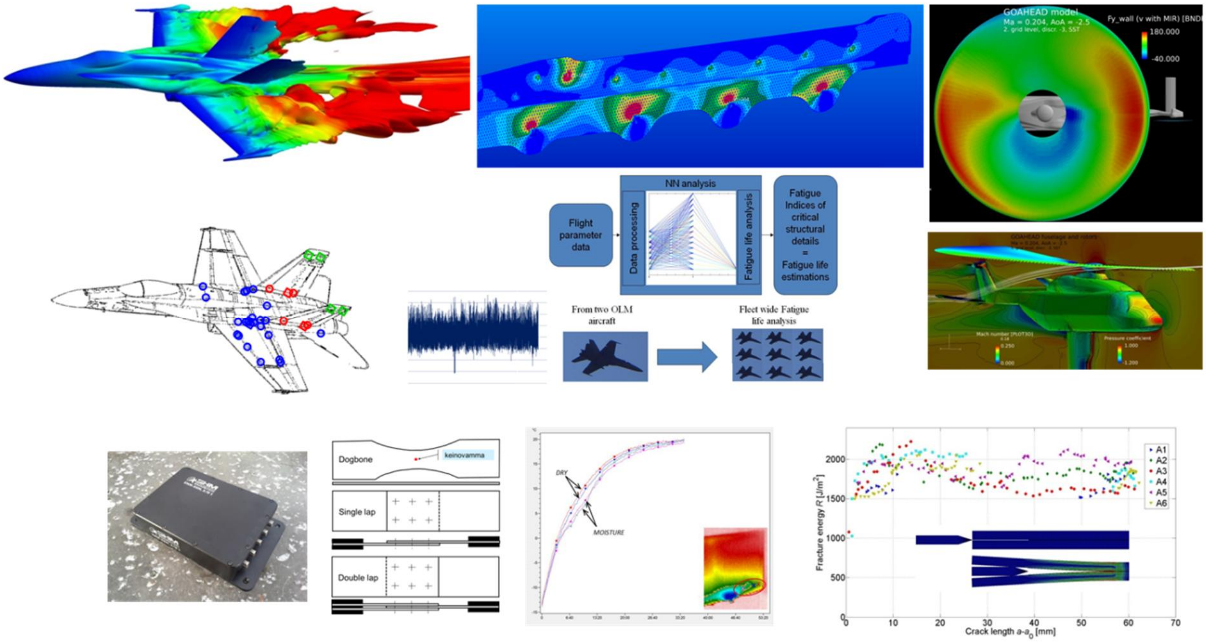

A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND MARCH 2013 – FEBRUARY 2015

Presented at the 34th Conference of the
International Committee on Aeronautical Fatigue and
Structural Integrity (ICAF),
Helsinki, Finland, 1-2 June 2015

Compiled by Aslak Siljander, Piritta Varis

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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Emmecon	*Emmecon Ltd:* Risto Hedman;
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FINLOGCOM JSC	*Finnish Defence Forces Logistics Command, Joint Systems Centre, Air Systems Division:* Hans Berger, Mikko Järvinen, Mikko Kahra, Ari Kivistö, Petri Korhonen, Riku Lahtinen, Lassi Latvanne, Rami Myllyniemi, Petri Pertola, Mika Siitonen, Ari Välikangas
FINAFSAC ACC	*Satakunta Air Command, Air Combat Centre, Flight Test Section:* Raimo Enberg, Hannu Heinelo, John Öström;
FINAFLAC	*Finnish Air Force, Lapland Air Command:* Peter Ylinen;
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	Patria Aviation Oy, Systems / Avionics: Tini Mäkelä, Marika Vuori.
VTT	*VTT Technical Research Centre of Finland:* Harri Janhunen, Juha Juntunen, Keijo Koski, Risto Laakso, Sauli Liukkonen, Sakari Merinen, Jarkko Metsäjoki, Tauno Ovaska, Enna Peltoniemi, Eetta Saarimäki, Jarmo Siivinen, Aslak Siljander, Tomi Suhonen, Tuomas Teittinen, Piritta Varis, Tommi Varis, Tomi Viitanen.

Espoo 21st May 2015

Editors

Contents

13.1 Introduction

The year 2015 marks the 97th 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. The fixed wing aircraft inventory of the FINAF at the time of writing this review is summarized in ***Fig. 1***.

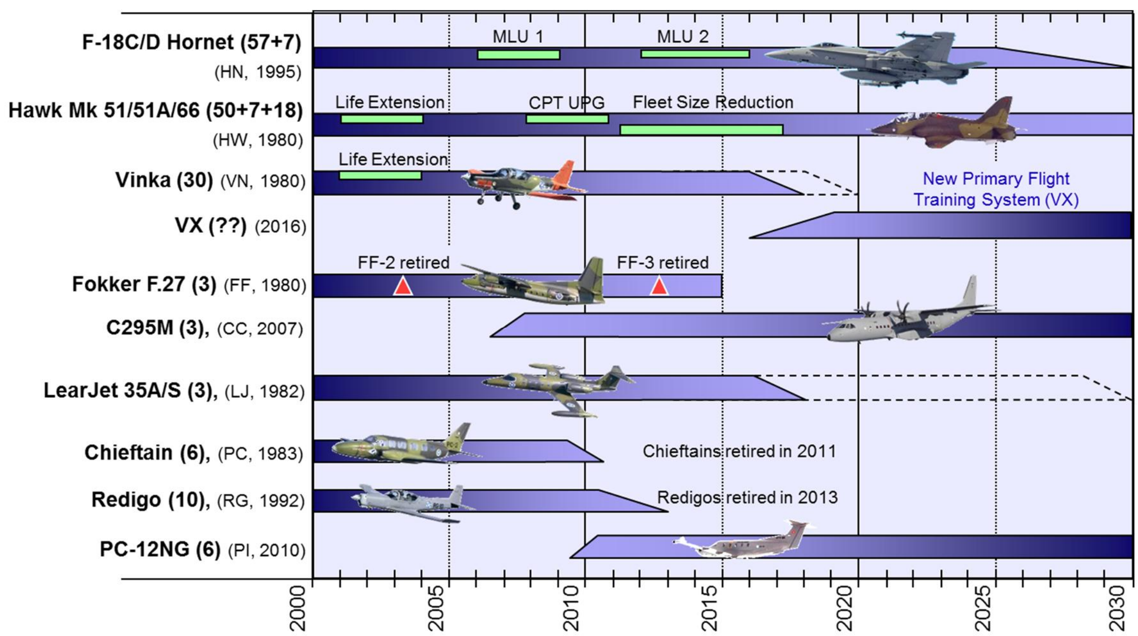

Figure 1: *An overview of the fixed wing aircraft inventory of the Finnish Air Force (FINAF). Picture by courtesy of the Joint Systems Centre.*

The 20 TTH/SAR NH90 helicopters purchased earlier by the Finnish Defense Forces (FDF) [1] are being retrofitted (by Patria) 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 ***Fig. 2***.

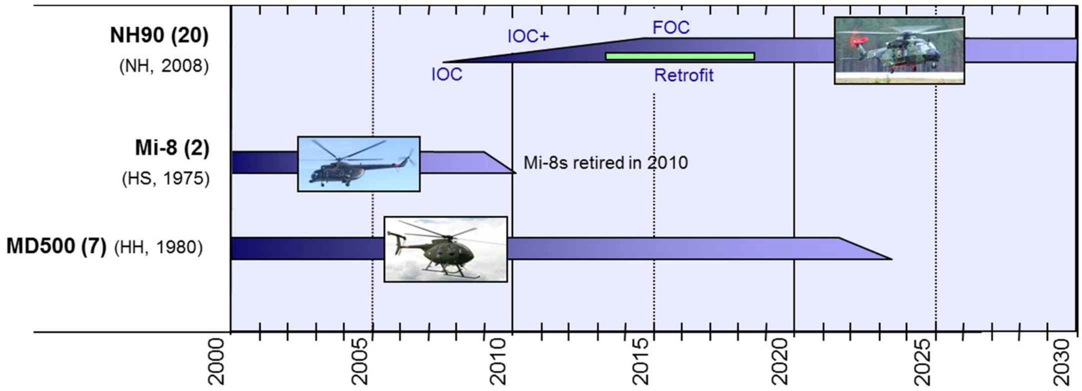

Figure 2: *An overview of the rotary wing aircraft inventory of the Finnish Defence Forces (FDF). Picture by courtesy of the Joint Systems Centre.*

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

13.1.1 Valmet Vinka

Previous activities related to the Valmet Vinka primary trainer of the FINAF were outlined in e.g. [1] Chapter 13.1.1. During the life extension program (LEP) of the Vinka primary trainers, the entire fleet was equipped with a g counter. The structural life consumption and severity of the usage is monitored by Patria Aviation by using the tail number-specific g counter. Patria also issues recommendations on 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. The first fleet leader will reach the 7000 FH limit during 2015.

Based on the g counter information, the primary trainers 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 on the basis of LEP assumptions, see ***Fig. 3***. It is possible to operate with Vinka until 2020 under its current type certificate. According to the FINAF's current plans the Vinkas planned withdrawal date is 2018. If there is a need to operate beyond 2020, the Vinka fleet will require another LEP.

The procurement for replacing the Vinkas is ongoing. The contract award for the new aircraft is estimated in the beginning of 2016. The Finnish Defense Forces Logistics Command has published a Request for Information (RFI) for the service procurement. This procurement covers the pilot training for Phases 1 & 2 using the FINAF's elementary and basic trainer aircraft, CAMO (Continuous Airworthiness Management Organization) and maintenance service of the fleet. The FINAF's current service contract terminates in the end of 2018, which is due to be renewed in this procurement.

