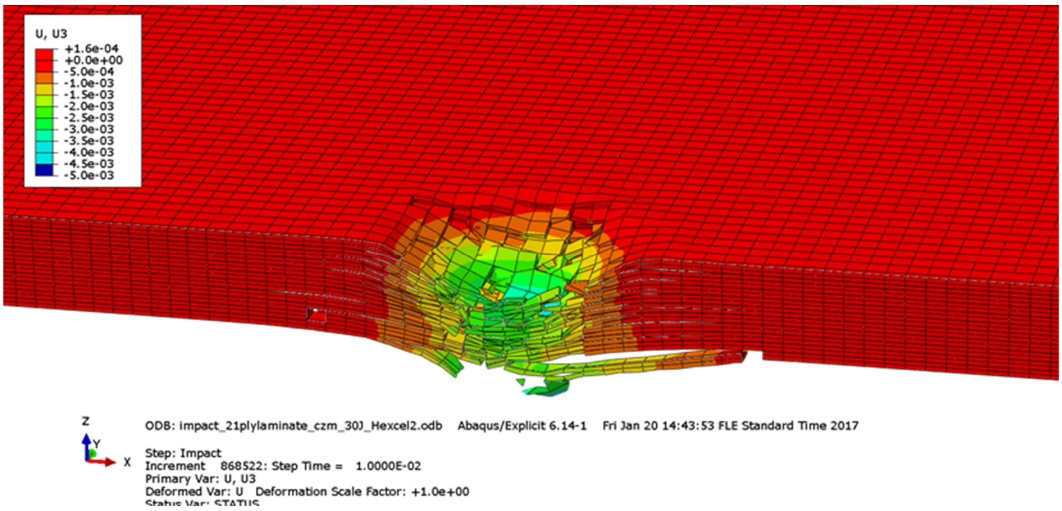


Figure 43: Simulated dent depth in the 100 mm x 150 mm monolithic laminate with 30 J impact energy. Figure by courtesy of VTT Ltd.

3.1.3.2 Sandwich panel test program at VTT

Another VTT's goal in the EDA Patchbond project was to test the performance of the existing Acousto Ultrasonic (AU) based Structural Health Monitoring (SHM) system in a small scale fatigue test program for the repaired sandwich panels. The idea in fatigue testing was to grow artificial bond line defects in the repaired area in a controlled manner such that the growth of the embedded defects could be monitored with the SHM system. To this end, VTT designed a highly experimental 4-point bending test set-up to evaluate the performance of the SHM system i) to detect the embedded artificial defects, and ii) to monitor anticipated defect growth. [64]

The tested sandwich panels were designed to mimic the original structure of the project demonstrator, as this would disclose the challenges of the monitoring method - primarily due to the signal attenuation in the honeycomb core. Another challenge for the used NDI method would be the thin face sheets (approx. 1.2 mm) of the specimen. Flat 350 x 350 mm sandwich test panels were manufactured for VTT by the project partners. The repaired sandwich panels included a different set of artificial defects. One of the sets can be seen in Figure 44.

