A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND MAY 2023 – APRIL 2025

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Preface

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Espoo, 17 April 2025

Editor

Contents

1 Introduction

Aeronautical life cycle support research activities in Finland and its embodiment, the national research network, have over the decades been solely advocated and coordinated by the Finnish Air Force (FINAF). The national research network supports the FINAF to optimize the use of their fleet in a cost-effective way, enabling the FINAF concentrating to carry out its primary objective – to secure Finland's airspace at any time, all year round.

The assigned research activities can broadly be divided into two categories: high-TRL (Technology Readiness Level) tasks that are related to finding pragmatic solutions for every day's challenges with only a minor effort, and low-TRL research tasks that feature a more scientific flavor, thus require more time to mature.

The FINAF has also found it advantageous that Finland belongs to the core of the international community of aeronautical fatigue research, being a member nation in the International Committee on Aeronautical Fatigue and Structural Integrity (ICAF). This commitment has been manifested in the numerous ICAF National Reviews since 2001. [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]

The Finnish Air Force is one of the oldest independent air forces in the world. It was founded in 1918 when the Swedish count Eric von Rosen donated the Thulin typ D reconnaissance plane which is credited as the first aircraft of the FINAF. The aircraft arrived at Vaasa on 6 March 1918, and the date has since been celebrated as the founding date of the Finnish Air Force [13]. After a lengthy period of steady development one can say that the last four years have changed, and will change, the FINAF more than ever in its history.

On 10 December 2021, the Government of Finland authorized the Finnish Defence Forces Logistics Command to sign a procurement contract with the Government of the United States on 64 Lockheed Martin F-35A Lightning II multi-role fighters [14]. The F-35A fleet will gradually replace the Boeing F/A-18C/D Hornets whose planned 30-year service life comes to an end by 2025–2030 (**Figure 1**, Chapter 1.3). The F-35A procurement is the biggest arms trade in Finland's history, and its impact is monumental in creating a credible defense capability. The procurement will define the Air Force's entire combat capability into the beginning of the 2060s.

Figure 1: *The current and future backbone of the Finnish air defense. The F-35A Lightning II will gradually replace the F/A-18C/D Hornet from 2025-2030. Figure courtesy of the FINAF.*

The second change in the defense environment was even more comprehensive and all-embracing. Finland's security policy has historically been based on a military non-alignment and firm national political consensus, but this environment was fundamentally altered when Russia launched its full-scale invasion of Ukraine in February 2022. Based on a reassessment of the international security landscape, Finland decided to apply for NATO membership in May 2022. Following all the NATO Allies had ratified Finland's Accession Protocol according to their national procedures, Finland deposited its instrument of accession to the North Atlantic Treaty in April 2023, becoming the 31st member country in NATO (**Figure 2**) [15], [16].

Figure 2: *Flag rising ceremony to mark Finland's accession to NATO at Headquarters on 4 April 2023 in Brussels [16]. Photo: Reuters.*

Territorial sovereignty is an essential element in national sovereignty. Regardless of being a member state of NATO, Finland still needs a strong national defence capability. The Finnish Defence Forces (FDF) has clearly set tasks to maintain a credible and preventive defence capability that secures Finland's territorial integrity. Responsibility for air operations, including air defense, surveillance, deterrence, and international co-operation, is with the FINAF. The observance of active air policy mission aims to secure Finland's airspace and react to airspace violations, if necessary. Finland's air doctrine in NATO combines national defensive heritage (dispersed operations, territorial defense) with new roles in collective deterrence and high-end air warfare. In the NATO era, this approach complements the alliance's collective defense principle, especially in northern Europe and the Baltic region.

The Finnish Air Force operates a modern, high-end fleet designed for multi-role combat, air defense, and reconnaissance. The current fixed wing aircraft inventory of the FINAF is summarized in **Figure 3**. Major changes since the last ICAF National Review [12] are decommissioning of the Valmet L-70 Vinka fleet and the F/A-18C Hornet fleet leader, HN-401 (Chapter 1.3).

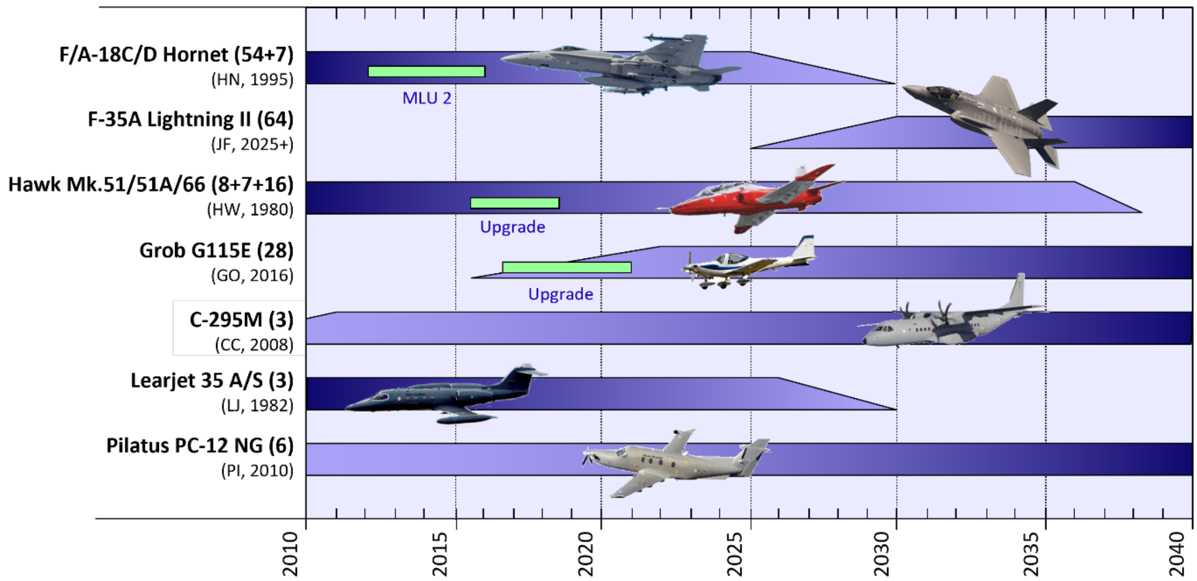

Figure 3: *An overview of the fixed wing aircraft inventory of the Finnish Air Force (FINAF). Figure courtesy of the Joint Systems Centre.*

The 20 TTH/SAR NH90 helicopters purchased earlier by the FDF were retrofitted (by Patria Aviation) and reached the Full Operational Condition (FOC) status. The retrofits (including the platform and various systems therein) started in 2014 and were completed in 2019. The assessment of NH90 maintenance system and tasks was finished during 2022. This will increase fleet availability in the future.

Presently, the MD500 fleet is going through a cockpit modification project in which avionics will be upgraded. The result will increase the MD500s' operative performance, improve their interoperability with the other branches, and facilitate pilot transitions into the NH90 platform. The modification will be completed in early 2026.

The current rotary wing aircraft inventory of the FDF is summarized in **Figure 4**.

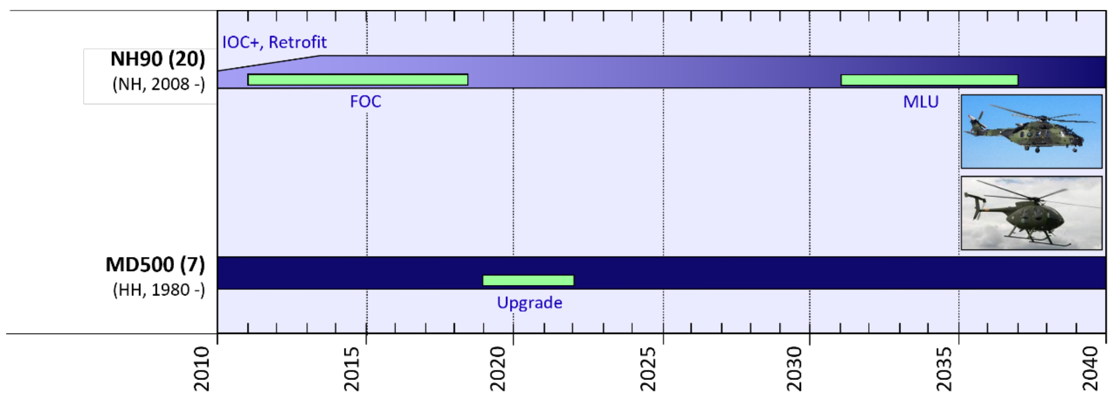

Figure 4: *An overview of the rotary wing aircraft inventory of the Finnish Defence Forces (FDF). Figure courtesy of the Joint Systems Centre.*

Before proceeding 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 next.

1.1 Grob G115E

The Grob G115E is a small, lightweight, two-seat piston-engine general aviation aircraft manufactured by Grob Aircraft in Germany for civil and military training purposes.