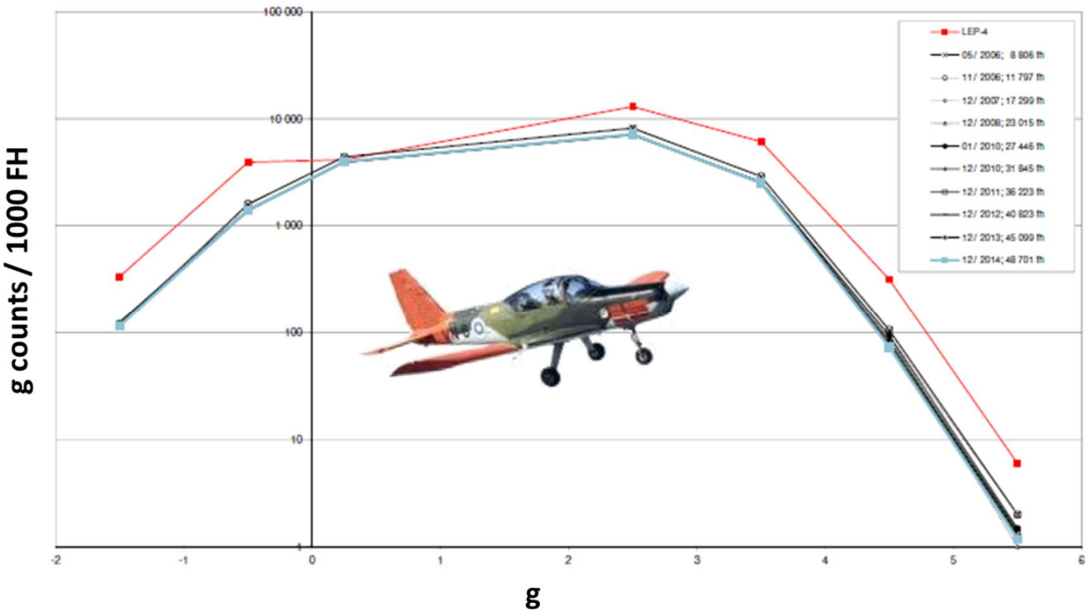

Figure 3: *The g counts per 1000 FH of the Valmet Vinka. From top to bottom: The spectrum representing the LEP design assumptions (LEP-4); the post LEP g counter spectrum as of May 2006; as of November 2006; as of December 2007; as of December 2008; as of January 2010; as of December 2010; as of December 2011; as of December 2012; and the updates from the previous review: as of December 2013; as of December 2014. All curves (excluding the red LEP-4) represent the fleet average from all Vinkas, as ranked according to the a/c center of gravity normal acceleration. Picture by courtesy of Patria Aviation.*

13.1.2 Hawk Mk51/51A and Mk66

In 2007, the Finnish Air Force purchased 18 pre-owned Hawk Mk.66s from Switzerland. These supplemented the Hawk Mk.51/51A fleet purchased earlier. In 2009, this was followed up by an order placed with Patria, for an extensive cockpit and avionics upgrade of the aircraft. The upgrade includes the replacement of all important avionics devices and cockpit display systems by new digital IT systems. The design is based on the upgrade already implemented on Mk.51/51A aircraft. Under the program, Patria was also responsible for developing software for the aircraft’s mainframe, the Mission Computer. All 18 modernized aircraft were delivered to the FINAF by January 2014. The aircraft which were not modernized will be retired by the end of 2018. Due to changes in the Hawk life cycle plans and the loss of two Mk66 jets, a new avionics upgrade project will start during 2016. Additional 7 Mk51 aircraft will be modernized by end of 2018. Thus, the 2019 fleet will consist of 31 Hawks: 8 MK51s, 7 Mk51As and 16 Mk66s.

13.1.3 F-18C/D Hornet

Between 2012 – 2015, Patria has conducted and is conducting the Mid-Life Upgrade 2 (MLU2) systems upgrade's series installations for the first 35 FINAF Hornet fighters and related manufacturing of components and harnesses. The work is taking place in conjunction with scheduled maintenance and structural updates of the aircraft. The goal of the FINAF is to upgrade all of its 62 fighters by the end of 2016. Patria has earlier implemented the first systems upgrade (MLU1) between 2007 – 2010 and performed the final assembly and testing of 57 single-seat F-18 C models when the fighters were purchased [1].

After the MLU2 upgrade the FINAF Hornets will have the ability to perform air-to-ground operations. This will reflect on training programs and the use of the aircraft. Other significant 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 MLU2-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'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. The MLU2 preparation work is done in cooperation with the Swiss Air Force.

The current structural life consumption of the FINAF F-18 fleet is shown in **Fig. 4**. As presented in the figure, the aircraft usage seems less severe than the design target. However, when compared to other F-18 operators the usage is more severe. The current target for the FINAF F-18 aircraft is 4500 FH and 0.75 FLE (simultaneously). To achieve this goal, the FINAF F-18 fleet needs a series of structural modifications and inspections. The first set of structural modifications (SRP1 – Structural Refurbishment Program 1) are designed and performed by Patria. Over half of the fleet is currently in the SRP1 configuration. Additional modifications were implemented to the SRP1 and the entire fleet will be on this SRP1+ configuration by the end of 2017. There is still more modifications and inspections needed after SRP1+ to achieve the 4500 FH goal. FINAF is also investigating the possibilities to extend the life of F-18s for 5 years, which equals approximately to 5000 FH.

It is worth noting that the structural life consumption (**Fig. 4**) is mainly decided based on a single detail of structure. The data collected from the said detail is processed by a piece of software provided by the aircraft manufacturer. As a result the structural life consumption for each aircraft in fleet is given.

Recently a new version of the software was taken into use by the FINAF and on average the results were lower for structural life consumption than using the previous software version.

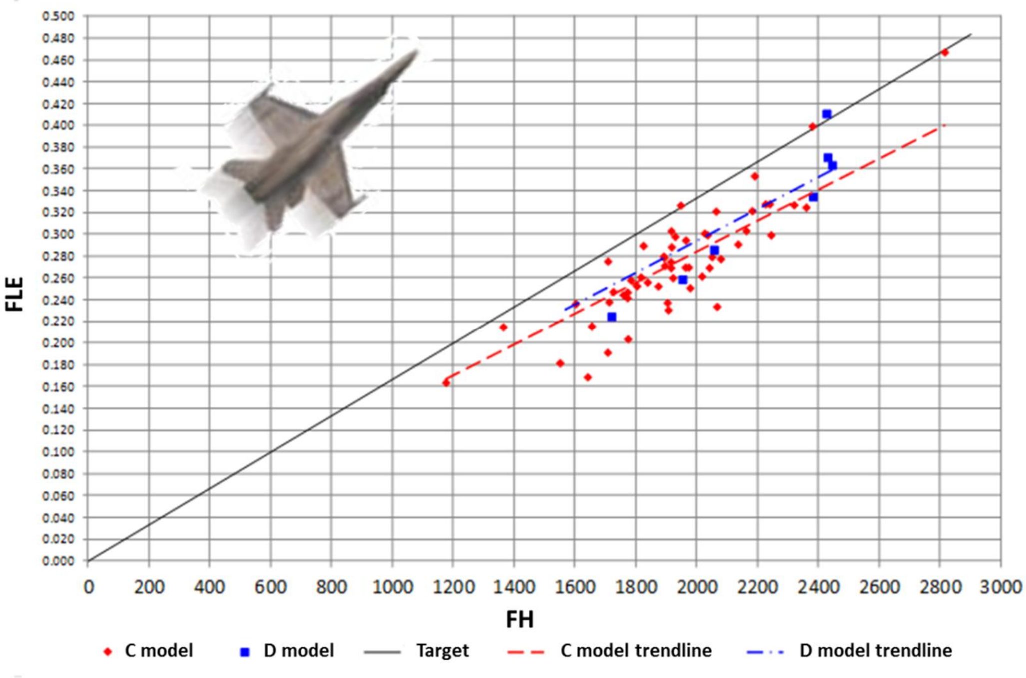

Figure 4: *Summary of the wing root fatigue life expended (FLE) of the FINAF F-18C/D fleet at the August 2014. The data is from all 62 aircraft included. The target is 4500 FH and simultaneously 0.75 FLE. Picture by courtesy of the Joint Systems Centre.*

13.1.4 Scope of the review

This national review on aeronautical fatigue concentrates on the fixed wing aircraft inventory of the FINAF related to fighter jets and associated pilot training aircraft. The FINAF inventory today includes 62 F-18C/D Hornet fighters, 8 Hawk Mk51, 7 Mk51A and 16 Mk66 jet trainers and 28 Valmet Vinka primary trainers. During the writing of this review, approximately 140 000 FH have been flown with the Hornets, 239500 FH with Mk51 and Mk51A Hawks and 25054 FH with Mk66 Hawks (6700 FH in Finland) and 168 000 FH with the Vinkas.

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

The severity of the Finnish usage in view of structural fatigue with the two jets of noteworthy maneuvering capability can be seen in ***Fig. 4*** (Hornet). Fig. 4 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 (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 February 2015 – although the 8th review but the 5th review as a full member – was compiled by Aslak Siljander and Piritta Varis (VTT).

The review comprises inputs from the organizations listed below (in alphabetical order):

Aalto	Aalto University, School of Engineering, Department of Applied Mechanics, Aeronautical Engineering, PO Box 14300, Puumiehenkuja 5 A , FI-00076 Aalto, Finland (http://appmech.aalto.fi/en/)
AFCOMFIN	Air Force Command Finland, Plans Division A5, Programmes Coordination Section, P. O. Box 30, 41161 Tikkakoski; Finland
Emmecon	Emmecon Ltd, P. O. Box 35, FI-53851 Lappeenranta, Finland (http://www.emmecon.fi/)
FINLOGCOM JSC	Finnish Defence Forces Logistics Command, Joint Systems Centre, Air Systems Division, P. O. Box 69, 33541 Tampere; Finland (http://www.ilmavoimat.fi/index_en.php)
Finflo	Finflo Ltd, Tekniikantie 12, FI-02150 Espoo, Finland (http://www.finflo.fi/)
Patria	Patria Aviation Oy, RTD & Aeronautical Engineering, FI-35600 Halli, Finland (http://www.patria.fi/)
VTT	VTT Smart Industry and Energy Systems / Lifetime Management, P. O. Box 1000, FI-02044 VTT, Finland (http://www.vtt.fi/?lang=en)

13.2 Current activities: ASIMP 2010-2012 and ASIMP 2013-2016

The Aircraft Structural Integrity Management Program (ASIMP) 2013-2016 with its various sub-programs [1] 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.

13.2.1 Loads and stresses

13.2.1.1 Computational fluid dynamics (CFD) – update

13.2.1.1.1 Validation and updating of helicopter flow simulations with actuator disks

In the ICAF 2013 review [1], helicopter CFD work aimed at modelling the flow field around the NH90 fuselage was described. A structured multi-block grid consisting of 99 blocks and having around 17 million cells was generated around the fuselage based on a representative geometric model. The flow induced by the main rotor was simulated by an analytical actuator disk model with the rotor represented by an axisymmetric overset grid block that can be tilted as desired. Test calculations performed with the domestic RANS-type FINFLO flow solver in two flight conditions gave reasonable solutions, but the results could not be compared with any reference data and the flow distributions at the rotor did not appear entirely realistic.

In spring 2014, a limited validation for the FINFLO helicopter simulations [2] could be performed on the basis of some data published of the EU research project GOAHEAD. In the project, a wind tunnel model consisting of a simplified NH90 fuselage and representative main and tail rotors had been studied computationally and experimentally, but useful data with and without rotors from just one flight condition representing fast cruise is publicly available. For the validation effort, the FINFLO model of the NH90 was modified to resemble the GOAHEAD model, and corresponding simulations were run. The comparison of results indicated that the FINFLO fuselage model is sufficiently correct and realistic, but the time-averaged rotor effects were poorly predicted by the applied actuator disk model.