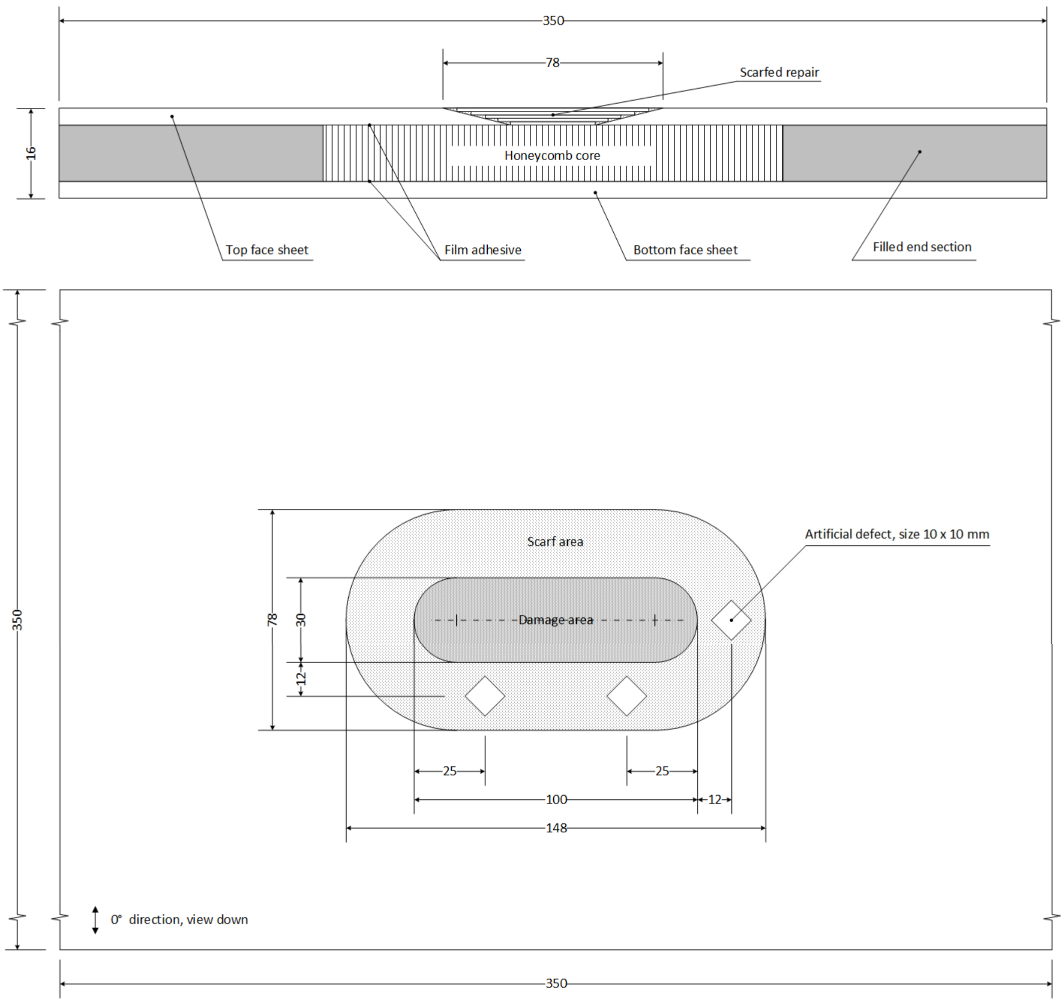


Figure 44: Repaired sandwich panel including a set of 10x10 mm artificial defects embedded in the scarfed area. Cross section on top and top view below. Panel thickness not in scale, top and bottom face sheet thickness was approx. 1.2 mm. Figure by courtesy of VTT Ltd.

The mechanical testing was realized as 4-point bending static and fatigue tests inducing moderate to high compressive strains on top of the repaired sandwich panels. Target strain level was set as high enough to provoke decent defect growth in the repaired area within reasonable time. NDIs were performed as initial checks for the repaired panels and to verify extension of the defects along testing. In addition, installed strain sensors enabled the evaluation of mechanics of the panels and facilitated the interpretation of the SHM results. The test set-up is illustrated in Figure 45.

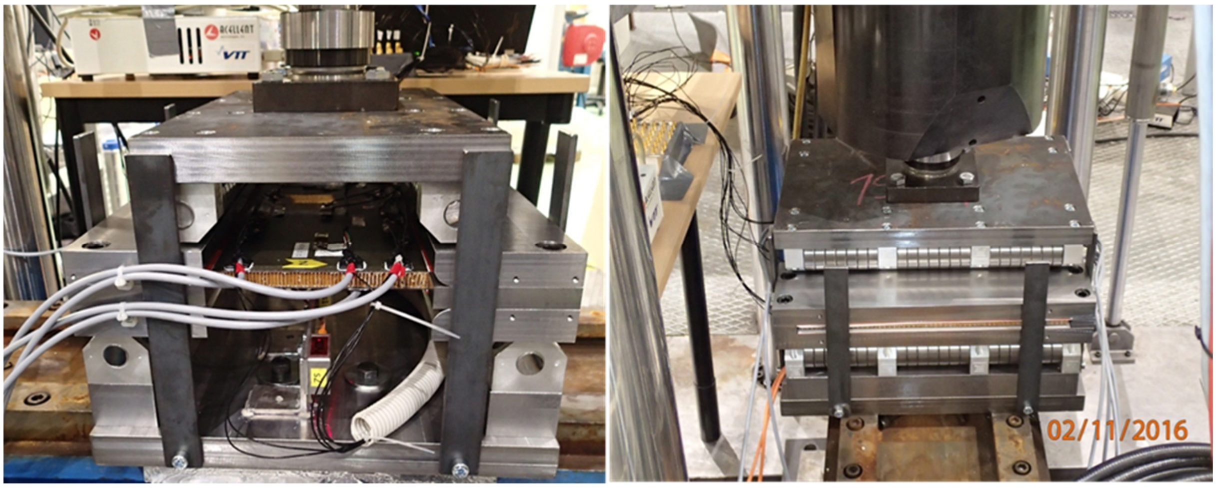


Figure 45: Sandwich panel ready for testing. Test specimen was supported by the steel shear boxes. Supports and loading bars consisted of roller bearings in order to allow free rotation of the shear box and specimen at the loading and support points. Figure by courtesy of VTT Ltd.

3.1.3.3 EDA Patchbond project NDI activities at VTT

In EDA Pachbond project different ultrasonic techniques were evaluated along with thermographic inspection. The purpose was to improve and optimize the Non-Destructive Inspection of monolithic carbon fiber reinforced plastics specimens as well as previously introduced repaired sandwich panels (Ref. Chapter 3.1.3.2). [65]

The ultrasonic inspections included both conventional pulse-echo and through-transmission techniques. The pulse-echo technique performed adequately for monolithic specimens. However, for the sandwich panels with a wet lay-up scarf repair, the material proved to be too noisy low Signal-to-Noise Ratio (SNR) and too thin for the pulse-echo technique, thus through-transmission technique and thermographic inspections were finally utilized.

Four different sandwich panels were inspected with active thermography. This inspection method was able to detect all flaws implemented in the specimens. However, sizing these flaws proved to be fairly inaccurate due to the noise in the image. The repair patch did not affect the detectability of the flaws considerably, and actually the method works the better the closer to the surface the defect is - e.g. for the top face sheet of the sandwich panels. Post-processing was applied to the thermographic image and the result can be seen in Figure 46.