In October 2016, a decision was made to acquire 28 Grob G115E aircraft for the Finnish Defence Forces to replace the retiring Valmet L-70 Vinka fleet for basic and basic training missions (Chapter 1.1 of Ref [12]). The aircraft were purchased from Babcock Aerospace Limited, which had previously operated them as a training platform for the Royal Air Force. The Grob G 115Es acquired for the FINAF had served in the United Kingdom with the British designation Tutor T1 since 1999. [17]

The Grobs designated as GO by the FINAF were delivered between 2016-2018. Before the start of flight training, the Grob fleet went through a cockpit modernization project. Avionic and communication systems upgrade, and state-of-the-art multi-function displays were fitted to bring the cockpit layout compatible with the other aircraft operated by the Defence Forces and meet the requirements of the future military aviation.

On the contrary to its predecessor, the structure of Grob G115E has been manufactured of composite materials. It is constructed predominantly from carbon fiber reinforced composites, has a tapered low wing, a 4-cylinder 134 kW/180 hp piston engine with a 3-bladed variable-pitch propeller, a fixed tricycle undercarriage, fixed horizontal and vertical stabilizers and conventional flight control surfaces. The large glass canopy renders clear all-round visibility to the crew (**Figure 5**).

Figure 5: *Grob G115E primary trainer aircraft (GO-27). Figure courtesy of the Finnish Defence Forces.*

National efforts related to the structure of the Grob G 115E aircraft are highlighted in Chapter 2.2.1.

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

The BAE Systems Hawk is a British single-engine two-seat advanced jet trainer which is operated in Finland by the Air Force Academy, primarily in advanced and tactical training roles. The Finnish Air Force became the first export customer of the type, and the first fifty 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**). However, in 2021 the first Mk.66 aircraft received a grey livery like the older model aircraft and the rest are expected to follow during the next years. The Hawk is also flown by the Air Force's official display team the Midnight Hawks. The FINAF Hawks bear the military designation HW. [18]

Figure 6: *BAE Systems Hawk advanced jet trainer variants in the FINAF fleet (from left to right): Hawk Mk.51, Hawk Mk.51A, and Hawk Mk.66. Figure courtesy of the FINAF.*

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 for the Mk.51 and Mk.51A fleet and started for the Mk.66 fleet in 2020. Along with the Mk.66s, the Finnish Hawks underwent an extensive cockpit upgrade program carried out by Patria Aviation. 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 the F/A-18C/D Hornet (see Chapter 1.3). In the first phase, all Mk.66s, seven Mk.51As, and one Mk.51 received the cockpit modification and were delivered to the FINAF by January 2018. Later, eight additional Mk.51s were modernized in 2016-2020 based on the refined Hawk life cycle plans and to compensate for the loss of two already modernized Mk.66 aircraft. Next, the FINAF Hawk fleet will undergo a modification where the new control column and throttle control handles are being replaced. The key function controls previously located in cockpit consoles will be integrated into the new handles which allow hands on throttle and stick (HOTAS) operation for a pilot.

The 2025 fleet consists of 31 upgraded Hawks[1]: 8 Mk.51s, 7 Mk.51As and 16 Mk.66s. The Hawks are scheduled to remain in service until the late 2030s. The current flight service

[1] On 15 May 2023, a Mk.51 (HW-320) was crashed without fatalities. Based on on-going air accident investigations it has become clear that the engine had already shut down in the air and was no longer running when the aircraft hit the ground. An interesting curiosity is that the HW-320 had been in an accident already in 1998 and repaired thereafter, so this is possibly the first case in the world when there had been four (4) ejections from the same airframe in an emergency. [53]

target will require extension to certified usage life (Fatigue Index and Flight Hour) by the Finnish Military Aviation Authority (FMAA). Required investigations for Fatigue Index limit re-certification were completed in 2023, and corresponding task for Flight Hour limit will be performed during 2025. Also, investigations for a new cockpit upgrade have been started whose purpose is to support the transition to the new fighter aircraft fleet of the FINAF.

The inherent fatigue tracking of each FINAF Hawk aircraft relies on counting g level exceedances and calculating a usage index i.e., Fatigue Index (FI) by the variant specific equations on a flight-by-flight basis. This method is adequate for monitoring the structural locations mainly influenced by the aircraft normal acceleration (multiplied by aircraft weight). However, the current FI tracking does not consider buffet loading which is the main driver for the structural fatigue issues e.g., in the empennage of the aircraft. The Fatigue Index summary of the Finnish Hawk fleet is shown in **Figure 7**.

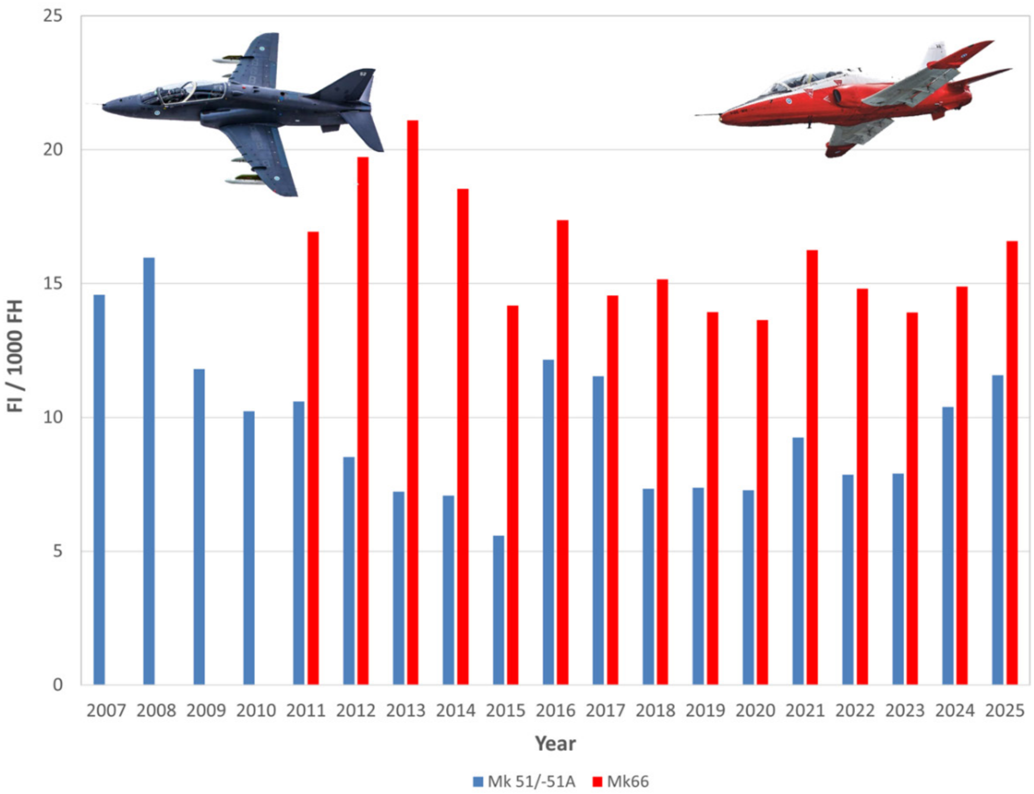

Figure 7: *Annual Fatigue Index (FI) accrual of the FINAF Hawk aircraft (Mk.51/51A in blue; Mk.66 in red). Figure courtesy of the Joint Systems Centre.*

1.3 F/A-18C/D Hornet

The Boeing F/A-18C (single-seat) and F/A-18D (two-seater) Hornet are twin-engine, carrier-capable, multirole jet fighters, forming the nucleus of the Finnish air defence. In 1992, Finland selected the Hornet to replace its aging Saab J35 Draken and MiG-21bis interceptors. The late-production Lot 17 aircraft entered Finnish service in 1995-2000, bearing the military designation HN. 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 Patria Finavitec (nowadays Patria Aviation) facility in Finland. [19]

The FINAF Hornet fleet consists of 61 aircraft: 54 C-models, and 7 D-models (**Figure 8**). Most of the fleet is divided between two operational fighter wings: Lapland Air Command (Fighter Squadron 11) at Rovaniemi Air Base and Karelia Air Command (Fighter Squadron 31) at Kuopio Rissala Air Base. The FINAF Hornets can also be deployed to operate from dispersed highway strips, if necessary.

Figure 8: *The FINAF F/A-18 Hornet multirole jet fighter variants: single-seat F/A-18C (HN-436) in the front, and two-seater F/A-18D (HN-467) in the back. Figure courtesy of the Finnish Defence Forces.*

It was recognized already in the planning 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, to keep the Hornet fleet at its highest level of performance, the fleet needs to be subjected to planned and systematic updates over its life span. At the heavier end of the spectrum there have been full-scale upgrades.

The Finnish F/A-18 fleet has undergone two extensive mid-life upgrades, designated as Mid-Life Upgrade (MLU) together with the partners: 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 first phase Mid-Life Upgrade, MLU 1, was focused on enhancing the FINAF Hornets' Air-to-Air (A/A) capability. The upgrade involved the incorporation of retrofit kits from the OEM: a Joint-Helmet-Mounted Cueing System (JHCMS) mated with the state-of-the-art AIM-9X Sidewinder infrared guided missile for improved close-in air combat performance. MLU 1 also introduced features to improve the pilot's situational awareness and joint operation capabilities. The MLU 1 was completed in 2006-2010. [20]

The primary objective in the second phase Mid-Life Upgrade, MLU 2, was to enable the FINAF Hornets' air-to-ground (A/G) capability by integrating various types of weapons (the short-range guided bomb JDAM, medium-range glide bomb JSOW and the long-range JASSM standoff missile), and modern self-protection, communication, navigation, and information distributions systems enhancing the pilot's situational awareness and interoperability of the aircraft in joint operations. Other examples of MLU 2 upgrades were the cockpit upgrades with new displays and the BOL countermeasures dispensers. The MLU 2 was completed in 2012-2016. [20]

From structural point of view, the MLU 2 upgrade included structural strengthening and 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.