Motivated by the findings of the validation, the actuator disk model of the FINFLO was completely replaced during late 2014. A method that combines momentum and blade element theories was interactively and iteratively coupled to the RANS solver in such a manner that a desired thrust vector can be produced by adjusting the control angles of virtual blades with twist. The blade element characteristics represent UH-60 main rotor airfoil data with extensions to extreme angles of attack and transonic Mach numbers. In addition, an automatic feedback control system for the blade angles was created to enable the thrust vector to be given as input. Patria Aviation defined the applied methods, and Finflo Ltd. implemented them into the FINFLO code.

In subsequent repeat simulations [3] of the GOAHEAD test case with rotors, the FINFLO results were dramatically improved. The flow and force distributions on the main rotor became significantly more realistic, as illustrated in **Fig. 5** containing the thrust loadings obtained with the new and old actuator disk model.

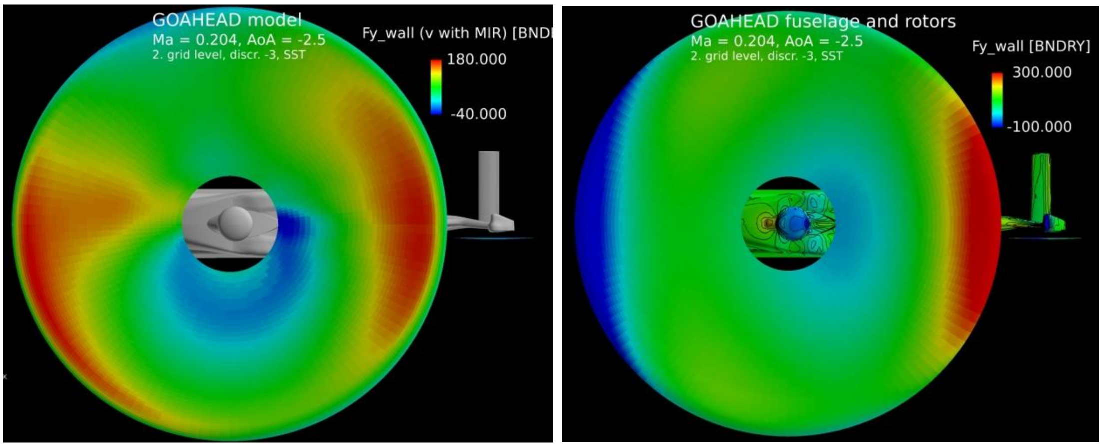

Figure 5: *Main rotor thrust distributions in the GOAHEAD test case at fast cruise computed with FINFLO using the new (left) and old (right) actuator disk models. Picture by courtesy of Patria Aviation.*

With the new actuator disks, the time-averaged rotor effects on the fuselage and tail surface became much better predicted. For example, **Fig. 6** shows how the main rotor wake emanating from its front sector hits the horizontal stabilizer, which increases the tail loads markedly. With the old actuator disk model, this effect was entirely missed.

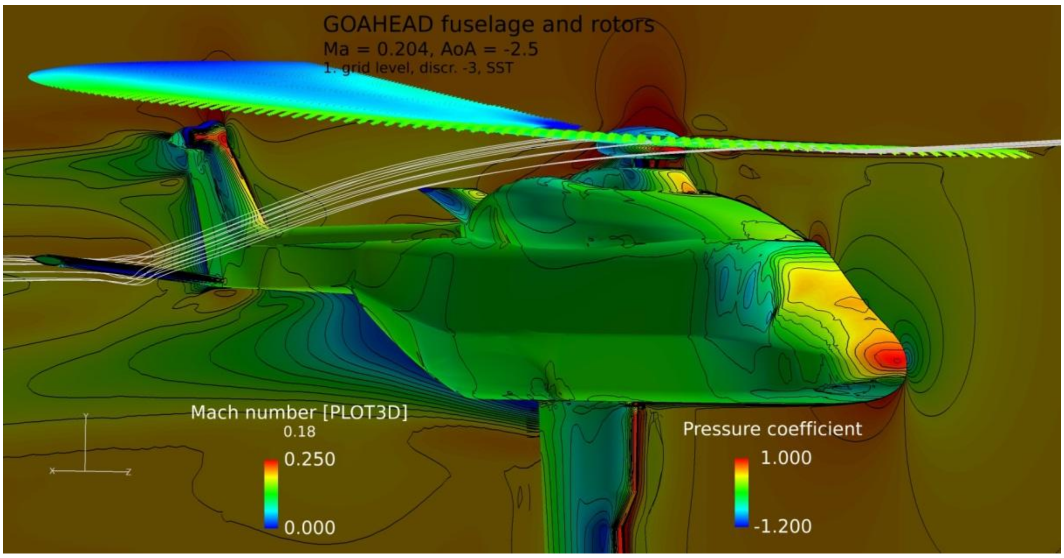

Figure 6: *Computed flowfield around the GOAHEAD model and streamlines of main rotor wake surrounding the horizontal stabilizer. Picture by courtesy of Patria Aviation.*

In addition to the single GOAHEAD test case, the new actuator disk model was tested with a simple detached rotor on a wide range of flow cases covering hover, extremely fast cruise, autorotation and even a vortex-ring state. Furthermore, the method was successfully applied to aircraft propellers at high thrust settings and at idle. The results always appear quite realistic, and the modes of automatic blade angle control for rotors and propellers respond quickly and correctly without oscillations. In the current state, time-averaged flow simulations for helicopter fuselages with actuator disks can be performed with improved confidence.

13.2.1.1.2 Computational Fluid Dynamics activities at Finflo Ltd.

Computational fluid dynamics (CFD) research at Finflo Ltd. is based on the in-house flow solver FINFLO. An essential feature of the code is a Chimera method applied in simulating flow fields around the F-18C fighter. Basic features of the method are described by [4]. Since then significant improvements have made in the algorithm. The Chimera method currently utilizes accurate wall distances, a refined interpolation method and a completely new dominating criterion for the overlapping grid blocks. The Chimera method is also applied for a prediction of helicopter rotor flow fields [5]. These simulations are time accurate and consequently time consuming. An actuator disk provides means to compute the rotor flow field as a steady-state solution. Several alternatives for the actuator disk model have been developed and the results compare fairly well with the time-accurate simulations.

As a part of the FINAF Hornet Mid Life Upgrade 2 (MLU2) Program, unsteady flow cases have been simulated using different approaches: URANS and Delayed Detached Eddy Simulation (DDES). The time-averaged loads predicted by these methods do not differ significantly from each other, but the DDES prediction contains higher frequencies. As compared to the steady-state RANS prediction there are significant differences in the time-accurate results. At a high angle of attack the simulated flow field remains often oscillatory even in the RANS simulation, but these oscillations are unphysical. An example of the simulated flow fields is a pull-up case at Ma = 0.75, AoA = 9.4° and $n_z = 5.1$ (***Fig. 7***).

Co-operation with CFSE and RUAG has been made for more than ten years. Meetings have been arranged to handle technical aspects and general CFD development, e.g. in Lausanne in July 2014. Recently the FINFLO and the NSMB codes were evaluated by calculating two flow cases at a high angle of attack for the F/A-18 [6].

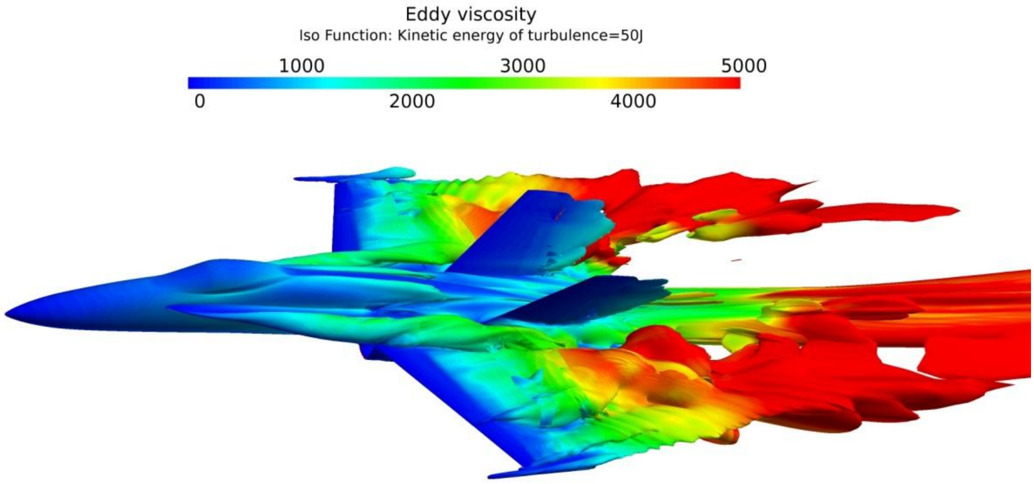

Figure 7: *An iso-surface of the kinetic energy of turbulence colored by the eddy viscosity in a pull-up case. Flight parameters are Ma = 0.75, AoA = 9.4° and* n_z *= 5.1. Picture by courtesy of Finflo Ltd.*

13.2.1.2 Hornet FE modeling – update

Previous development phases of the global and detailed finite element (FE) modeling of the FINAF F-18C Hornet have been outlined in [1] Chapter 13.2.1.3. Since then some new detailed FE models have been prepared: aft fuselage lower outboard longeron [7], vertical tail lower rib [8], wing root intercostals Y453, Y470.5 and Y488 [9], and inner wing outboard trailing edge flap hinge [10], ***Fig. 8***. According to these analyses, the aft fuselage lower outboard longeron is Full Life in the FINAF usage, but the other parts have some fatigue issues and require pre-emptive repair actions. New analyses with previously prepared detailed FE models of vertical tail stub Y590.5 and bulkhead Y508 wing root shear tie were performed [11] to define transfer functions for life estimation based on strain gauges installed in HOLM instrumentation modification, see reference [1] Chapter 13.2.2.1.2 and this report's Chapter 13.2.2.1.1.