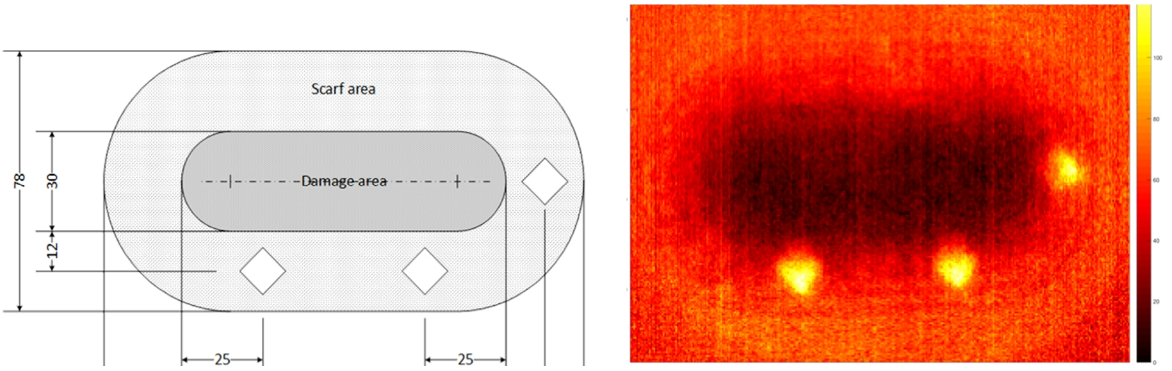


Figure 46: Post-processed thermographic image of the repaired sandwich panel including artificial defects. The result represents average of the frames after the flash in between 0.9 - 1.1 sec. Figure by courtesy of VTT Ltd.

Ultrasonic through-transmission technique produced the highest SNR, thus out-performing other tested techniques clearly. The downside of through-transmission is that, because there is a transmitting probe on one side and a receiving probe on the other side of the specimen, it needs access on both sides of the tested material, so using this technique might be challenging.

For this purpose a specific fixture tool, which held the probes aligned, was manufactured. The 2.25 MHz probe was selected for through-transmission experiment, allowing lower attenuation of the ultrasound while maintaining a good resolution. Through-transmission produced the best results allowing clear detection and sizing of the artificial flaws. The result from one experiment can be seen in Figure 47.

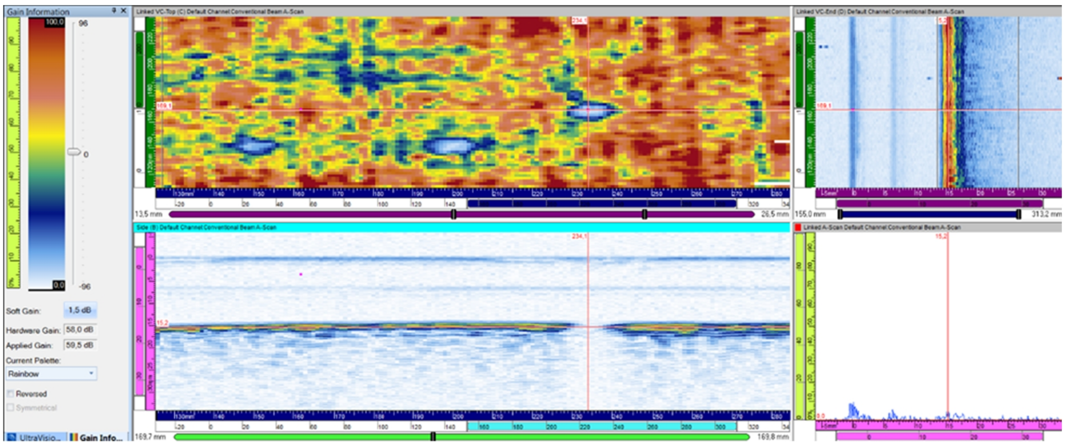


Figure 47: Through-transmission ultrasound (with 2.25 MHz probe) images of the repaired sandwich panel including 3x10x10 mm artificial defects. All flaws were detected and measured accurately enough. The flaws were sized from left to right: 8x8 mm, 10x10 mm, and 8x9 mm respectively. Figure by courtesy of VTT Ltd.

3.1.3.4 EDA Patchbond project SHM activities at VTT

Acousto Ultrasonic instrumentation of the sandwich panel consisted of 12 single 1/4”-PZT (Piezoelectric lead Zirconate Titanate) sensors from Acellent Technologies, Inc. AU measurements were performed using Acellent’s ScanGenie hardware. Measurement software Acess was used to acquire data from 60 different paths (like path 5 → 6 in Figure 48) with three different actuation signals, so in total 180 measurements were executed discretely. Data was measured with 48 MHz sampling frequency. Samples were recorded without averaging.

Progressive defect can be detected from received signals amplitude and phase. Detection is usually done from scatter signal that is done by comparing measured signals with reference measurements done from intact structure. Detection is done by means of correlation factors, variance and frequency components. Analysis of the results are under way at the moment of writing this review.