Along with the MLU 2 upgrade, the FINAF F/A-18C/D Hornet reached its Full Operational Capability (FOC) that expands the operational envelope for a true multi-role aircraft. The Finnish pilots are now enabled to exercise the full potential of the Hornet in joint operations with a wide range of air-to-air and air-to-ground capabilities. One example of the joint operations is air-to-air (AAR) refueling training, as the AAR qualification is part of the flight training of the Finnish F/A-18 pilots (**Figure 9**).

Figure 9: *Three FINAF F/A-18C Hornet fighter jets (HN-426, HN-456, HN-435) conducting air-to-air (AAR) refueling training missions with the Royal Netherlands Air Force Airbus A330-243 Multi-Role Tanker Transport aircraft (T-059) of the Multinational Multi-Role Tanker Transport Fleet (MMF) in April 2024. Figure courtesy of the FINAF.*

The expanded mission envelope is reflected in training programs and the operational use of the aircraft and thus affects the airframe stressing. Fatigue tracking of the FINAF Hornet fleet is currently based on: 1. Flight Hours (FH), 2. Wing Root Fatigue Life Expended (WR FLE) -value, and 3. T*-value (time spent in a buffet-dominating Point In The Sky, PITS) for the Vertical Tail [38]. Summary of the WR FLE of the FINAF F/A-18C/D fleet is presented in **Figure 10**.

It is known that the WR FLE is primarily dependent on the aircraft's normal acceleration, so it does not provide useful fatigue information about the structural locations prone to the buffeting. As the Vertical Tail of the F/A-18 aircraft is typically buffeting-strained structure, a more useful usage index, developed by the international F/A-18A/B/C/D Hornet user's community, has been put into practice in the FINAF. A T* (T star) value indicates time spent [h] in the PITS that contributes most of the fatigue damage for the Vertical Tail. Summary of the T*-values of the FINAF F/A-18C/D fleet is presented in **Figure 11**.

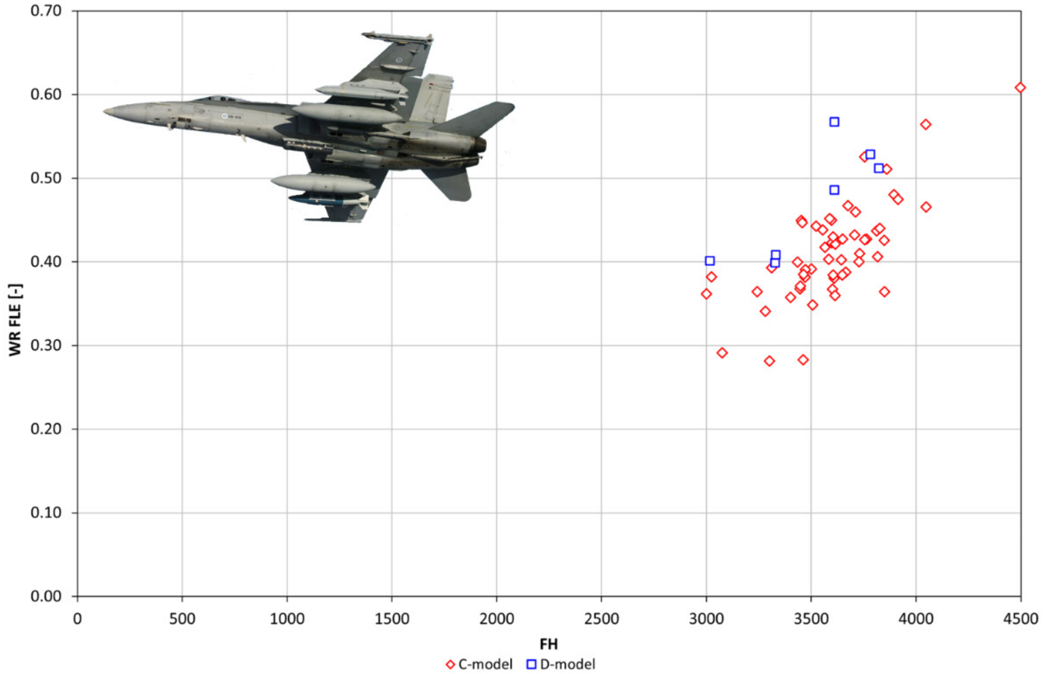

Figure 10: *Summary of the Wing Root Fatigue Life Expended (FLE) of the FINAF F/A-18C/D fleet. The data still covers all the 62 aircraft [38]. Note that the fleet leader had reached its service life target 4.500 FH. Figure courtesy of the Joint Systems Centre.*

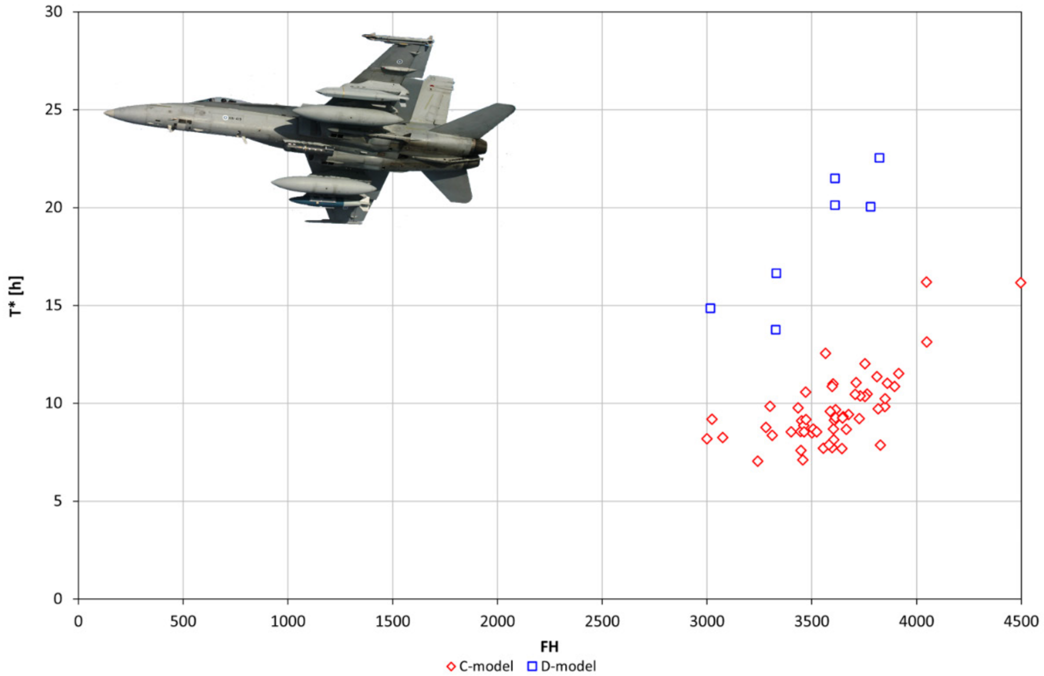

Figure 11: *Summary of the Vertical Tail fatigue tracking (T*-value) of the FINAF F/A-18C/D fleet. The data still covers all the 62 aircraft [38]. Note that the fleet leader had reached its service life target 4.500 FH. Figure courtesy of the Joint Systems Centre.*

The Finnish F/A-18C/D fleet can accomplish its operations safely and reliably until the mid-2020s. The decommissioning of the Hornet fleet will start in 2025 (excluding HN-401). Phasing out the aircraft becomes a reality when they are about to reach their structural flight hour limits between 2025 and 2030. Then the Lockheed Martin F-35A Lightning IIs will replace an obsolescent Hornet fleet (see Chapter 1.4).

The first decommissioned FINAF F/A-18C Hornet aircraft, HN-401, had its last flight on 26 April 2024. The HN-401 was completed on the Patria (then Finavitec) assembly line in Halli being the first Hornet assembled in Finland (**Figure 12**). The aircraft was handed over to the Finnish Air Force on July 5, 1996. [21]

In service the HN-401 was selected as a so-called fleet leader role, i.e. the aircraft had been selected for flight missions that are known to stress the structure more than average. The purpose for accelerating the operating profile, which differs from the other aircraft in the fleet, has been to collect proactive information about the fatigue of the airframe and ensure that the planned life cycle of the Hornet fleet can be achieved by proactive MRO measures in accordance with the life cycle plan. The HN-401 had been in service for over 27 years, flown approximately 4 500 FH, and had thus reached its service life target.