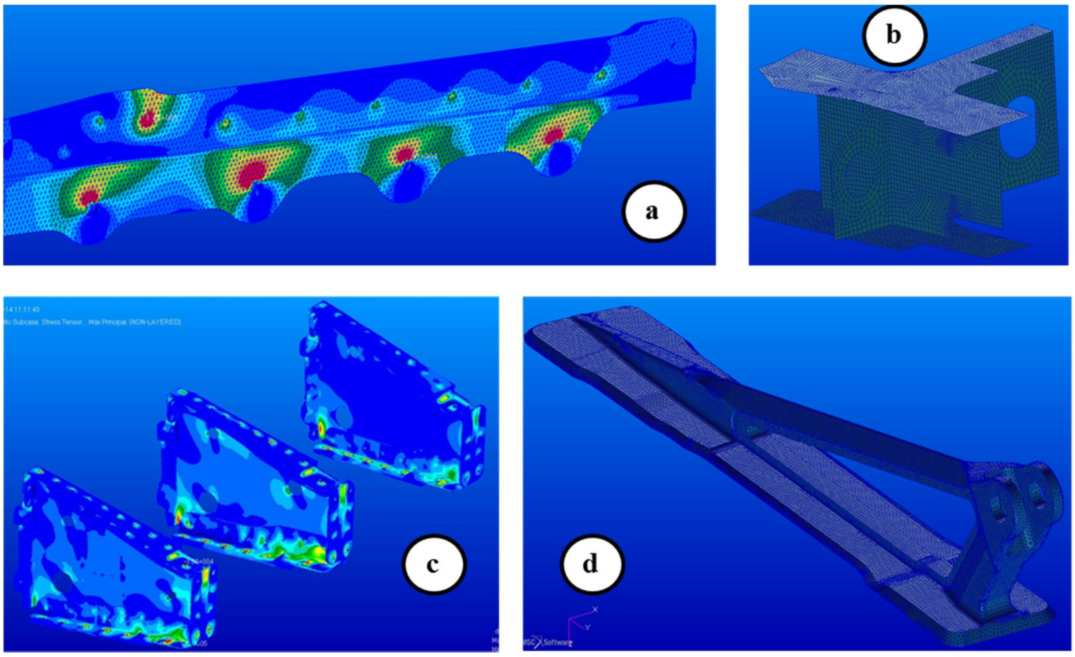

***Figure 8*: *Detailed FE models: **a)** aft fuselage lower outboard longeron, **b)** vertical tail lower rib, **c)** wing root intercostals Y453, Y470.5 and Y488, and **d)** inner wing outboard trailing edge flap hinge. Pictures by courtesy of Patria Aviation.*

The FINAF F-18 global FE-model was revised with some bug fixes and adjustments (e.g. control surface hinge lines) [12]. The global FE-model strain results for the HOLM strain gage locations were also compared with HOLM ground calibration loading and flight measurement data and the realism of CFD/FE loads on different areas of the a/c were assessed for 17 symmetric and 5 unsymmetric FINFLO load cases. The unsymmetric load cases can be applied in both directions.

Parallel to Patria's transfer function activities described above, the new and updated transfer functions have been transferred to VTT's HOLM ground station for damage analyses therein [13] [14].

13.2.2 Fatigue tracking systems

13.2.2.1 FINAF F-18 HOLM jets in routine squadron service

Previous research activities of the two FINAF F-18 HOLM (Hornet Operational Loads Measurement program) jets can be found in [1] Chapter 13.2.2.1. Like the other Hornets, the two HOLM jets, with tail numbers HN 432 and HN 416, are rotated in the Satakunta, Lapland and Karelian Air Commands.

The “production” version of the HOLM onboard system has collected statistically reliable flight data from FINAF’s routine fleet usage since 2006, and since then FINAF squadrons have continuously delivered flight data to VTT for data analyses. To date VTT has analyzed 1817 flights, and reported 1554 flights in the semi-annual fatigue tracking results reports [15]. However, following the 2013 restructuring and associated budget cuts within the Finnish Defence Forces and thus within the FINAF as well, several analysis activities at VTT have been discontinued.

Related to flight data analyses, VTT has studied continuous-time fatigue damage analysis based on two methods, the stress life and strain life methods. According to the studies, the continuous-time fatigue damage analyses give more accurate damage histories, from which the cumulative damage can be observed in time domain with respect to flight parameter and strain gage data [16].

The HOLM ground analysis environment has been updated to correspond to the HOLM modifications [17] [18] [19] (see next section).

In addition to the HOLM onboard measurement system modification (see next section) the ground analysis environment with its in-house developed programs has been updated.

The HOLM fatigue analysis database has been updated [20] [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.

The HN structural damage database has also been updated. The database has been used e.g. in screening the fatigue critical structural locations of the FINAF F-18C/D configurations and to help focusing the proactive maintenance planning activities. All observations emerged in the FISIF community (up to FISIF PMM 2012 (05/2012)) have been added to the database. Additionally, the graphical user interface GUI 4.0 has been updated. [22]

As a part of the international F/A-18 cooperation the FINAF assigned VTT to prepare a HOLM data set i.e. the specific collection of measured data excluding the analysis results to be supplied to the FISIF partners and to be used as they see fit. During this time frame two datasets were provided [23] [24] .

13.2.2.1.1 HOLM modification

The FINAF has routinely been running the Hornet Operational Loads Measurement (HOLM) program since 2006. The goal in this program is to quantify the effects of operational usage by the FINAF on the structure of the F/A-18 aircraft and therefore to support the aircraft structural integrity management. The flying in the structurally challenging AOA-Q combinations (→ buffeting) is reflecting as increasing the number of external signs of fatigue on Vertical Tail in the Finnish fleet and therefore makes this assembly as one of the current hot spots of the aircraft. Another structurally interesting area is the Y508 Former's shear tie region which, in case of fatigue cracking, could lead to time-consuming (wings off) repair. There are doubts if buffeting would be the prime factor for driving the Y508 cracks also.

As a step to cope with the on-going structural issues the FINAF started modification process in which the existing HOLM instrumentation was extended to support the national aircraft structural integrity management plan, ***Fig. 9***. The modification helps assessing the structural impact of new training missions. In addition to the HOLM system modifications, some of the current strain sensors were relocated into a more acute (i.e. fatigue critical) structural locations.

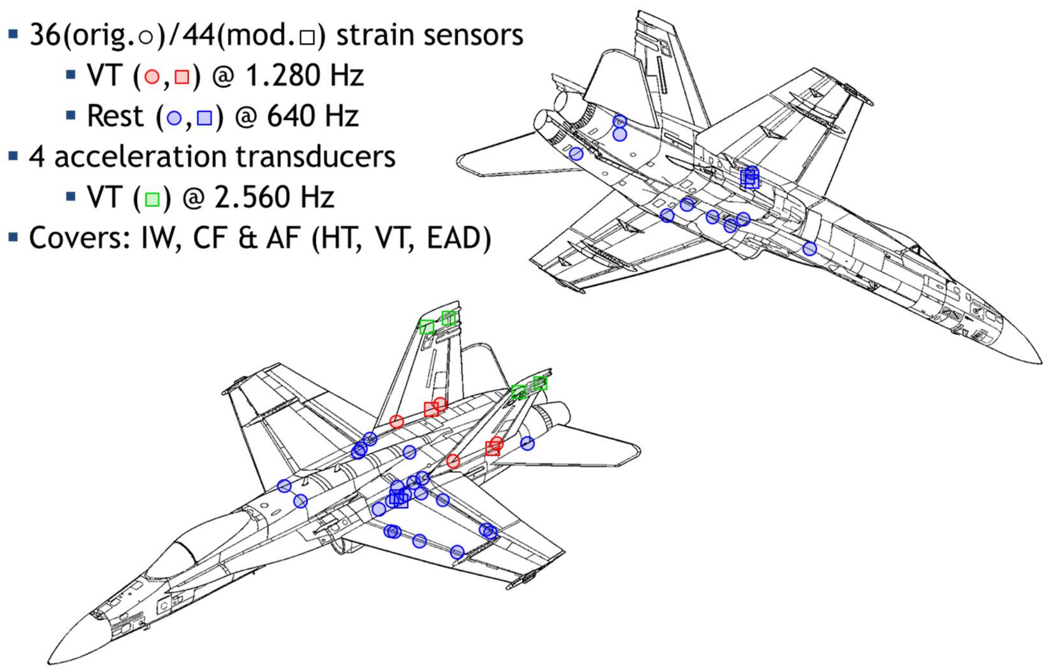

Figure 9: *An overview of the onboard HOLM system (the HOLM measurands) after the HOLM modification. Rectangular symbols denote the new strain gauge locations and the colors indicate sampling rates. Picture by courtesy of VTT.*

The existing on-board HOLM system for the two FINAF F/A-18 Hornets (HN-416 and HN-432) [1] Chapter 13.2.2.1 was modified to account for the increased buffet-induced dynamic stressing of the FY508 and the vertical tail regions. The existing data acquisition system was upgraded and a total of 12 new channels (8 strains + 4 accelerations) and associated LRU, system cable harnesses and other needed accessories were added and the systems were calibrated mechanically and electrically to these two HOLM jets, ***Fig. 9***. [25] [26] [27] [28] [29] [30]. The two HOLM jets are slightly different in their instrumentation suite.

13.2.2.2 Parameter based fatigue life analysis - update

Previous development phases of the parameter based fatigue life analysis system have been presented in [1] Chapter 13.2.2.3. The parameter based fatigue life analysis is an individual aircraft fatigue life monitoring system developed for the FINAF F-18 Hornet fleet by Patria Aviation, **Fig. 10**. The parameter based fatigue life 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 (Safe-life) estimates are calculated for 17 structural locations; each consisting of 1-3 features (e.g. 3 fastener holes in the same structure).

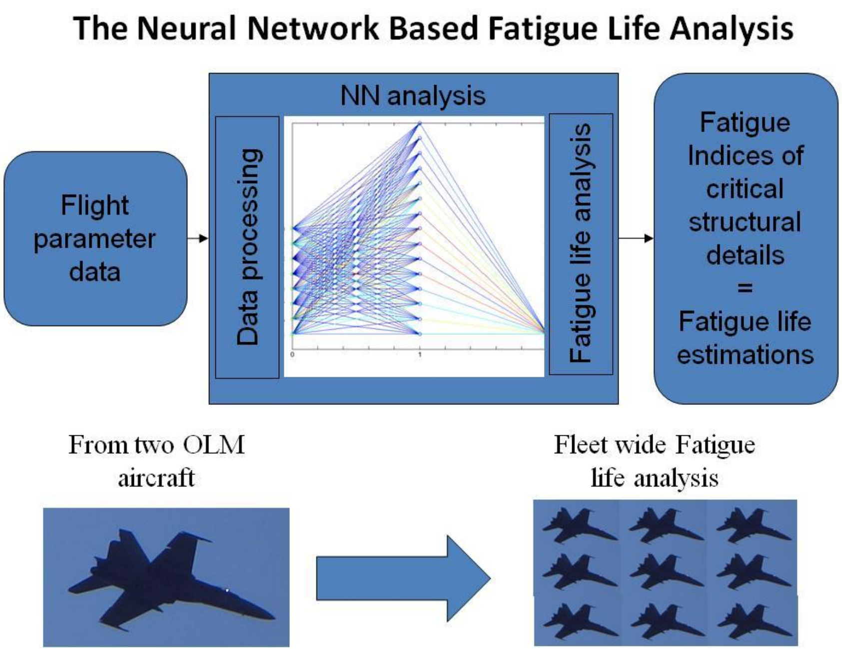

Figure 10: *Data flow of the applied monitoring method. Picture by courtesy of Patria Aviation.*

The parameter based fatigue life analysis is now a qualified system and its results are part of the decision making process in the fatigue life management of the FINAF F-18 fleet. 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 FLE results for some critical locations are still unreliable by absolute value due to problems in the transfer function produced by FEM, but as the performance of the ANNs for all locations have been verified to be of good quality, the FLE results for all locations are usable for relative comparisons between individual aircraft or for examining FLE trends in function of time.