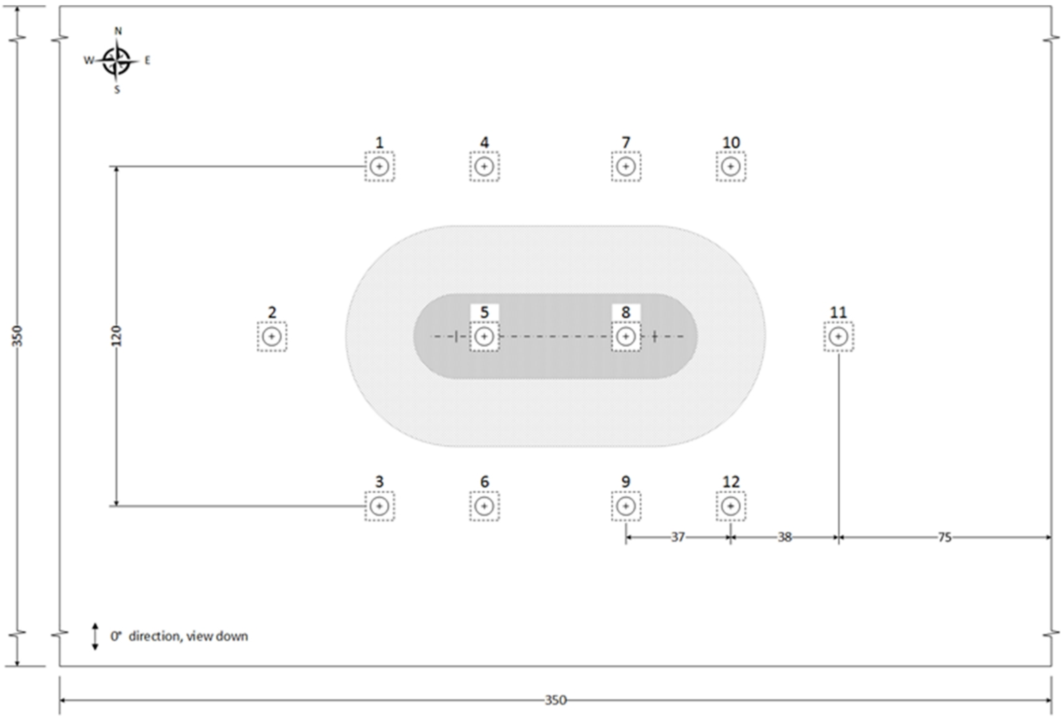


Figure 48: PZT-sensor layout and numbering on top of the sandwich panel. Figure by courtesy of VTT Ltd.

3.2 Thermal spraying of the FINAF F/A-18 Aileron's hydraulic cylinder's flange completed

Previous thermal spray activities of the Aileron cylinder were reported in Chapter 13.3.3 of Ref. [2]. An update is provided below.

Thermal spray coatings produced using five spraying methods were assessed with metallographic samples (microstructure and instrumented indentation), as well as the performance in view of abrasive wear characteristics. The goal of the assessments was to find the most suitable coating method to be considered for industrial production. [73]

The assessed spraying methods were: twin wire arc spray, high velocity air fuel (HVAF, Kermetico AK-07), high velocity oxygen fuel (HVOF, DJ Hybrid), high velocity oxygen fuel (HVOF, CJS Carbide Jet Spray) and supersonic particle deposition (SPD, Kinetics 4000). All coating tests were conducted on small-scale specimens (a bulk 15-5PH steel which was heat treated to have matching properties to the original component) and compared with each other.

On the basis of the metallographic sample indentations, the best performing coating methods were HVAF and DJ (HVOF) in view of hardness and Young's modulus, respectively. In comparison to the bulk material, these two methods provided greater hardness but lower Young's modulus.

In view of abrasion, all studied coatings performed clearly better than the base material which was treated identical to the original component's bulk material (15-5PH steel). The overall ranking order of the studied coatings was DJ (best), CJS, HVAF, CJS and SPD (worst).

In view of adhesion, the HVAF was the winner while DJ (HVOF) and CJS shared the second place.

The overall winner was HVAF followed by DJ (HVOF). It was recommended that DJ (HVOF) be selected for the production method, since Patria already has DJ (HVOF) in use, and because DJ (HVOF) provided adequate characteristics for the thermal spray repair application of the F/A-18 Hornet Aileron's hydraulic cylinder's flange. An overview of the thermal sprayed component using the DJ (HVOF) flange is provided in Figure 49.