Figure 12: *The unofficial rollout view of the first Finnish-assembled F/A-18C Hornet, HN-401, in Halli on April 3, 1996. The material distribution of the yet unpainted aircraft is clearly distinguishable, like the use of composite materials (carbon fiber reinforced plastic) of the structural surfaces. Photo: Jyrki Laukkanen.*

1.4 F-35A Lightning II

On 10 December 2012, the Ministry of Defence in Finland announced that the F-35A (conventional take-off and landing variant) Lightning II had met the requirements of outlined under four main categories: military capability, security of supply[2], industrial participation, and affordability, and thus 64 F-35As will gradually replace the aging F/A-18C/D Hornet capability in 2025-2030 (**Figure 13**). The Finnish Air Force will use the F-35 capability until the 2060s. [14]

The production of the first Lockheed Martin F-35A Lightning II multi-role fighters for Finland is underway at the manufacturer's Fort Worth facility in the United States. The forward fuselages of Finland's F-35A fighters are being manufactured in the United States. Once the forward fuselage is completed, it proceeds to the production phase where the four major components of the fighter—the forward fuselage, center fuselage, wing assemblies, and aft section—are joined together. Then the aircraft moves to the final stages of assembly on the production line in Fort Worth.

The aircraft will be delivered with system update version 3, known as the TR-3 (Technical Refresh) standard that enables the newest Block 4 capability. Finland's first F-35A, (national serial JF-501), will be handed over to the FINAF at a rollout ceremony in late autumn 2025, after which the FINAF will deploy its first eight aircraft into service during the practical part of the F-35A initial training at Ebbing Air Base, Arkansas. The first delivery in-country is expected at the end of 2026, to Lapland Air Command in Rovaniemi. At the same time, the FINAF will begin F-35 training domestically when the personnel trained in the United States start to provide conversion training for the F-35 system integration in Finland. The F-35 will achieve initial operational capability (IOC) by the end of 2027, and full operational capability (FOC) by the end of 2030. From 2031 onwards the F-35 system will serve as the main fleet of the FINAF. [22], [23], [24], [25]

Figure 13: *The Finnish Air Force F/A-18C/Ds (HN-408/HN-466) conducting interoperability training with the United States Air Force F-35A Lightning II (20-5570) from the 48th Fighter Wing. Figure courtesy of the FINAF.*

[2] The term security of supply refers to Finland's industrial capabilities and the ability to maintain operational tempo and sustain operations if the supply of spare parts or getting support services from the F-35 global support system is disrupted.

The components of F-35 multi-role fighters for partner and customer nations are manufactured in several F-35 user countries under the multinational F-35 Program. In the coming years, the components of the F-35 will also be manufactured in Finland as Patria begins to produce forward fuselages and subcomponents for the F-35 Program at its Jämsä Halli facility, as part of the industrial participation within the F-35 Program. Industrial participation by Finnish companies will also include Insta, Millog, and Finnair engineering. [23]

The introduction of the F-35 system widens the range of the FINAF operations, bringing with new capabilities that enable smooth joint combat operations with the Air Force, Army and Navy. A fundamental change in transitioning from the F/A-18C/D to the F-35A fleet is better situational awareness to be achieved with increased data processing. The F-35's capacity to fuse its sensor data and disseminate information in real-time offer significant benefit to the entire defence network. In addition to enabling joint combat operations, the F-35A fighter itself is a versatile weapon system. The F-35 capability is clearly superior to that of the Hornet's in all tasks and for example in the capacity to fire at moving targets, detect launches of ballistic missiles, and intercept cruise missiles.

The FINAF trains regularly operations from other than a home base to be capable of a quick dispersal of the fleet across the country. The last annual road-based exercise "BAANA 24" took place in September 2024, in Ranua, Finland. This was also the very first time when the US Air Force pilots practiced landing on a road in Europe. Two F-35A Lightning II fighters landed on a 30 m wide highway strip as part of the Finnish Air Force road-based exercise, which also featured the participation of personnel and assets from Allied countries Germany and the United States. The exercise provided US personnel with an opportunity to learn from their Finnish counterparts' experience and improve their ability to rapidly deploy and employ airpower from unconventional locations. [26]

Figure 14: *The United States Air Force F-35A aircraft assigned to the 493rd Fighter Squadron, 48th Fighter Wing, currently based at Royal Air Force Lakenheath in the United Kingdom, demonstrated landing and take-off operations during the road-based exercise on the Finnish highway strip, in September 2024 to practice Agile Combat Employment, which increases the ability of partners to collaborate in a high-intensity environment, improving readiness, responsiveness, and interoperability. Figure courtesy of NATO.*

1.5 MVX Project

The Finnish Border Guard is responsible for Finland's border security, and border patrol aircraft are vital for the surveillance of Finland's extensive land and sea borders. Main tasks of the aircraft are to monitor land and sea borders, to search and rescue, to identify vessels in the Baltic Sea, and to detect, manage and combat marine environmental damage. In addition, the aircraft participate in the control of Finland's territorial integrity and support other authorities in monitoring the state of the Baltic Sea.

The current Dornier 228 surveillance aircraft, introduced in 1995, are reaching the end of their life cycle and are becoming increasingly difficult to maintain. The Finnish Border Guard will replace the outdated Dornier 228s with two new multipurpose aircraft during 2026-2027. The Finnish Border Guard discovered that only a manned aircraft results operationally practical and cost-effective solution ensuing versatile tasks in demanding Finnish conditions.

In the MVX project's Request for Information (RFI) procedure, potential aircraft suppliers were identified in 2020, and a new detailed information request was submitted in April 2022. During the spending limits discussion held on 5 April 2022, the Government decided to allocate EUR 163 million for the purchase of multipurpose aircraft to replace the Dornier 228 surveillance aircraft.

Sierra Nevada Corporation (SNC) was selected as the supplier of the following multirole aircraft for the Finnish Border Guard. The procurement contains two aircraft solutions based on Bombardier's Challenger 650 business jet, which SNC will modify to meet the operational needs of the Finnish Border Guard. The Agreement was signed in Helsinki on June 27, 2024, and the aircraft are planned to enter service in 2026 and 2027. [27]

Figure 15: *Finland committed to the acquisition of two Sierra Nevada Corporation's RAPCON-X-configured Bombardier Challenger 650 aircraft. Figure courtesy of the Finnish Border Guard.*

1.6 Scope of the review

This national review on aeronautical fatigue concentrates on the fixed wing aircraft of the FINAF related to fighter aircraft and associated pilot training aircraft. The FINAF inventory includes: 61 F/A-18C/D Hornet fighters, 8 Hawk Mk.51, 7 Mk.51A and 16 Mk.66 jet trainers, and 28 Grob G115E primary trainers. By now, approx. 228 000 FH have been flown with the Hornets, 287 000 FH with the Hawks, and 5 066 FH with the Grobs.

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 (**Figure 7** (Hawk) and **Figure 10**, **Figure 11** (Hornet)) clearly demonstrates the need to maintain, further develop and apply concrete and systematic efforts to cope with the structural deterioration effects.

In 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 member nation. The 11th national review as a full member about the aeronautical fatigue investigations in Finland May 2023 - April 2025 was compiled by Tomi Viitanen (VTT).

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TAU	Tampere University, Plastics and Elastomer Technology, FI-33014 Tampere, Finland (https://www.tuni.fi/en).
Trano	Trano Oy, Vetikonkuja 13, FI-04300 Tuusula, Finland.
Trueflaw	Trueflaw Ltd, Tillinmäentie 3 Tila A113, FI-02330 Espoo, Finland (https://trueflaw.com/).
VTT	VTT Technical Research Centre of Finland Ltd. P. O. Box 1000, FI-02044 VTT, Finland (https://www.vttresearch.com/en).

2 Current activities: ASIMP 2023-2025

The Aircraft Structural Integrity Management Program (ASIMP) with its yearly basis assignments is ongoing. This chapter promotes highlights of the achievements from the past research period.

2.1 Loads and stresses

2.1.1 Computational Fluid Dynamics at Elomatic Ltd.

Elomatic Ltd's Computational Fluid Dynamics (CFD) research relies on its in-house flow solver, FINFLO. In Finland, the F/A-18 research is conducted in collaboration with Patria Aviation Ltd, which also uses FINFLO. Additionally, Elomatic is partnering with Swiss companies CFSE and RUAG on projects investigating the lifespan of the F/A-18 Hornet's structures [51].

Recently, the FINFLO flow solver and MSC Nastran structural code [40] were coupled using MpCCI, a code coupling software developed by SCAI Fraunhofer in Germany [41]. MpCCI offers an application-independent interface that facilitates direct coupling between various simulation codes, enabling real-time data exchange—for instance, between CFD and FEM (Finite Element Method) codes—for Fluid-Structure Interaction (FSI) simulations. The MpCCI visualizer shows the development of wetted surfaces in both models during iterations. The simulations use explicit coupling between the codes, with the primary outcome being the aerodynamic loading on deformed aircraft components.

The solution system is applied to the F/A-18C with a Mach number Ma = 0.2755 and an angle of attack $\alpha = 30°$. The FE model includes 1 658 546 degrees of freedom and 116 762 surface elements, while the CFD model consists of 50 915 328 cells and 125 536 surface elements. Detached-eddy simulation (DES) is used for the time-dependent flow field. In **Figure 16**, instantaneous streaklines are shown to compare the results with data from NASA's F-18 High Angle-of-Attack (Alpha) Research Vehicle (HARV) test [32]. The deformation history is typically displayed through animations, as in **Figure 17** showing a single frame from the geometry history, colored by the pressure distribution on the aircraft's surface.