The technical background of the analysis is comprehensively explained in the ICAF presentation at 2007 [31]. Previous development phases of the parameter based fatigue life analysis system was presented in [1] Chapter 13.2.2.3. A presentation of the current status, usage and experiences of the monitoring method for FINAF fleet management is found in the Symposium presentation [32].

13.2.2.2.1 Analysis development

Since the ICAF 2013 [1] the analysis has been extended by adding the wing root intercostal locations [Chapter 13.2.1.2] in the system. Two new HOLM strain gages were needed for this and neural networks for them were trained and evaluated [33]. Then the individual aircraft fatigue tracking for these locations was performed for the whole FINAF F-18 fleet flights for years 2000-2007 (flights available for Patria at that time) [34].

As the FINAF F-18 fleet go through structural repairs and modifications, the fatigue life analysis parameters may also change. For example some structural part could be replaced or its fatigue life expenditure is removed (removed initial cracks) or slowed down (reduced stress level). Future development is to define individual fatigue analysis parameters for each aircraft which take into account life improvement factors of the repairs.

13.2.2.2.2 In-service maintenance

Previous performance review of the system has been conducted two years ago concerning years 2011-2012. Continuous performance assessment is also required in the future, because the operating environment is under constant change. The need for retraining of the ANN is decided on the grounds of the assessment.

13.2.2.2.3 Coverage of the analyses

Extending the coverage of analyzed flights has been delayed but recently flight parameter data from the years 2008-2014 were received for analysis. Then almost full service life of the FINAF's F-18s will be covered. Also early flights from 1995 to 1999 are planned to be analyzed in the near future. The coverage of the structural locations is already extensive but new needs might always arise.

13.2.2.3 Research efforts towards an OLM replacement system (Hawk Upgrade 2)

13.2.2.3.1 Structural health monitoring (SHM) – update

Previous activities related to the fatigue tracking activities of the FINAF Hawks were highlighted in previous ICAF reviews e.g. [1] Chapter 13.2.2.4, including the investigations related to the replacement of the Mk66's obsolete ESDA (electronic structural data acquisition system) onboard monitoring system.

Emmecon's SHM system (strain measurement and analysis) has further been developed since the previous review, ***Fig. 11***. One FINAF Mk66 jet trainer was equipped with Emmecon's onboard SHM prototype system during the jet's normal squadron service. During the three-month normal squadron service period (63 flights total) the SHM system collected in-flight data from two structural locations (vertical fin and tailplane).

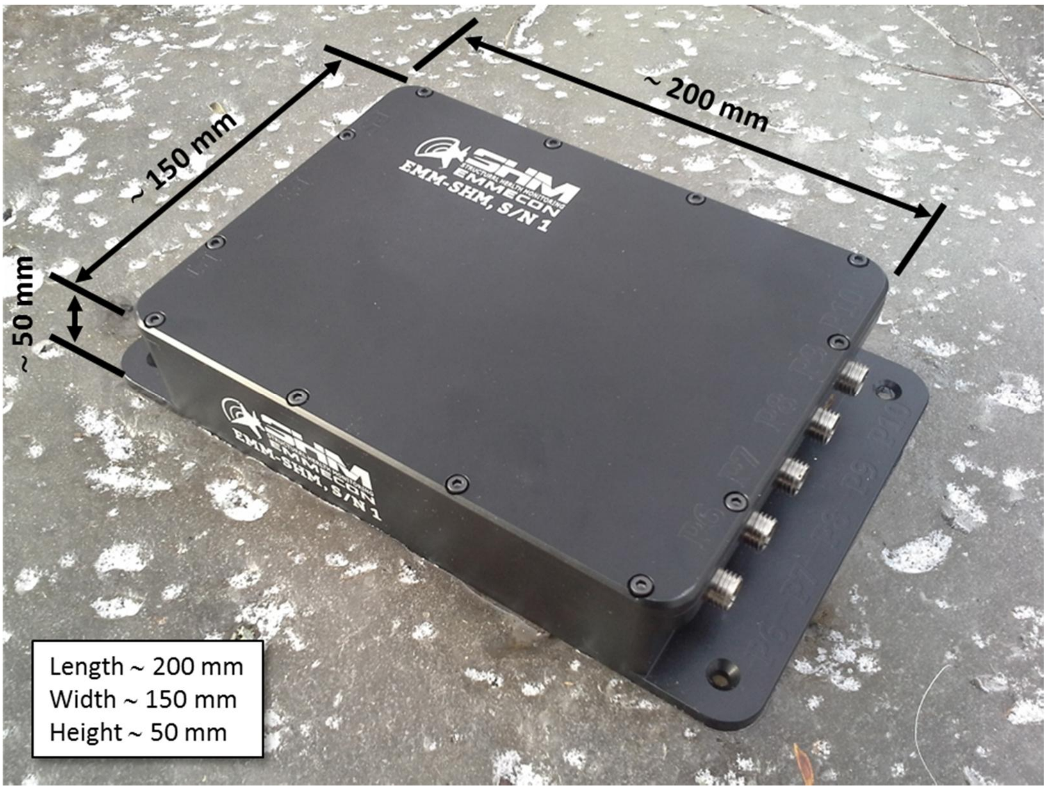

Figure 11: *An overview of Emmecon's SHM system. Picture by courtesy of Emmecon Ltd.*

The onboard data acquisition, processing and storage of the prototype SHM system was functional as anticipated during the squadron service period. Post-flight analyses of the in-flight data however revealed two issues. First, the EMI protection (protection against electromagnetic interferences) of the cabling of the vertical fin strain gauges was not adequate to shield the VHF signals emitting from the VHF antenna (located at the tip of the vertical fin) thus causing unwanted disturbances on the measurement signal. Second, the prototype SHM's operating system was not stable in all situations, as the operating system was observed to be vulnerable in events where the aircraft's main powers are switched off.

The above issues have been eliminated in the updated prototype SHM system. The goal is to install updated prototype SHM systems to a few Mk66 aircraft (2-3 jets) during 2015 for new squadron flight trials.

13.2.2.3.2 Mk66 structural life and the mini OLM activities

To come up with the most potential fatigue critical structural details of the FINAF's Mk66 jet trainer fleet and the associated integrity management plan, the fatigue critical structural details and the long experience in their rework activities from the older FINAF Mk 51/51A fleet were assessed. Estimates for the onset of Mk66 structural fatigue damage for the most important structural assemblies were made by utilising the Mk 51/51A cracking observations, maintenance records, the cumulative flight syllabi data and the data from previous OLM programs [1] Chapter 3.4 and from the above Mk66 SHM experiences.

A decision has been made within the FINAF to instrument one Mk66 jet trainer with a mini OLM system capable of collecting enough in-flight data from dedicated test flights as well as from normal squadron service, to come up with an average spectrum for the most important structural assemblies. The aircraft is being instrumented at the writing of this review (***Fig. 12***) and the flights (tens of flights rather than hundreds of flights) will be flown during 2015.

***Figure 12**: An overview of Mk66 tailplane mini OLM instrumentation. Picture by courtesy of VTT Ltd.*

The fatigue damage estimates obtained, as described above, will be fine-tuned using the average usage spectrum from the planned flights. Another use of the average usage spectrum is to come up with the structural integrity management plan for the remaining service life of the FINAF Mk66 fleet. Yet another goal with the use of the new in-flight data is to develop and teach the first prototype neural network (NN) for the Mk66's tail. After the mini OLM flights, the prototype NN will then be tuned using the in-flight data obtained from the data obtained from the 2-3 SHM equipped Mk66 jets, as soon as statistically enough flights with the onboard SHM systems have been flown.

13.2.3 Structural integrity of composite materials

13.2.3.1 Thermographic studies – update

Previous activities have been reported in [1] Chapter 13.2.3.1. Penetrated water or moisture ingress in the composite sandwich structures has caused problems in aircraft structures. Flight surfaces have been lost during the flights, because moisture corrodes the honeycomb and further reduces the strength of the adhesive. Water (moisture) can also cause additional defects during the composite repairs, which have resulted in the expansion of the moisture (in closed cavity), hence causing skin blow core phenomena during the curing cycle (heating) of the repair.

The number of penetrated water-induced failures 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 have been working in close co-operation to develop a method to detect moisture and efficiently remove it from the structures. More than 50 rudders of the FINAF F/A-18 jets have been inspected during the period and water has been detected from around 20 % of inspected rudders.

The procedure is divided to three phases:

1. X-ray inspection, which can indicate suspected water in one or multiple honeycombs.
2. Drying procedure (several hours)
3. Thermographic inspection to verify remaining water.
    - If water is detected after thermographic inspection, the procedure steps 2 and 3 are repeated as long as structure is found to be dry.

X-ray inspection can detect assumed water ingress, if the water has filled most of one or several honeycomb cells. The drawback is that there is no certainty, if the indication is from water or excess adhesive/resin from manufacturing process. If doubt of water ingress is observed during X-ray inspection, structure will go through special drying procedure.

A gentle procedure to remove the water is applied to the honeycomb composite structure, because it is essential not to cause skin blow core effect during the drying phase. Honeycomb composite structure is heated under a low vacuum to vaporize moisture from the structure. The heating takes place for several hours.