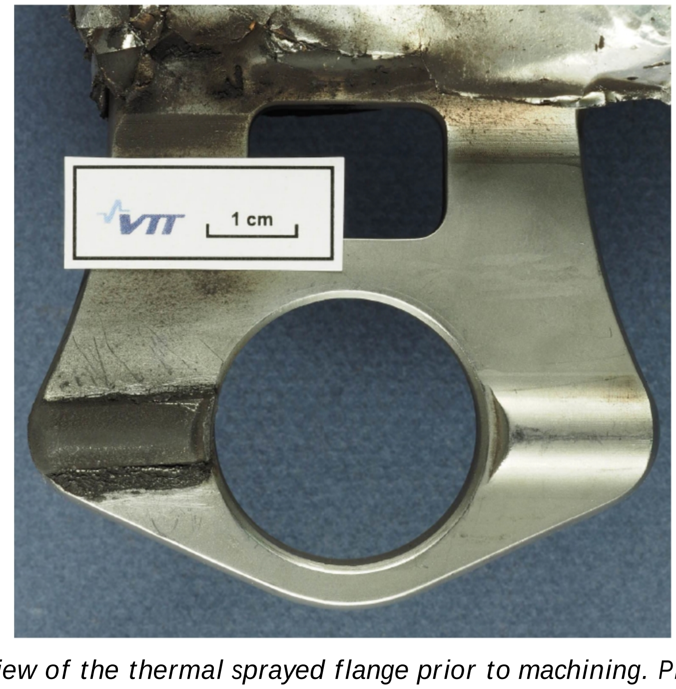


Figure 49: An overview of the thermal sprayed flange prior to machining. Picture courtesy by VTT Ltd.

3.3 Engine integrity

3.3.1 VTT research on engine integrity

VTT research on engine integrity for the FINAF yielded 3 million USD savings to the Finnish taxpayers while supporting the technology-based security of supply. With experimental research support of VTT, the FINAF could increase the operational life (flight hours) of the High Pressure Turbine (HPT) blades of the F/A-18C/D Hornet jet engines (2 x General Electric F404-GE-402 turbofan engine). The FINAF sent the VTT research results with some used HPT blades to the engine manufacturer, and based on the research results and operational experience, GE increased the life limit of HPT blades by approx. 10 %. The FINAF has adopted the new life limit into operational use since May 2015. The 10 % increase in life yielded approx. 3 million USD savings to the taxpayers, with a nearly hundredfold return on the research investment (ROI).

Since then, VTT has developed new capabilities for characterization of materials and structural integrity of in other industry sectors: power plant components. The new capabilities include Small Punch testing of miniature samples (∅ 8 mm x 0.5 mm) in tensile or creep testing configuration. The miniature samples can be extracted with minimal damage to the component while representing well the localized properties. The method is supported by a Code of Practice, but VTT is also participating in a joint European effort aiming to develop an EN standard on the technique.

Further information on VTT's experimental research activities related to the HPT blades is provided in Chapter 13.2.7 of Ref. [66]. The following provides an update.

3.3.2 Analysis of the FINAF F/A-18 Hornet Low Pressure Turbine blades

Three FINAF F/A-18C Hornet Low Pressure Turbine (LPT) blades were received for investigation that aimed to determine in-service effects such as coating condition, microstructural degradation, cracking and attachment wear, and also to determine the 3D and cross-section geometry of the blades. The blades #6221 and #6645 were removed after 2496 EFH (Engine Flight Hour) and 3890 EOT (Engine Operation Time) after reaching the end of their nominal life. The blade #6710 had seen 1363 EFH and 2130 EOT in an engine that had sucked in snow when the aircraft incidentally veered off the runway. [74]

The blades were photographed, 3D laser scanned (dimensional geometry), inspected (stereo microscopy) and then sectioned at selected locations for subsequent metallographic investigations.

The crystallographic orientation did not show significant deviations from the expected status. No obvious life-threatening damage in terms of coating condition, thermal blade material degradation or cracking was observed in any of the inspected LPT blades. The fully served blade #6645 included one 0.1 mm deep crack in a location and orientation that was not threatening the blade integrity (Figure 50).

In the blade #6710 with the snow bank incident (rapid in-service cooling), there was some limited coating delamination at the base plate and on the blade root area. The observed modest microstructural degradation of the blades was not considered to indicate life-threatening damage either.

The dovetail area of the blades investigated showed some wear marks at the contact surfaces and deformation of the base material under the contact surfaces and some lamellar cracking, but there was no indication of fatigue cracking developing from these lamellar cracks or from the outer surface of the waist of the blades. Therefore a modest extension of operating hours could be justified.