Figure 16: *HARV flight test (left) and FINFLO simulation streaklines (right) at constant flight path with a = 30° and Ma = 0.2755. Figure courtesy of Elomatic Ltd.*

Figure 17: *Instantaneous distribution of the pressure coefficient on the aircraft's surface at angle-of-attack = 30 deg and Ma = 0.2755. Figure courtesy of Elomatic Ltd.*

Coupled simulations can also provide structural deformations as a function of time. **Figure 18** depicts time history of lateral deformations of the Vertical Tails of the F/A-18 aircraft. In this case symmetric bending of the Vertical Tails is apparent.

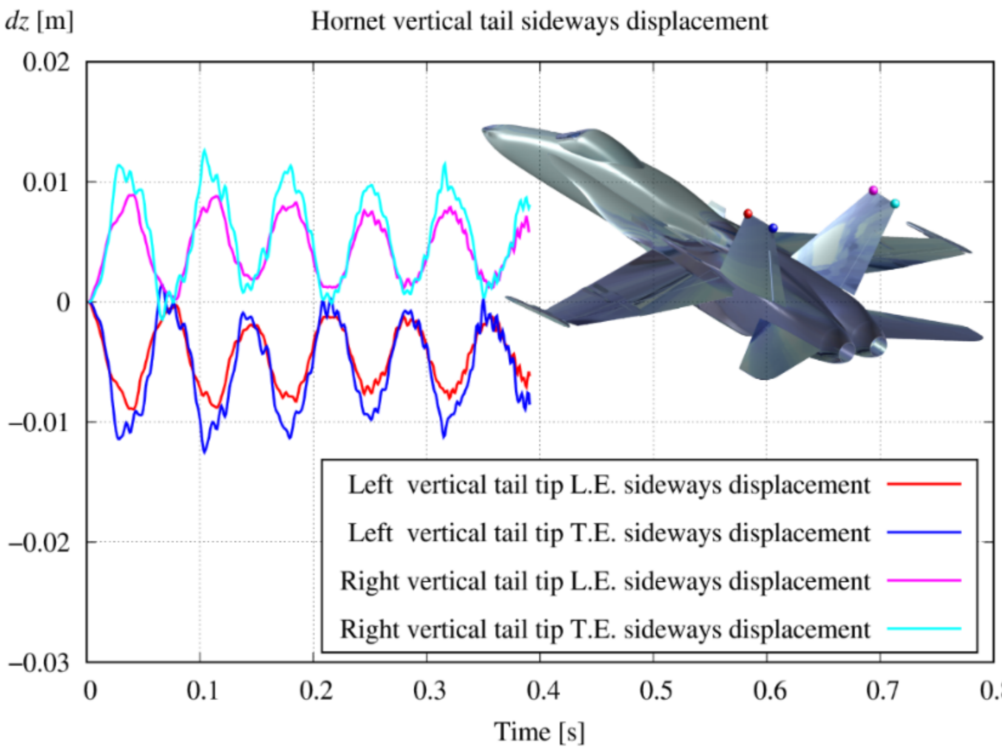


Figure 18: *Lateral deformations of the Vertical Tails as a result of the FSI simulations. Figure courtesy of Elomatic Ltd.*

2.2 Loads monitoring and fatigue tracking systems

2.2.1 Last phases of the Grob G115E national MRO capability – project

It has been in the culture of the FINAF to be self-sustaining with their aircraft to a certain level. This for instance enables domestic life cycle support, modifications or repairs. With this background the Finnish Defence Forces has funded a project in which Patria Aviation with its partners VTT and Tampere University have built a basic technical understanding of the Grob G115E basic trainer fleet and developed a partial national maintenance, repair and overhaul (MRO) capability for the type.

The first step of the project, an aerodynamic model of the aircraft and initial computations with it, were described in the ICAF 2019 report (Chapter 2.1.4 of Ref. [10]). Applications and enhancements of the CFD model were further described in the ICAF 2021 report (Chapter 2.1.5 of Ref. [11]). It also contained preliminary information about the then ongoing mini-OLM flight test program i.e., a small-scale operational load measurement project (Chapter 2.2.7 of Ref. [11]).

In the mini-OLM program two separate onboard data acquisition systems were used. The main system recorded data from 40 strain channels, 8 temperature sensors, pitot and static pressure sensors and an accelerometer. The other system was a standalone gyro platform, which recorded for instance attitude, angular velocities, and accelerations, in addition to pitot and static pressures. During the flight test phase consisting of 22 flights and 21 flight hours, all the normal and acrobatic maneuvers of the aircraft were flown covering the whole flight envelope with a varying mass and center of gravity.

The strain channels were calibrated to indicate loads. From the flight test data supplemented with the calibration results, global loads were calculated using a neural network analysis. Control surface loads were directly calculated using control system calibration results. The flight test data supported by the CFD results have for instance been utilized when solving problems related to control surface attachments.

The next step of the project was static ground tests to the main structural components. During the ground tests structural responses were measured from each component when loaded with a clearly defined load or load sets. Depending on the component, up to 35 load cases were used. The limit load levels for the tests were derived from either FAR Part 23 requirements or previously described flight tests. The actual load levels used during the testing were kept low, as a fraction of the limit loads, as the aircraft will return to the FINAF operation.

The purpose of the ground tests was to deepen understanding of the structural behavior and to collect data to be utilized when validating FE models of the components. For these tests, the instrumentation was extended to a total of 260 strain channels supported by 6-8 displacement sensors depending on the article. In addition, 3D Digital Image Correlation (DIC) method was utilized in most of the measurements to get full-field deformation data from the main areas of interest of the tested components. The work done during the mini-OLM program and static ground tests was described in more detail in the ICAF 2023 report (Chapter 2.2.1 of Ref. [12]) and reference [35].

At present, the last two phases of the project, defining the material data and making FE model of the primary structure, are close to completion.

The goal of the material test series was to define the material models (stiffness parameters/matrices) to be used when constructing the global FE-model described below. Another goal was to gather strength data from different materials and lay-ups to be used in future strength analyses, when for example a compliance of a repair has to be demonstrated. For some materials used in the structures of Grob G115E, basic material data is available in open sources such as WL-datasheets. However, these materials were also tested to supplement the data.

The focus of the material test series was set on defining the material models for single reinforced layers. These being defined, the material models for all the lay-ups in the aircraft structure can be calculated. Thus, the majority of the test specimens were purposed to define a material parameter(s) for a single reinforced layer. However, some of the most critical lay-ups were also tested as such. In addition to specimens representing only one material or layer, also the most critical sandwich- and monolithic lay-ups found in the aircraft were tested. These critical lay-ups are found for example in the wing and horizontal stabilizer roots. The main goal of tests conducted using real lay-ups was to study the failure mechanisms of the sandwich-structures and possibly gather strength data beyond the first ply failure strength when it comes to monolithic laminates.

The present FE model is a global model of the primary structure as shown in **Figure 19**. The global FE-model is validated "in parts" i.e. validating the results of FE-modelled different components such as wings separately from the global assembled model using the ground test results. In the future the model will be fine-tuned or detailed models will be constructed based on the need or if more detailed information is obtained.

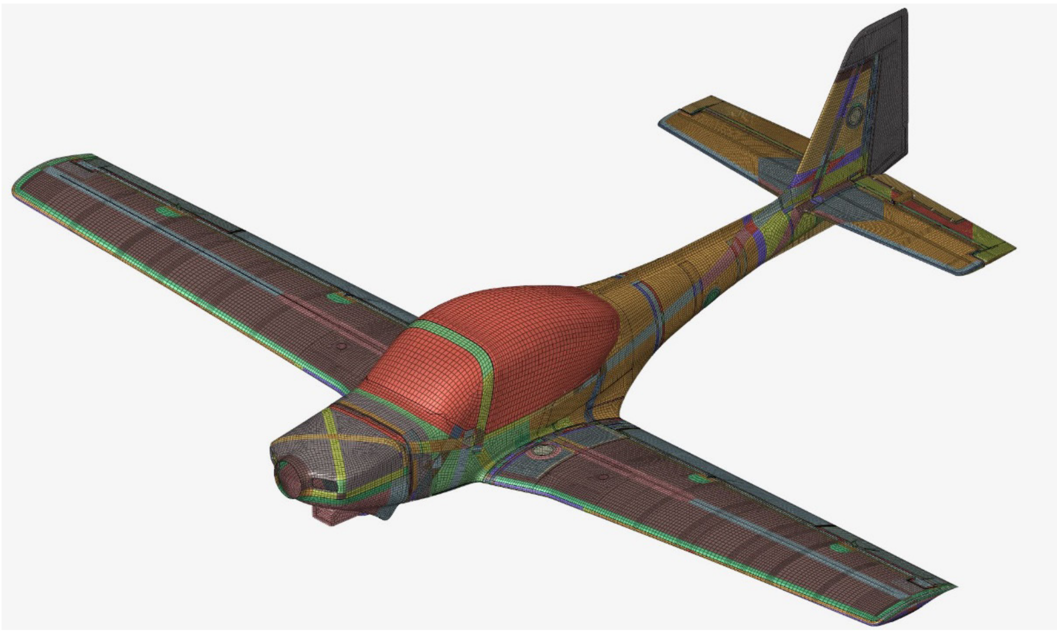


Figure 19: *Global FE model of the G115E primary structure. Figure courtesy of Patria Aviation.*