Thermographic inspection based on the phase transition of water exploits the phase transition energy that is needed for the ingressed water to be defrosted (melted). Water ingress indication is observed in a specific phase transition temperature and the indication insures the presence of water. Another advantage of this method is that no additional excitation source is needed for the tests. Method based on the phase transition can be especially exploited during the long period of arctic weather conditions in Finland and other cold areas. Composite structures can be left outside in freezing conditions overnight and inspected when they have been brought in to warm conditions. The non-contact thermographic inspections are conducted during the warm-up period in the hangar, ***Fig. 13.***

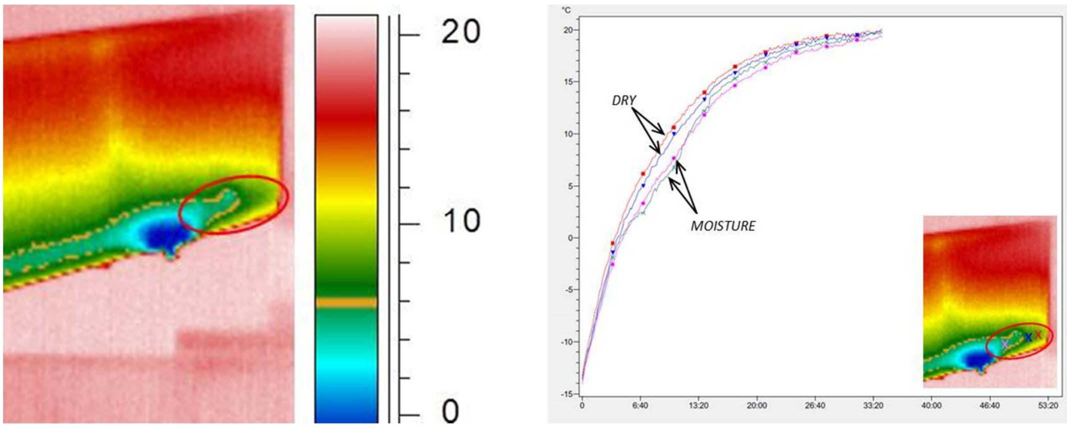

Figure 13: *An example of the thermographic inspection based on the phase transition of water. Abnormal warming is observed within the circled area (left). The measurement locations are displayed with symbols "X" (right); each warm-up curve's color is related to the same color "X" (lower right within the circled area). Moisture ingress/penetrated water can be observed from the curves denoted with "MOISTURE". Picture by courtesy of VTT.*

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.

13.2.3.2 Fracture mechanics based analysis and tests of delaminations

Previous fracture mechanics-based studies on composite structures were highlighted in [1] Chapter 13.2.3.2. The work on numerical fracture mechanics using virtual crack closure technique (VCCT) has been continued and it is described below. The work concentrated on the applicability of VCCT on analysis of ductile adhesive joints. The software tool used in the work was ABAQUS. Analysis work was supported by experimental tests in mode I loading.

The fracture mechanics based analysis work on adhesively bonded joints was continued in mode II loading. A test specimen was designed to be used in end notched flexure (ENF) test in three point bending [35]. The purpose was to design a specimen with stable crack growth and without the excessive frictional effect due to loading of the specimen. The specimen consists of aluminum adherends and FM 300-2 film adhesive. Preliminary simulations show that a stable crack propagation of approximately 5 mm is possible to obtain with careful selection of adherend thickness and initial crack size. Therefore it is possible to obtain also propagation values for the adhesive in mode II loading. Typically the crack propagation is unstable in the ENF test and only insert values are obtained.

Based on the work performed on VCCT analysis two publications are prepared. The previously reported work on analysis of the FINAF F-18 trailing edge flap delaminations is published as a poster presentation in ICAF 2015 [36]. The second paper with the title 'Applicability of VCCT in Model I Loading of Yielding Adhesive Bonded Joint – a Case Study' is submitted for publication in International Journal of Adhesion and Adhesives [37]. The paper is under peer review process. In addition, a paper including simulations performed on wedge test specimens is under preparation. The simulation of wedge test is illustrated in ***Fig. 14***.

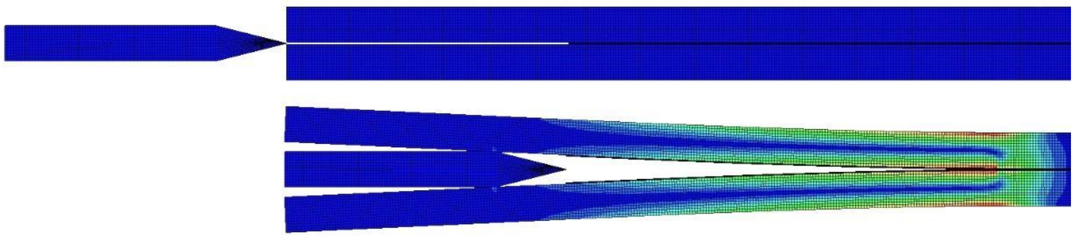

Figure 14: *Simulation of the wedge test specimen). Picture by courtesy of Aalto University.*

The experimental work in mode I loading was continued. The double cantilevered beam (DCB) with aluminum adherends and FM 300-2 adhesive film was used. The tests are performed on specimens with either two or one adhesive film layer. On the average the propagation G_I values are similar for both cases but in case of one adhesive film the bridging effect of the carrier is more significant. In addition the behavior of the crack in the beginning is different as illustrated in ***Fig. 15***.

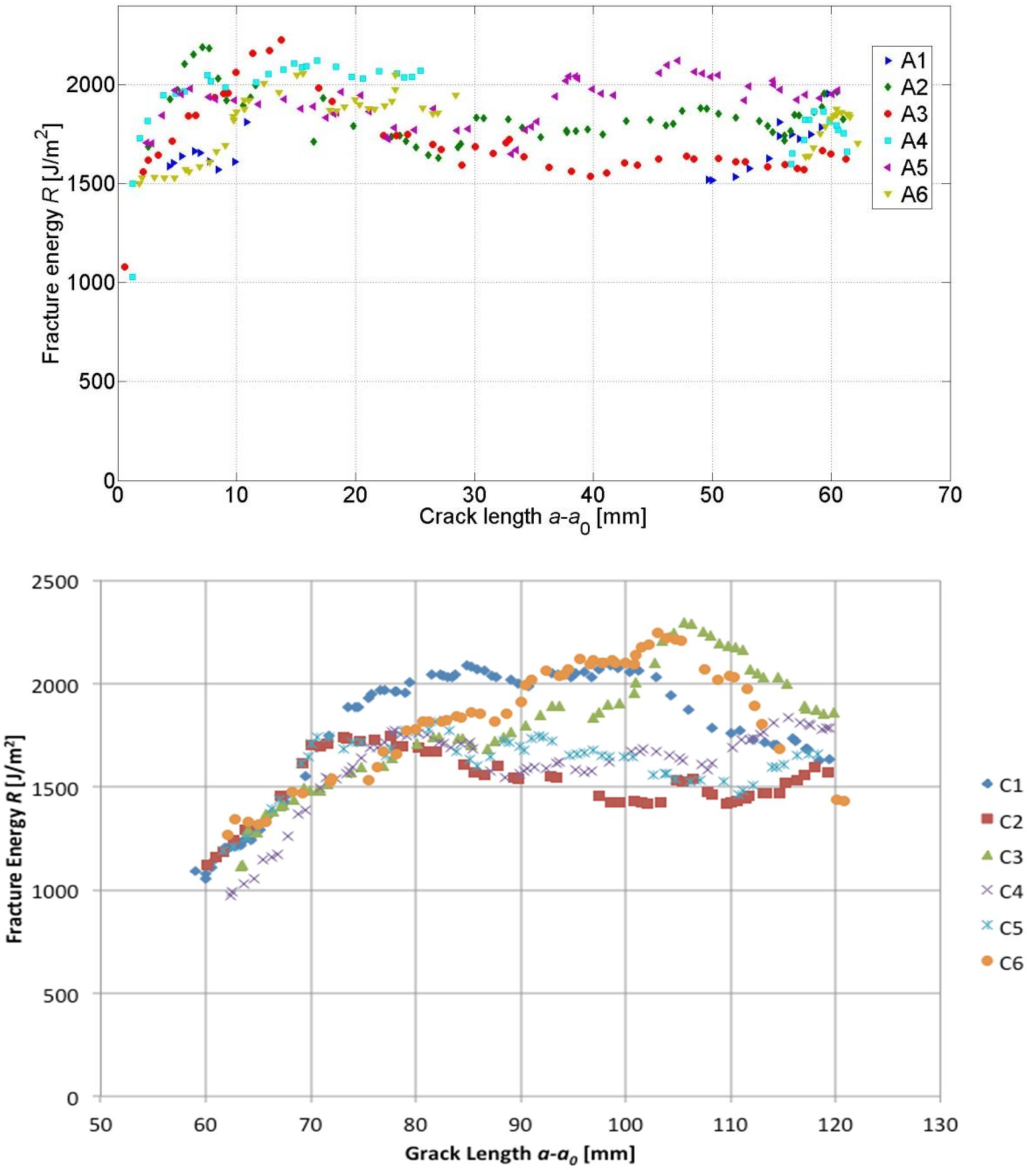

Figure 15: *Fracture energy of DCB specimens with two (above) or one (below) adhesive layers. Picture by courtesy of Aalto University.*

13.2.4 Structural integrity of metallic materials

Previous surface renewal activities have been reported in [1] Chapter 13.2.4. The following summarizes the research efforts since the previous review.

13.2.4.1 Verification of repair methods (JoBolt)

The influence of repair methods and fastener types for fatigue behaviour were studied using test coupons manufactured of aluminium. Patria Aviation Oy designed, manufactured and planned the tests and administered the test program. The coupon tests were designed to complement earlier fatigue tests [1] [38] [39]

[40] [41] [42] [43] of the FINAF F-18 repair methods. The coupon fatigue tests were performed by VTT. Three different coupon types were utilised: a basic dogbone coupon (7050-T7451), a lap joint coupon (7075-T76) and a double-lap coupon (7075-T76), ***Fig. 16.*** A total of 52 + 24 + 25 coupons were tested (basic dogbone, lap joint and double-lap, respectively).

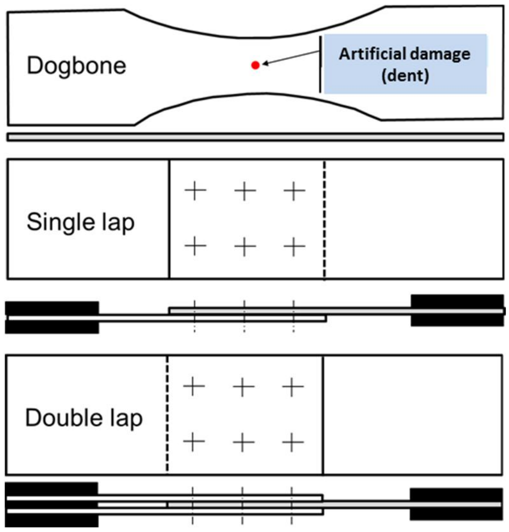

Figure 16**:** *An overview of the three coupon types. Picture by courtesy of Patria Aviation Oy and VTT.*

With the lap joint and double-lap joint coupons with Jo-Bolt fasteners the aim was to emulate a region within the FINAF F-18 Hornet’s Inner Wing Front Spar (holes #170 - #173 modification). Further, the Interference Fit Hi-Loks were planned to be replaced using Cold Worked holes and oversized Jo-Bolt fasteners (NAS1671-3L-5 for the lap joints and NAS1671-3L-8 for the double-lap joints), whose fatigue characteristics were not adequately known prior to the planned tests. According to the HSB 63511-02 (Handbuch Strukturberechnung) the blind (non-driven) rivets such as Jo-Bolts are known to have very low fatigue life (10 % - 25 %) compared to the Hi-Loks, and no data on the effect of Cold Work were available prior to the tests.