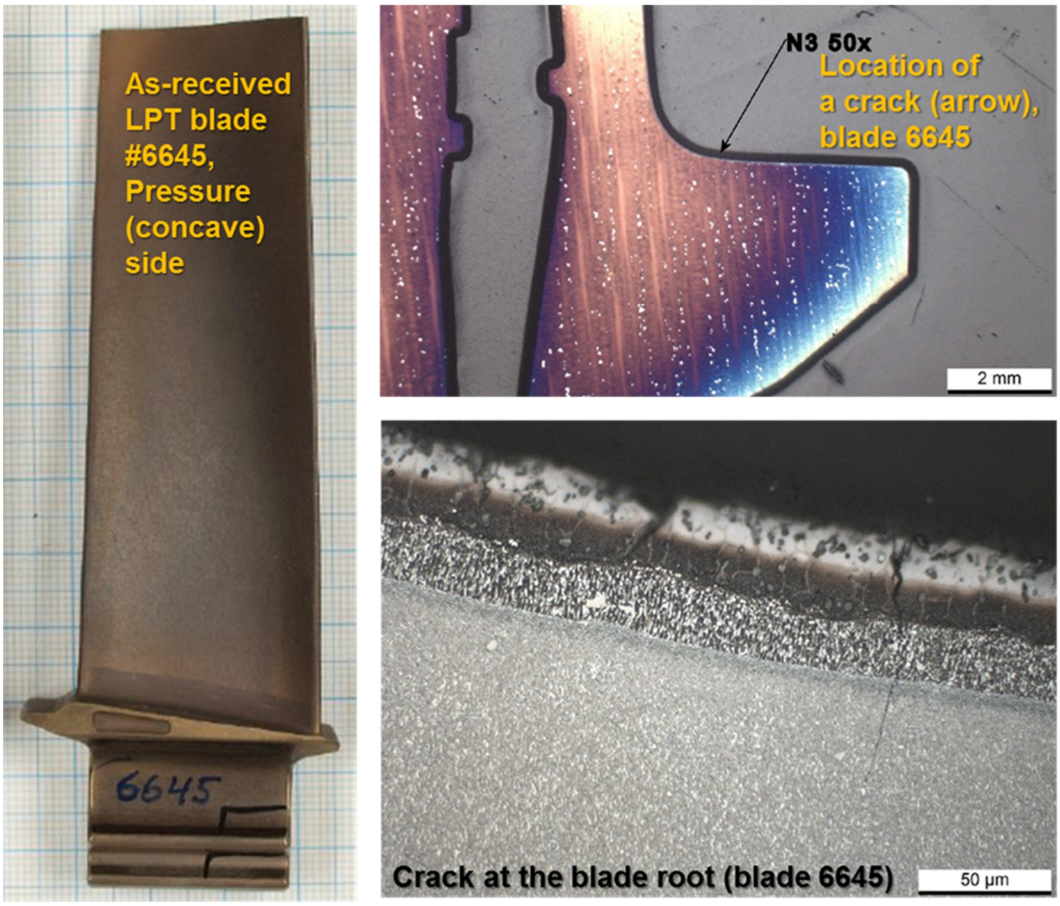


Figure 50: Examples of the metallographic assessments of the Low Pressure Turbine blades. Picture by courtesy of VTT Ltd.

3.3.3 Analysis of the FINAF F/A-18 Hornet High Pressure Turbine blades

Three of the FINAF F/A-18C Hornet High Pressure Turbine (HPT) blades flown the extra 10 % were removed from service and subsequently subjected to metallographic investigation to compare the blade condition after 3160 EOT against the condition of previously studied blades which had been used up to a nominal life of 2800 EOT. The main effort on damage characterisation was concentrated on overheating on the concave side of the blade, microstructural degradation and depth of cracks at the leading edge (Figure 51). [75]

The concave side's overheating did penetrate the blade's wall in one of the three inspected blades and thus exceeded the acceptance criteria. Nevertheless, the overheating damage does not seem to threaten the blade life, and can be easily monitored by visual inspection. Only in one blade some cooling holes at the blade tip were blocked by debris, but this was not believed to be life threatening either.

The maximum crack depth at the leading edge after 3160 EOT did not exceed that of previously assessed blades after nominal 2800 EOT. Also the gamma prime (γ') depleted zone inside the cracks was continuous up to and within the crack tip which suggests sufficiently slow crack growth to justify the previous decision to extend the blade life from 2800 EOT by 10 %.