2.2.2 The FINAF HOLM aircraft in routine squadron service

The FINAF has routinely been running the Hornet Operational Loads Measurement (HOLM) program since 2006 [4]. The goal in this program is to quantify the effects of operational loads on the structure of the F/A-18C/D Hornet aircraft and thus support the national aircraft structural integrity efforts. The HOLM program employs two Boeing F/A-18C Hornet aircraft (HN-416 and HN-432) with originally identical, but afterwards diverged onboard data acquisition systems (**Figure 20**) and instrumentation (Ref. [9] Chapters 2.2.2, 2.2.4). 44 strain sensors, in all, have been fitted on globally important locations as well as in the vicinity of structural locations addressed to be fatigue critical. In addition, four accelerometers have been installed in the top section of the Vertical Tails. Concurrently the HOLM system monitors and records 250+ flight parameters from the MIL-STD-1553 data buses of the aircraft. The optimized sampling rates of the strains vary from 1280 Hz in the highly vibrating structural locations (e.g., Vertical Tail) to 640 Hz elsewhere. The sampling rate of the accelerometers is 2560 Hz.

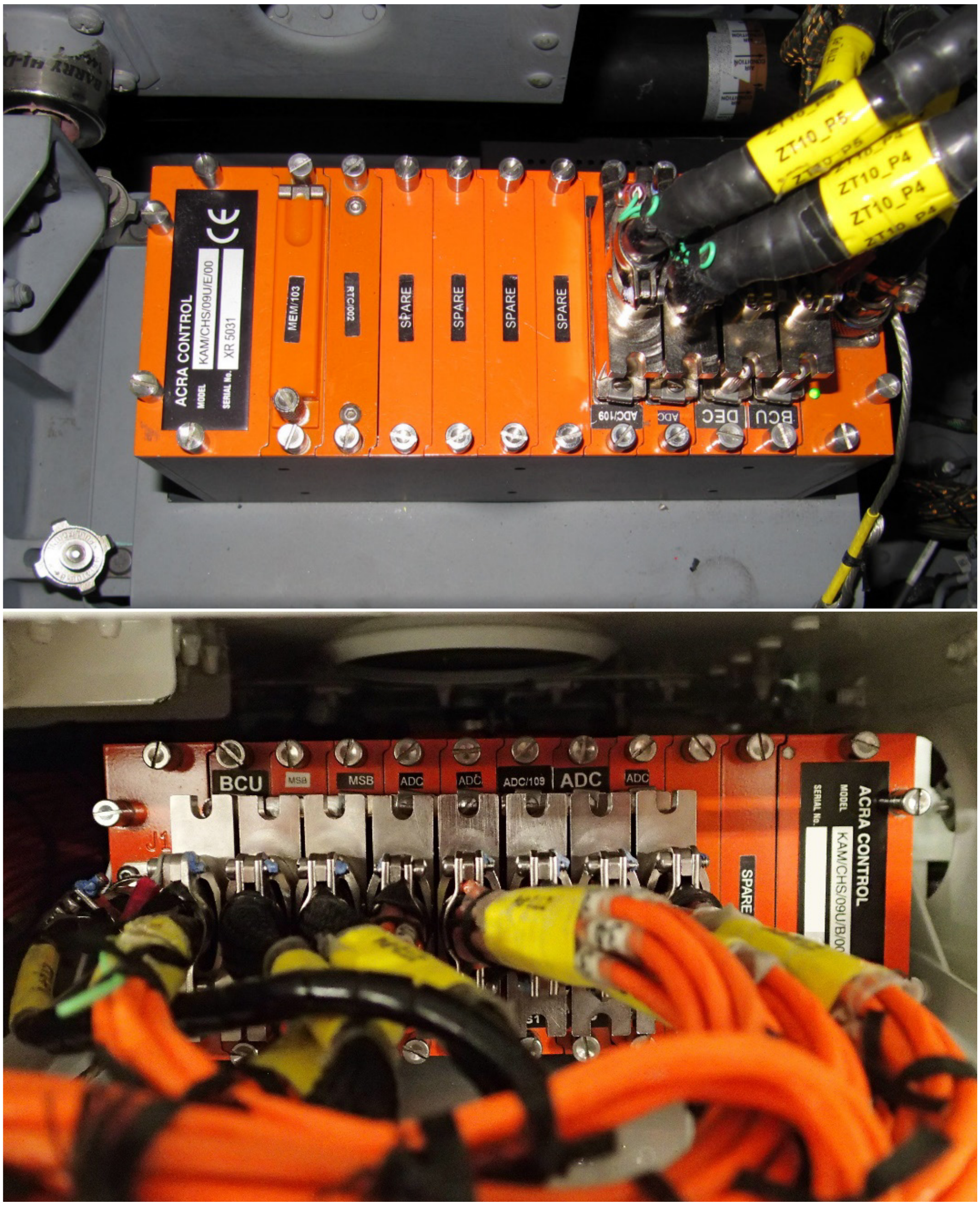


Figure 20: *HOLM DAU Master Unit (top), and Slave Unit (bottom). Figure courtesy of VTT.*

Prior introducing the onboard HOLM system into service, the ground calibration tests (i.e. mechanical calibrations) for the system were performed, as highlighted in Chapter 13.5.1.3.3 of Ref. [4] and Chapter 2.2.4 of Ref. [9].

The onboard HOLM instrumentation has also been shunt calibrated on a regular basis by VTT in support of Patria Aviation. The annual electrical calibrations of HN-416 and HN-432 reveal whether any changes in the measuring chain have occurred and 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 practically all the recordable response 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. [47], [48], [49]

To date, VTT has analyzed with the HOLM ground analysis environment more than 4000 flights from routine fleet operations and prepared several fatigue analysis reports, e.g. Ref. [37]. These reports summarize fatigue life estimates of the critical and instrumented locations of the structure in a versatile way, such as from a syllabus, a sub-assembly, and from buffeting point of view. The ground analysis environment is based on the COTS software enhanced with the in-house codes (sequences and functions). The data flow is supported by the HOLM fatigue analysis database that combines seamlessly the data and information in the HOLM ground analysis environment. In addition to the fatigue analyses results, the database includes all the relevant information of the data analysis process. A remarkable advantage is the possibility to compare the results on a flight-by-flight basis in between various sources (SAFE and HOLM), and as a recurring process, to track the trends of the results.

After 18+ years of service in harsh environment, with a few exceptions, the hardware is still working well, and the quality of the recorded HOLM data has remained outstanding, that is, the HOLM data forms a good basis for all the subsequent analyses and data sets needed, like the FINAF F/A-18 Hornet Basic Operational Spectrum ver 2 “BOS2” (Chapter 2.2.5 in Ref. [9]) that was compiled on the basis of the HOLM and SAFE data in co-operation with VTT and Patria or for the parameter based fatigue life analysis (Chapter 2.2.3 in Ref. [12]).

2.2.3 Research efforts towards Hawk structural integrity management

The inherent fatigue tracking system for each FINAF Hawk aircraft has been based on counting g level exceedances and calculating a usage index i.e., Fatigue Index (FI) by the variant specific equations. This method is adequate for monitoring the structural locations mainly influenced by aircraft normal acceleration (multiplied by weight). However, current FI tracking does not take buffet loading into account which is the main driver for the structural fatigue issues e.g., in the empennage of the Hawk aircraft.

Particularly the aging FINAF Hawk Mk.51/51A fleet requires careful planning and monitoring of use to get the maximum benefit out of it. Therefore, a regular monitoring report describing the fatigue situation of the fleet was introduced some years ago. The main parameters followed in the report have been Fatigue Index (FI), Flight Hour (FH) and recently also Neural Network Fatigue Index (NNFI) of the tail. The fatigue situation is pulled together as a color code for each aircraft, on the basis of which the flight training designer can choose a suitable aircraft, for example, for fatiguing air-combat exercise or, on the other hand, for lighter orienteering exercise.

The Hawk NNFI is based on the Neural Network investigations for the FINAF Hawks, which were explained in the previous ICAF reports, e.g. in Chapter 2.2.6.1, of Ref. [11]. Shortly, NN is an algorithm for calculating fatigue damage for critical structural parts by using recorded flight parameters data as input. Before NN can be used it must be developed by separate training data to find the right correlations between each flight parameter and structural load. In FINAF Hawks the training data sets have been acquired with Emmecon’s Data Acquisition Unit (DAU), (Chapter 2.2.4.1 of Ref. [12]). Right now, there are some updates going on to the DAUs to ensure their operation until the next decade.