The dogbone specimen tests were performed to get information on how deep dents and blended/polished dents affect to the shot peened structures’ fatigue life. Before 8/2013 there was no ability in Patria to repair shot peened areas correctly using the flap peening or shot peening; landing gear parts were shot peened and surface treated by Finnair engine repair shop (now part of GA Telesis). Now Patria has also the flap peen and manual shot peening capabilities, aimed at the peening of e.g. Y488 Bulkhead/Match Angle chafing and the HT Bootstrap and the nicks and gouges therein. A summary of the fatigue tests performed is provided in **Tables 1-2**.

Table 1: *Summary of the fatigue test performed, dogbone coupons. Table by courtesy of Patria Aviation Oy.*

Series ID	SP(1)	W/O SP	AD(2)	PC(3)	P(4)	CA(5)	S_{max}(6) [MPa]	S_{max}(6) [MPa]	S_{max}(6) [MPa]	VA(7)	# of coupons
YHN0012390-1	•					•	360	320	250		12
YHN0012390-2	•		•			•	360	320	250		12
YHN0012390-3	•		•		•	•	360	320	250		12
YHN0012390-4	•									•	3
YHN0012390-5	•		•							•	3
YHN0012390-6	•		•		•					•	3
YHN0012390-7	•		•	•	•					•	3
YHN0012390-8		•	•		•					•	3

Table remarks:

1SP = Shot peening (performed prior to tests)
2AD = Artificial damage (produced before the tests): a dent mark (approx. 0.5 mm depth) punctured using a pyramid tip of 2.5 mm width
3PC = Pre-cycling
4P = Polish: The ratio of polish area radius and the artificial damage depth about 10, surface roughness 0.4 – 0.6 µm (R_a)
5CA = Constant amplitude loading (R = -0.3)
6S_{max} = maximum stress [MPa], there were 4 coupons per maximum stress level in the CA tests
7VA = Variable amplitude loading (see ***Fig. 17*** for spectrum details)

Table 2: *Summary of the fatigue test performed, lap and double-lap coupons. Table by courtesy of Patria Aviation Oy.*

Series ID	Lap joint	Double-lap joint	W/O C/W(3)	C/W(4)	Maximum applied gross section stress S_{max} [MPa] / # of coupons per stress level				# of coupons
YHN0012400(1)	•		•		110 / 4	90 / 4	70 / 4		12
YHN0012410(1)	•			•	110 / 4	90 / 4	70 / 4		12
YHN0012420(2)		•	•		130 / 4	110 / 4	90 / 4	70 / 1	13
YHN0012430(2)		•		•	170 / 4	150 / 4	130 / 4		12

Table remarks:

1Jo-Bolt fastener NAS1671-3L-5 (cold working according to PS 19180)
2Jo-Bolt fastener NAS1671-3L-8 (cold working according to PS 19180)
3W/O C/W = Without cold working
4Cold working applied

The specimens were subjected to either constant amplitude or variable amplitude loading, ***Fig. 17***.

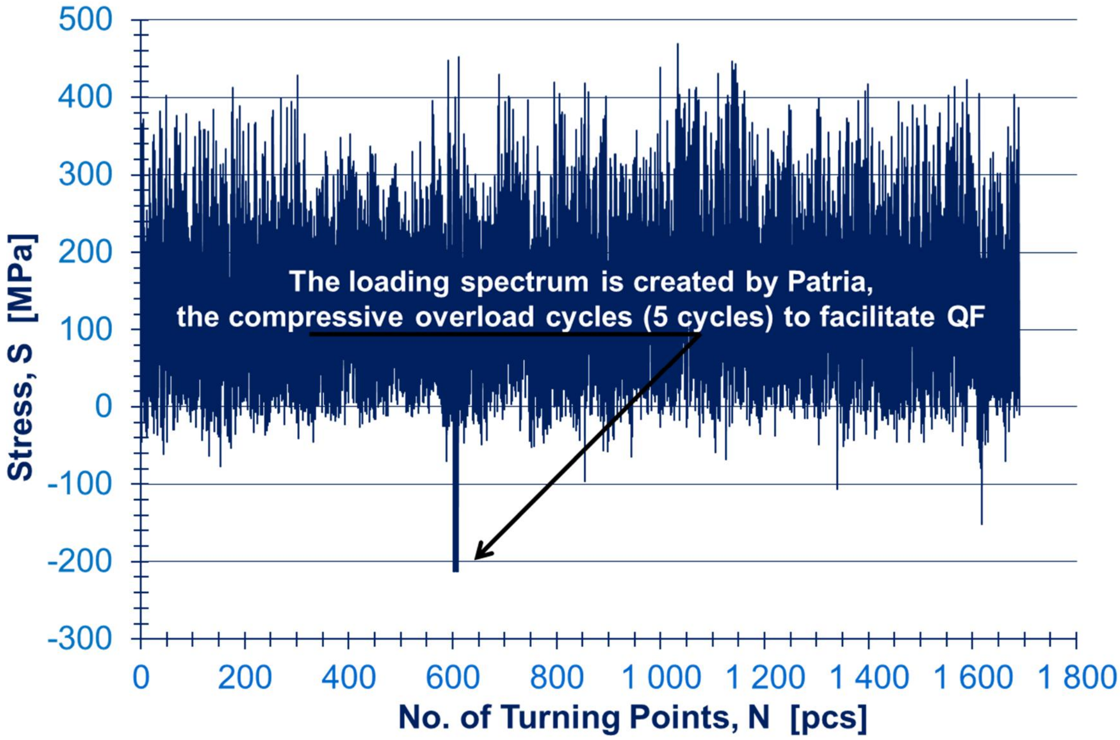

Figure 17: *An overview of the variable amplitude loading spectrum for the dogbone coupons: HOLM S47 (Y488 BLKHD). Picture by courtesy of Patria Aviation Oy.*

For the dogbone coupons the following observations could be made (***Fig. 18***):

- The fatigue life of the dogbone coupons with shot peening and sharp dents was surprisingly good in that the dents appear to affect less than the K_t theory. In fact, the fatigue life was better than basic material Al 7050-T7451 without shot peening (MIL-HDBK-5H values).
- The achieved shot peening LIF (life improvement factor) was 4 … 10 depending on the stress level. Sharp edge removal from the coupons prior to the tests was noticed to be important.
- Blending and polishing inside the shot peened area is a bad solution (fatigue life was lower than without dent removal). Repair shot peening is required.
- During the dent removal process, the Confidence Cut is mandatory

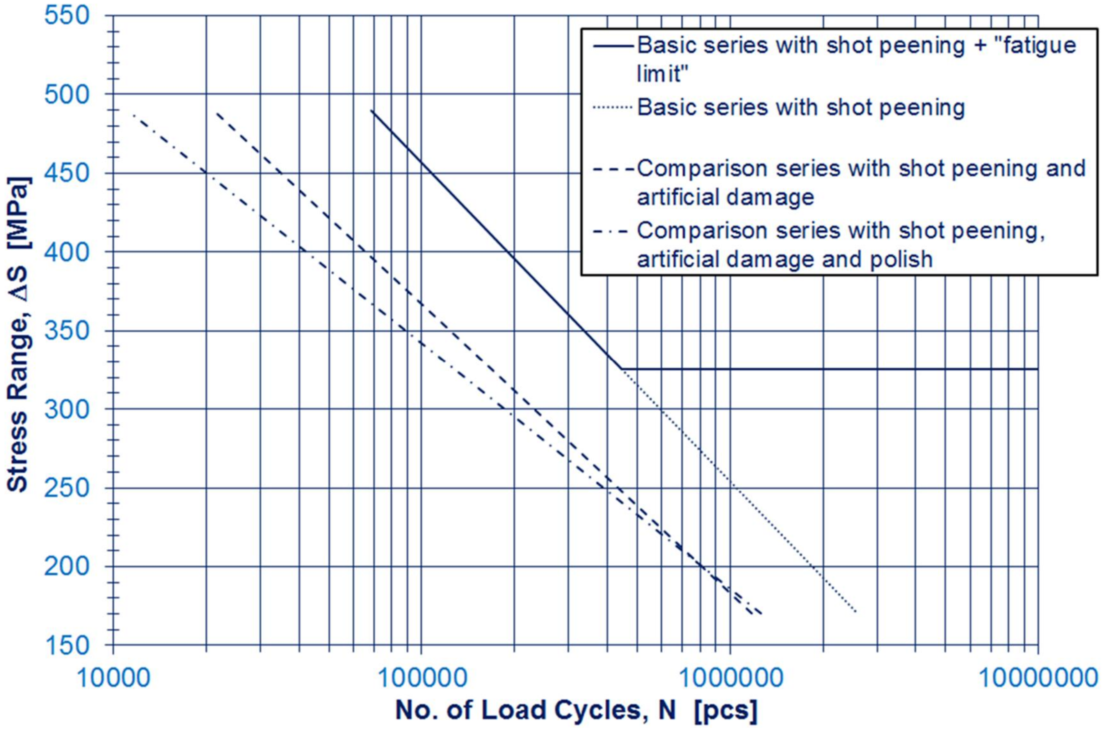

Figure 18*: *Summary of the dogbone coupons' results (constant amplitude loading), natural logarithm fitting in the test results. Picture by courtesy of Patria Aviation Oy.

For the Jo-Bolt tests (lap and double-lap coupons) the following observations could be made (***Fig. 19***):

- CW (cold worked) Jo-Bolt joint seems to be as good as the I/F (interference) fit Hi-Lok (tested earlier). Confirmation for the Inner Wing Front Spar modification, it can be done twice: the first oversize before 0.4 FLE and the second oversize at 0.8 FLE (for exceeding latter limit)
- The cold worked LIF (life improvement factor) for the Jo-Bolt joint is approx. 1.3 (single lap joint) and approx. 2 (double lap joint).
- In the single lap joint coupons the secondary bending effect is dominant. The fatigue life of the Jo-Bolt joint is barely as good as the Hi-Lok joint (single lap joint, Class 2 holes).
- The HSB 63511-02 blind rivet "LIF" of 0.1 … 0.25 can be neglected for Jo-Bolt joints. The HSB "LIF" is valid for CherryMax-type blind rivets.