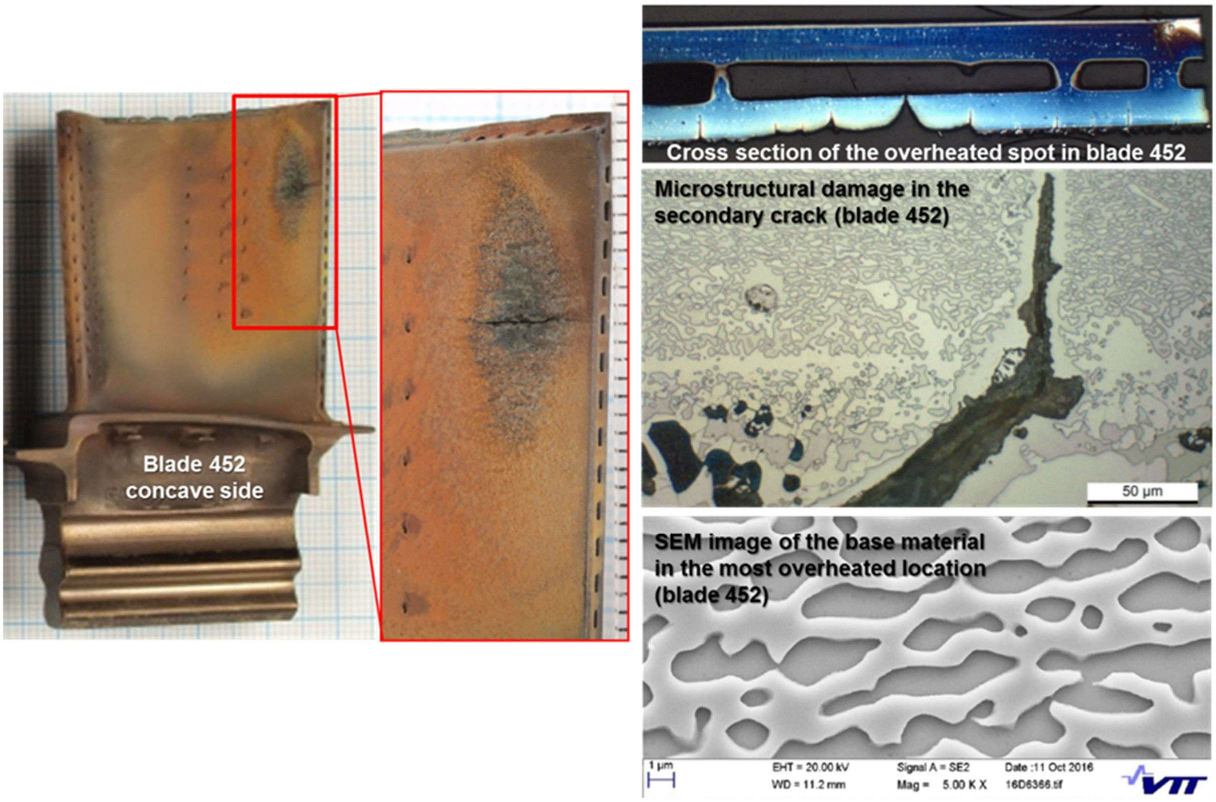


Figure 51: Examples of the metallographic assessments of an overheated turbine blade. Picture by courtesy of VTT Ltd.

3.4 Integrity of mechanical components

3.4.1 Aircraft component failure prognosis related Early Warning System (EWS)

The purpose of maintenance is safety and reliability. Thou nowadays with complex systems it seems based on the statistics that scheduled maintenance does not necessary increase the system reliability and due to human error may actually decrease the safety and reliability. One option would be to run systems to failure, but that is not a reasonable option in aircraft systems. What is left over is the maintenance procedure called condition based maintenance.

In the condition based maintenance, a maintenance person makes a decision about the maintenance need based on the system condition. The information for the decision can be received by eye observation or by using some measuring equipment. The purpose of the EWS is to provide an extra tool for the maintenance personnel to support the condition based maintenance decision making process.

In practice, EWS tries to forecast the subsystem failures of the FINAF's aircraft systems. The starting point is the process data of the aircraft systems. Thus what is done in a broad level is data analysis on the aircraft systems process data. The research of EWS is especially focusing on the subset of data analysis methods called Machine Learning (ML) methods or vernacularly Artificial Intelligence (AI) methods.

Machine learning can be categorized in two subclasses: supervised learning and unsupervised learning, and they have significantly different roles in system health diagnostics approaches like the EWS. In supervised learning the data must be labeled and the labels can be taught to the machine. When labels for the data instances are not available, then machine learning can only be implemented by in a form of unsupervised learning.

A typical system has a vast amount of data describing the healthy runs and relatively small amount of or no data describing the system failures. Thus the two labeled data groups are significantly imbalanced or one of the groups is totally missing, which causes difficulties in implementing supervised learning. Unsupervised learning is usually implementable for any data, but the interpretation of the results is not typically straight forward.

In the EWS project, one case study was done on flight control surfaces of the FINAF F/A-18 fighter aircraft [76]. In this case the Leading Edge Flaps (LEFs) of the aircraft tend to seize in several cases. Thus the data from both classes, healthy data and failure data, were covered. The case was interesting from the research point of view since it enabled the use of Supervised Learning and, on the other hand, gave a good validation base for the studies on the unsupervised learning methods.

In the LEF failure study [76] the unsupervised learning methods were used to find failure indications out of the healthy data before the actual failures. The used methods were Self Organizing Map (SOM) and K-mean clustering. Both methods performed well and the failure indicators were found before the actual failures. Figure 52 demonstrates how the healthy data was clustered differently before the failure compared to the normal data.

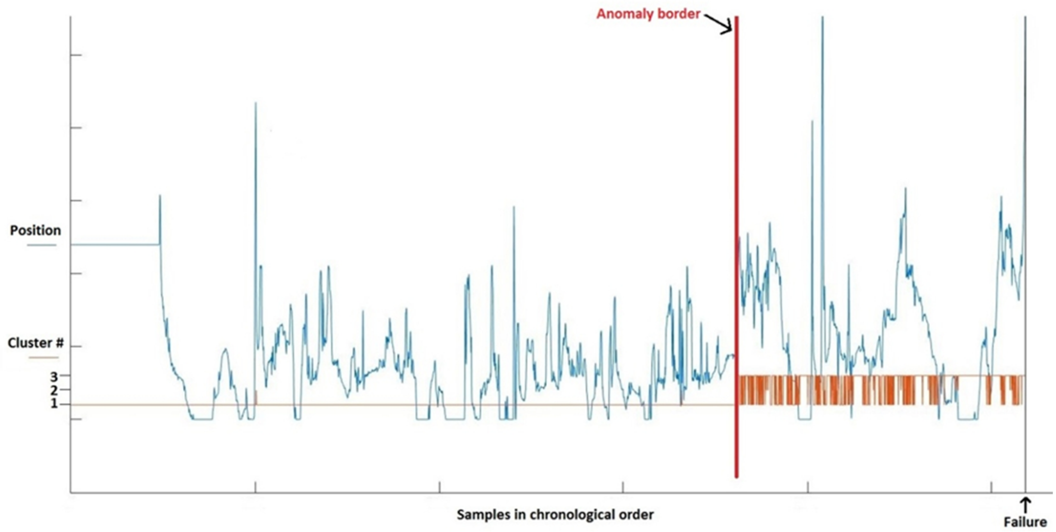


Figure 52: This figure presents the one position parameter of process data from the healthy and properly running system, but before the actual failures the clustering method reveals the exceptional behavior in the data. Figure by courtesy of Tampere University of Technology.