2.3 Structural integrity of composite materials and adhesively bonded joints

2.3.1 Surface quality inspection for adhesively bonded joints

Composite structures of vehicles of aeronautics fleets are frequently repaired using adhesively bonded repair patches. The repair process includes several work steps, which are critical for the outcome – to reach the highest quality. Perhaps the main concern related to bonded repairs is so-called weak bond. In this case, the adhesively bonded repair will not have sufficient interfacial adhesion between adhesive and the adherend structure. The surface quality for interfacial adhesion is the determining factor for the strong interface. The interfacial failure mode would provide significantly lower joint strength, which could lead to premature loss of performance or even loss of the bonded patch.

The surface quality on the bond surface plays a critical role in the bonding process. Currently, the surface quality of composite adherends is based on qualitative assurance by technician or expert responsible for the surface treatment process. In term of the organizational procedure, the quality is ensured via technical qualification of the working staff, experience, and monitoring (visual observation). From the quality point of view, a certain quantitative approach would minimize the dependencies related to human errors and human decision making based on qualitative factors. Different techniques for surface quality inspection have been developed and studies are available in current scientific literature. One of the measuring techniques for quality inspection is the contact angle (CA) measurement. CA measurement is based on techniques of probe liquid's droplet placing on the surface being inspected. CA describes the nominal shape of the droplet, after various surface treatments, as shown in **Figure 21**.

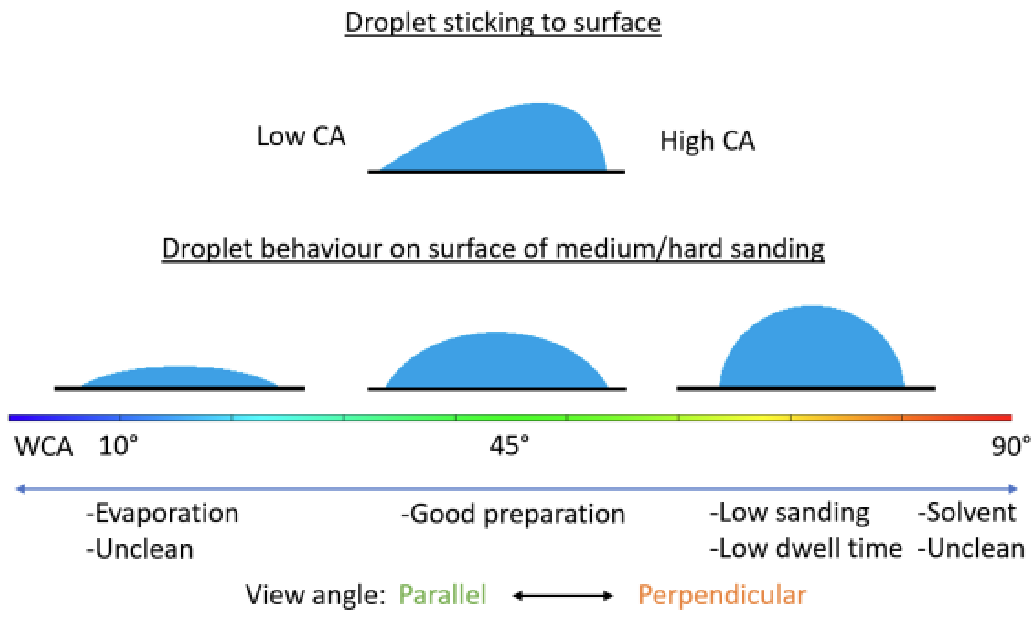


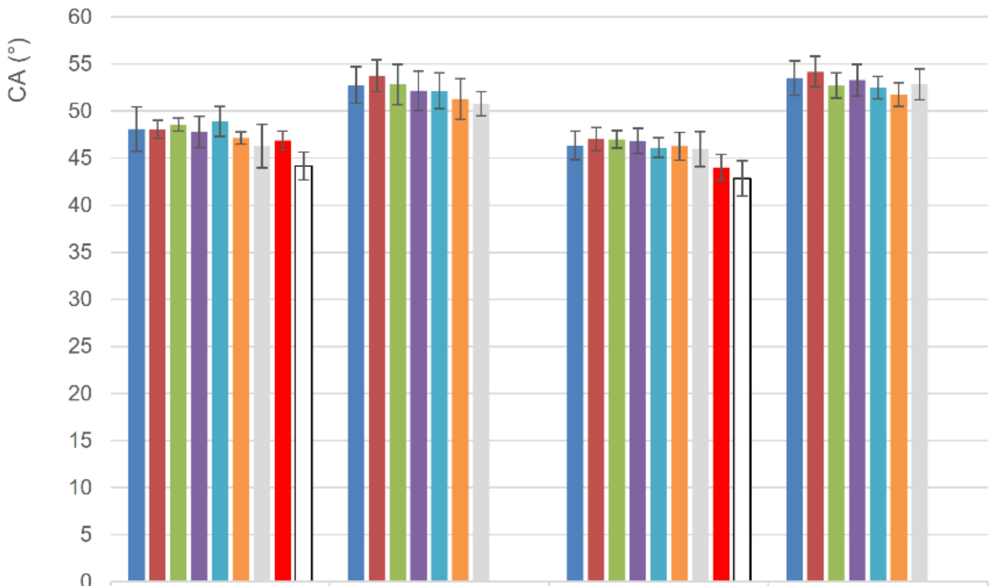
Figure 21: *Droplet shapes and how different phenomena affect water contact angle (WCA) based on the experiments. WCA values on surfaces with medium or hard sanding should be in the green area, around 45°. [36]*

For studying the applicability of the contact angle measurements for adhesively bonded joints – especially for composite structures, the joint project called "*A Review of Surface Analysis Technologies for Increasing Robustness of Composite Bonding in the Fleet*" was organized between three nations: Finland, Switzerland, and United States of America.

Partner organizations of the project were Tampere University, Elomatic, Zurich University of Applied Sciences, and United States Navy.

During the project, different CA measuring devices were compared and studied for the purpose. The focus was on portable devices, but laboratory devices were also considered for reference measurements. Commercially available portable devices, in this study, were BTG 3001 SA by Brighton Science, PCA-11 by Kyowa, MSA by Krüss, and SurfaSpector by SITA. The objectives were formulated to study reliability, repeatability of measurements, and applicability of devices. The user experience was also studied and data collected during the project – the differences in device operation can be crucial in fleet operation. The test program was divided into two phases, i.e., screening and mechanical testing. The project's main results have been published [28], [29], [30], [31], [39]. Majority of the work focused on CA measurements using water as probe liquid.

In the first research phase, the sensitivity of CA results in various factors was studied. **Figure 22** remarks the time dependency after surface treatment of composite (Carbon Fiber Reinforced Plastic, CFRP) related to measurements of CA. **Figure 22** shows two different surface treatments designated 'Med' and 'Hard' referring to medium and hard sanding, respectively. The first step in surface treatment process included the removal of peel ply. The medium sanding refers to so-called normal treatment, while the hard sanding could already break surfaces of fibers. The CA time dependency presents a decreasing trend within a few degrees (of CA). The sensitivity analyses also included factors like surface roughness and different contaminations.



	A Med CA(m)	A Med2 CA(m)	A Hard CA(m)	A Hard2 CA(m)
0min	48.1	52.8	46.4	53.5
15min	48.1	53.7	47.0	54.2
30min	48.6	52.8	47.0	52.7
1h	47.8	52.2	46.8	53.3
2h	48.9	52.2	46.1	52.5
3h	47.1	51.3	46.3	51.7
4h	46.3	50.8	46.0	52.8
6h	46.9		44.0	
8h	44.2		42.9	

Figure 22: *CA-related time dependency for medium and hard sanding test series. [36]*

In the second phase of the project, the strength of adhesive joints and CA measured prior joining were compared for analysis. The experimental program consisted of three different types of specimens (joints), namely single lap joint (SLJ), double strap joint (DSJ), and double cantilever beam (DCB). The SLJ specimens in this study provided significant delamination failure mode due to high peel stresses at the edges of the joint. The delamination failure mode was not of interest to the project. Similar kind of issues with the failure mode were noticed for the DCB joints but this outcome was dependent on the applied CFRP grade (reinforcement, matrix). The strength of DSJ specimens and CA measured on adherend surfaces is shown in **Figure 23**. The results are shown with different adherend materials, adhesives, and contaminations (if applied). Low CA was found to represent high joint strength, and moderate correlation was found in the CA-strength abscissa.