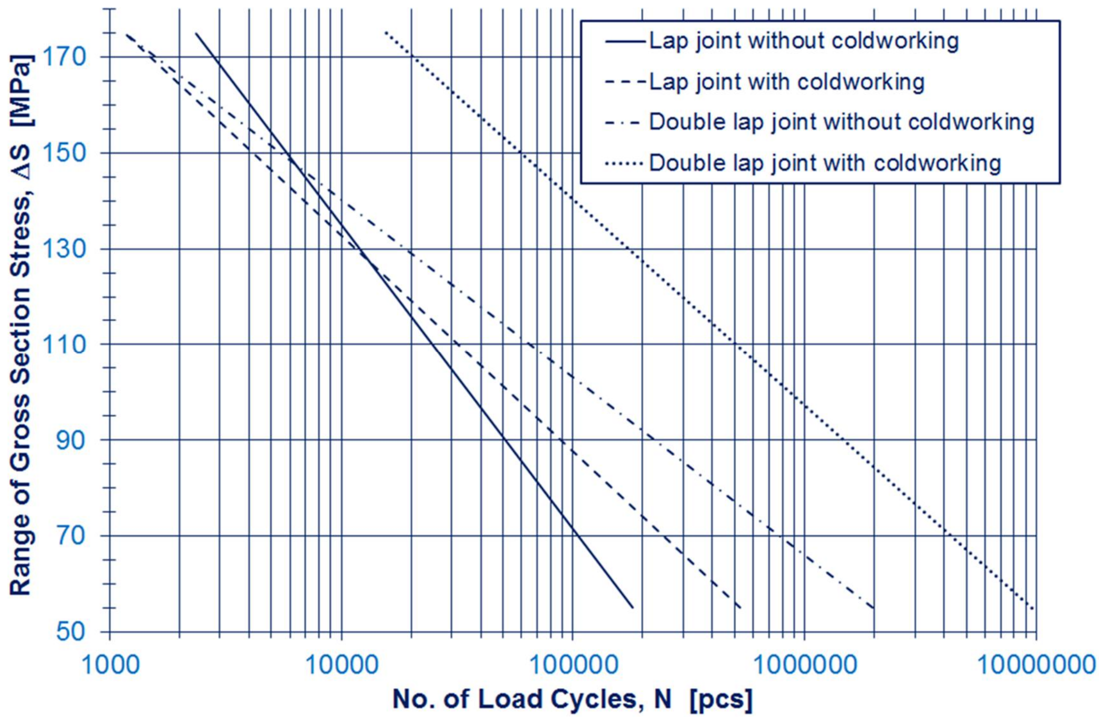

Figure 19**:** *Summary of the lap coupon and double-lap coupon results (constant amplitude loading), natural logarithm fitting in the test results. Picture by courtesy of Patria Aviation Oy.*

All in all, the artificial dents were relatively deep (30 % stress increase) which may not be typical for small fleet blends, therefore the blend/polish may work better in reality than in these tests. More different joint specimen tests, based on the needs specified by planned future repairs, are being planned for the dent removal (manual shot peening repairs/manual flap peening repairs) including associated confidence cut studies [44] [45].

13.2.4.2 FISIF Hole Salvage project

Under the auspices of the FISIF, a collaborative coupon testing program was conducted. As per the Canadian plan, the open-hole coupons were etched (by Australia), then pre-cycled (by Switzerland), after which the specimens were shipped to Patria, Finland, where the coupons' hole was first reamed (oversized), then cold worked (split sleeve) followed by interference fit or clearance fit fastener installation in order to have the coupons represent in-service usage. Patria then provided the coupons to VTT who conducted spectrum fatigue tests on the coupons and investigated the fracture surface characteristics using quantitative fractography on coupons with a hole with either clearance fit or interference fit. Detailed analysis has been done [46].

13.2.5 Repair technologies

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

13.2.5.1.1 DIARC plasma coating for reliable and durable structural bonding of metals – update

Previous metal bonding activities, specifically those related to DIARC plasma coatings, have been reported earlier in [1] Chapter 13.2.5.2.1. More recent achievements are outlined below.

Grit blast silane and AC-130 sol-gel treatments were tested to assess their performance in aluminum, titanium and stainless steel structural epoxy bonding. Static single lap shear and static double lap shear specimens were tested as dry and wet at room temperature. Wedge tests were performed in a hot and wet exposure and in hot fresh water and salt water immersions. Acceptable field level methods were found for unclad and clad 7075 aluminum bonding without primers. With titanium and stainless steel, the use of BR 6747-1 primer was found to be necessary for durable adhesion. In a case study, AC-130 sol-gel without a primer on naval grade 5083 aluminum provided good results also when immersed in Baltic Sea water. Due to copyright restrictions, further in-depth information of the study and the results can be found in [47].

13.2.5.1.2 An experimental study on the fatigue performance of CFRP and BFRP repaired aluminum plates

Cracked aluminum plates were repaired with multidirectional carbon/epoxy and boron/epoxy reinforcements. Aircraft repair conditions were simulated by using a steel bonding rig that constrained the effective thermal expansion to the level measured from real locally heated aircraft structures. Residual thermal stresses were varied using the rig and by varying the curing and testing temperatures. The repairs were tested using a variable amplitude loading (R = -0.14) with anti-buckling edge supports. The residual thermal stresses had a rectilinear and distinct effect on the crack growth rate. The structural support against bending had a significant effect on the fatigue life of the repairs. The fatigue life improvement factor with the center-cracked single-sided repairs was greatest with the wet-laminated carbon/epoxy repairs having a stiffness ratio of 1.04. With edge-cracked specimens the longest life was achieved with the double-sided boron/epoxy repairs having a stiffness ratio of 0.65. The cracked aluminum plate 2024-T3 clad had the longest fatigue life, followed by the S07-1020 and 7075-T6 clad aluminum grades. Due to copyright restrictions, further in-depth information of the study and the results can be found in [48].

13.3 Related activities

13.3.1 Environmentally friendly corrosion protection studies

As reported earlier in [1] Chapter 13.3.1, the joint European EDA ECOCOAT project (European Defense Agency, Environmentally Compliant Coatings in Aeronautic) was successfully completed. Sol-gel based inorganic-organic hybrid coatings were developed and coated on aeronautical parts including cadmium plated steel with two aims: To protect the cadmium-plating against the corrosion initiated especially by runway de-icing chemicals, and targeting the hybrid coating to provide alternative coating solutions for cadmium plating as well as hexavalent chromium conversion coatings.

Since then and during the current reporting period, Finnish efforts within Patria have continued. The three-fold aim at Patria is to **a)** tailor the hybrid coating to be applied to certain FINAF F/A-18 landing gear components such that **b)** the hybrid coating could be painted and finally **c)** obtain the airworthiness approval to the new coating.

13.3.2 EDA PATCHBOND

The PATCHBOND project (duration 4 years, started in November 2014) deals with bolt-free damage repairs of composite primary aircraft structures. The joint European Ad Hoc Research & Technology Project PATCHBOND is being conducted under the auspices of EDA (European Defence Agency in the framework of EDA R&T Category B projects).

Repair of damaged fixed and rotary wing platforms is a considerable matter for all European countries. Damage repairs of primary composite structures are commonly performed by the application of bolted plates. This method introduces additional damage to the structure especially for composite structures where the reinforcement fibres are cut by the drilling of the bolt holes. In some cases bolted repairs are not possible, for instance in the case of damaged sandwich structures. Thus, complex (bolted) alternatives may have to be developed to restore the load path.

A better repair method is the application of adhesive bonded composite patches instead of bolted plates. This method is already used for secondary structures but is not accepted by the airworthiness authorities for the repair of primary structures. Therefore boltless repair methods for primary composite structures have to be developed that are compliant with the airworthiness requirements. The project covers the whole range from damage assessment, numerical analysis, repair design procedures, materials and processes, inspection, structural health monitoring and quality control, up to certification aspects.

Several European research partners take part in the project, alphabetically: Finland (Aalto University, Patria Aviation Oy, VTT Ltd.), Germany (WIWeB, Airbus Defence and Space), the Netherlands (NLR, KVE Composites Repair, Fokker Services B.V.), Norway (FFI, NDLO, DolphiTech, FiReCo, Light Structures) and Spain (INTA).

13.3.3 Thermal spray activities to restore structural integrity of subsystem components

As there are several on-aircraft parts and subsystem components (e.g. hydraulics, flight controls etc.) that wear out during normal service, the FINAF initiated a study with VTT to investigate possibilities to develop in-country capabilities related to restoring the structural integrity of the worn parts thus supporting maintenance, repair and overhaul (MRO) activities and improving the management and sustainment of spares and component life cycle. One such subsystem component wearing out in normal service is the FINAF F-18 Aileron's hydraulic cylinder's flange, ***Fig. 20***.

Figure 20: *An overview of the Aileron's hydraulic cylinder's worn flange. Picture by courtesy of the FINAF.*

Thermal spraying is a process of particulate deposition in which the molten, semi-molten or solid particles are deposited on to substrate. The coating microstructure results from the deposition of the particles on the coated surface. The particle powder for the thermal spray coatings was selected, acquired and then sieved to achieve better particle size distribution for the thermal spray activities. Test specimens of the Aileron's hydraulic cylinder flange material were prepared, onto which several thermal spray surface coating methods were applied (one thermal spray per specimen). Five thermal spray methods were investigated:

- Arc Spray (twin wire arc spray)
- HVAF (High Velocity Air Fuel)
- HVOF DJ (High Velocity Oxygen Fuel, "Diamond Jet")
- HVOF CJS (High Velocity Oxygen Fuel, "Carbide Jet Spray")
- SPD (Supersonic Particle Deposition)

The sprayed specimens were then subjected to test to evaluate microstructure, hardness, Young's modulus, wear (abrasion) as well as cohesion and adhesion characteristics for each of the 5 thermal spray methods. The work is on-going.

Once the research and associated analysis efforts are completed, the chosen "winner" thermal spray method will be applied to spray the actual Aileron's hydraulic cylinder hinge and subsequently to investigate the optimal machining procedures to obtain the desired dimensions. The goal is to transfer the developed repair capability from an applied research facility to an in-country industrial entity.

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Summary

This document was prepared for the delivery to the 34th Conference of the International Committee on Aeronautical Fatigue and Structural Integrity scheduled to be held in Helsinki, Finland on 1-2 June 2015.

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

The review summarizes fatigue related research programs and investigations on specific military fixed wing aircraft since the previous Finnish National Review (tabled in the 33rd Conference, ICAF, Jerusalem, Israel) up to February 2015.

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