In order to achieve the results, a pre-manipulation (Figure 52), or feature extraction, as it is known in machine learning terminology, was needed before the machine learning. Feature extraction was done based on the prior knowledge of the system by interviewing the experts of the system. By this manner irrelevant data was censored out and the relevant data was organized properly in order to have good results out of the ML.

Unsupervised learning methods provided a tool to divide the healthy data into two classes: pure healthy data and failure indicating healthy data. Since the two class labels for healthy data were available, supervised learning was possible. Three supervised learning methods: Neural Network (NN), Support Vector Machine (SVM) and Radial Basis Function (RBF) were trained with the two classes of healthy data to make the distinction between the two classes. From the training some data was saved for testing and the testing showed that the supervised learning machines in issue were capable of making the classification in a level, which could be used in practical decision support.

The EWS research continues and currently focuses strongly on unsupervised learning in order to have decision support information out of the systems, from which there is no failure data available. This is justified because in practice there is not enough or no failure data available from most of the systems. The EWS tries to find maintenance decision support value for any system that has process data. Figure 53 demonstrates the conceptual functioning of the EWS that is: from system process data, with sophisticated data analysis methods, valuable information about the system condition will be received.

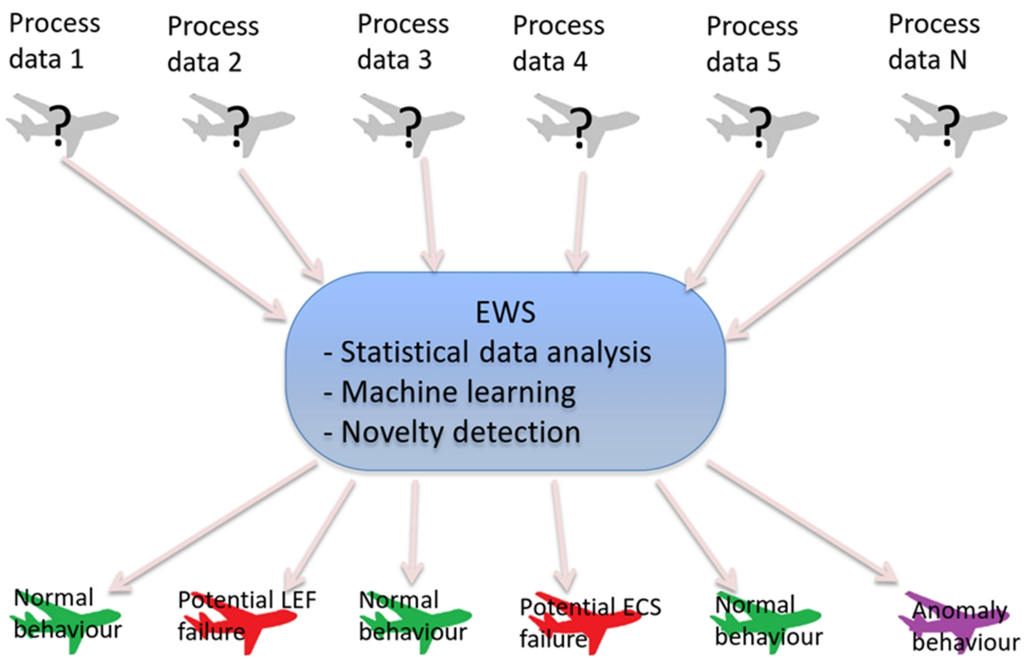


Figure 53: The concept of the EWS. First layer is the system process data, the second layer is data analysis, and the third layer is the interpretation about the system condition. Figure by courtesy of Tampere University of Technology.

In the EWS project the software for independent operation on the FINAF servers is under development. Currently the tool is capable of mining relevant parameters out of the data, like landing gear times from takeoffs and landings of the aircraft. Also, some conventional statistical reliability data analyses and spare part stock estimation with obsolesce aspect research are ongoing in the project.

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Summary

This document was prepared for the delivery to the 35th Conference of the International Committee on Aeronautical Fatigue and Structural Integrity scheduled to be held in Nagoya, Japan on 5-6 June 2017.

A review is given of the aircraft structural fatigue research and associated activities which form part of the programs within the Finnish Air Force Command (AFCOMFIN), the Finnish Defence Force Logistics Command, Joint Systems Centre (FINLOGCOM JSC), Air Systems Division; Aalto University; Emmecon Ltd; Finflo Ltd; Patria Aviation Oy; Trueflaw Ltd; Tampere University of Technology; and VTT Technical Research Centre of Finland Ltd (VTT).

The review summarizes fatigue related research programs and investigations on specific military fixed wing aircraft since the previous Finnish National Review (presented in the 34th Conference, ICAF, Helsinki, Finland) up to March 2017.

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