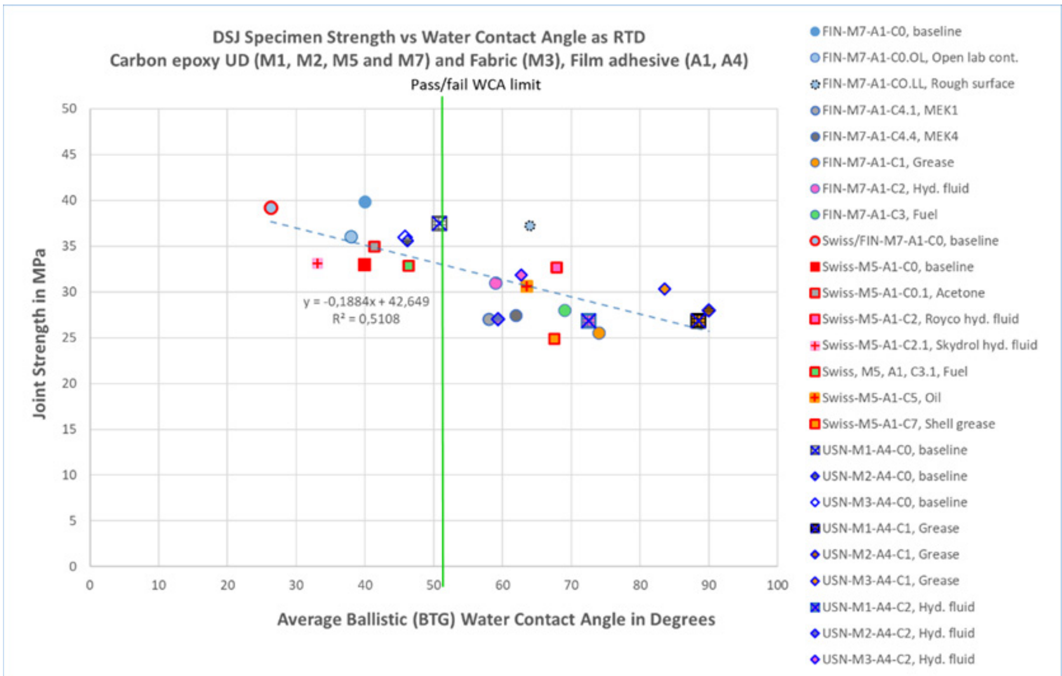


Figure 23: *The correlation between CA values measured on adherends prior to bonding and DSJ joint strength measured for the bonded specimens. [28]*

2.3.2 High strain rate loading research

Other research activities at Tampere University included investigations of CFRP laminates under high-strain rate loadings [42]. The Split Hopkinson Pressure Bar (SHPB) device was used for the experiments. The specimens were trimmed out of a 28-ply laminate. In addition to traditional out-of-plane specimens, also a new specimen design was developed [42]. The new design was developed for studying high strain rate loaded CFRP with delamination between plies.

The load-strain response and damage were monitored and recorded. The techniques included high-speed infrared (IR) and optical imaging with Digital Image Correlation (DIC) to gain real-time strain and temperature. Additionally, the damage evolution and final fracture pattern were observed using the in-situ ultra-high speed synchrotron X-ray phase contrast imaging (XPCI) in collaboration with the ID-19 beamline at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. The ESRF facility required careful test planning and precise SHPB synchronization with the X-ray source (**Figure 24**).

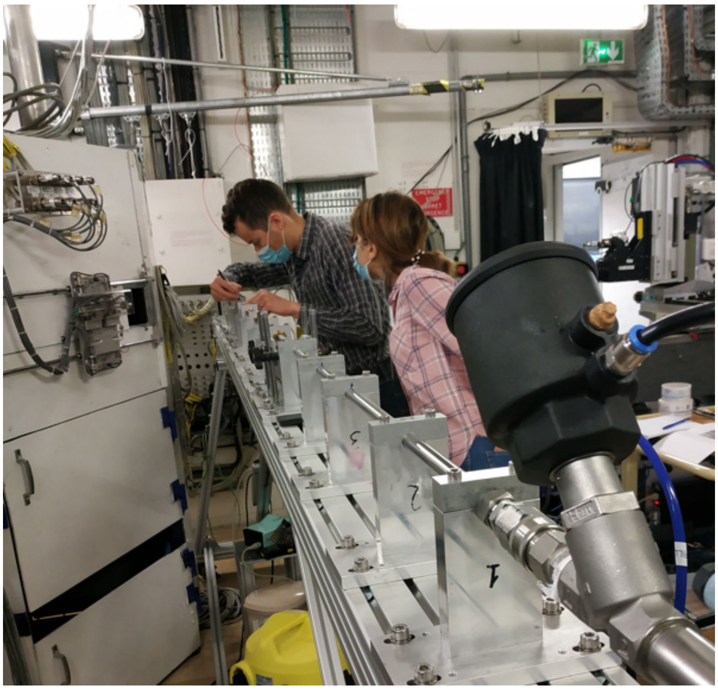


Figure 24: *The setting of the Split Hopkinson Pressure Bar device with the X-ray phase contrast imaging (XPCI) system at the European Synchrotron Radiation Facility, ID-19 beamline. Figure courtesy of Tampere University.*

The CFRP specimens as well as the test system parts used in the experiments were modelled using three-dimensional FE models. For CFRP, two modelling approaches for defining the composite were applied to comparisons: a layer-by-layer approach and the homogenized (laminate) approach. In the homogenized model, the laminate properties (computed via laminate theory) were used in the FE model. Delamination propagation was modelled into the FE models using Virtual Crack Closure Technique (VCCT). Delamination propagation plane, for the two modelling approaches, are shown in **Figure 25**.

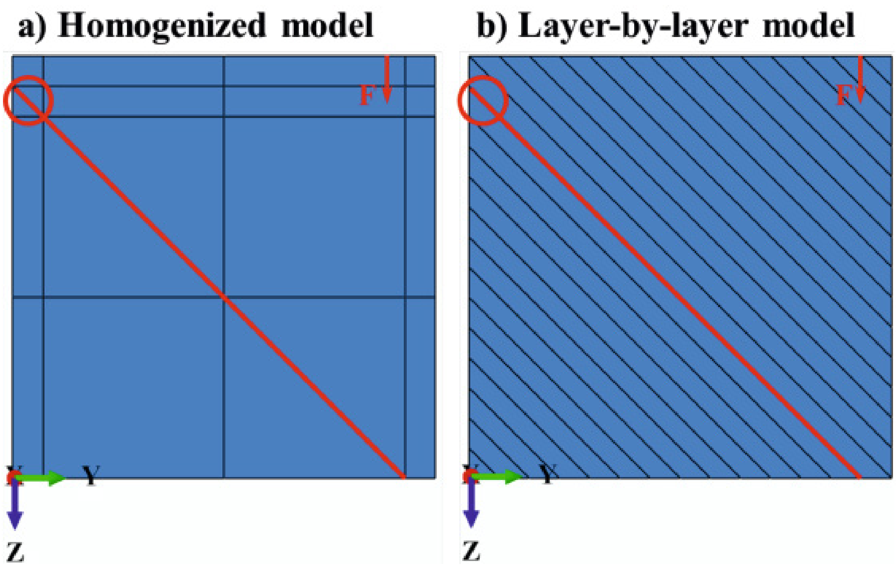


Figure 25: *Two modelling approaches, i.e., homogenized (left) and layer-by-layer (right) to model CFRP under high-strain rate response. The modelled delamination plane is shown as a red diagonal line. [42]*

The comparison of experimental and numerical force-time curves stated that the analyses are typically overestimating maximum force (from SHPB strain on bar part), and stiffness degradation. This could be explained by simplified damage modelling in which only one interlaminar delamination is modelled. Naturally, other micro-failure modes take place during the experiments. The comparison of the two modelling approaches did not provide significant difference in terms of maximum force. However, it was found that the correct use of strain (bar parts) for comparing calculated force of models and experiments is important. An example of the delamination model in the SHPB specimen model is shown in **Figure 26**. Tampere University has also performed other composite related research work in the field of impact [43], [45] and the understanding about the high strain rate behavior improves the capabilities to simulated low-to-high speed load scenarios in structures.

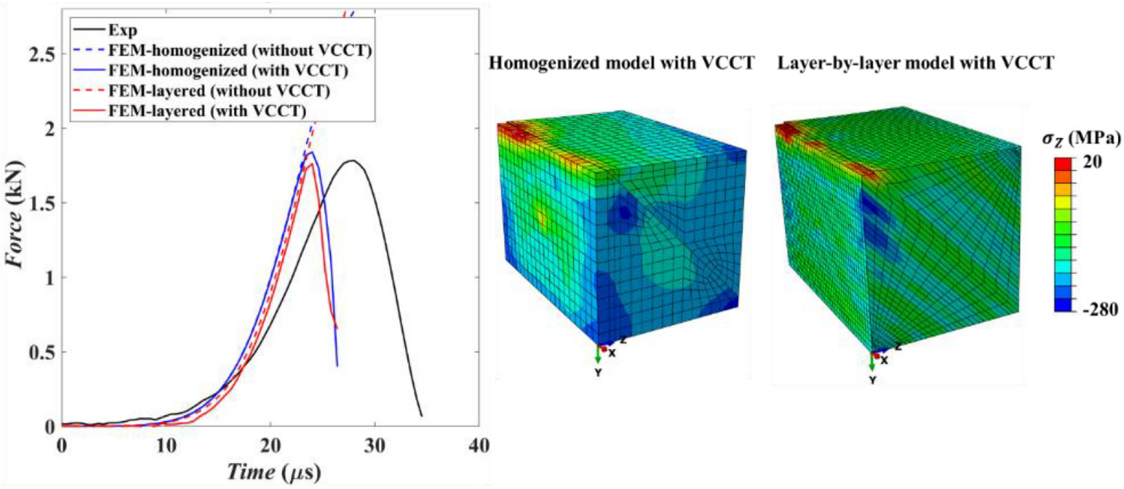


Figure 26: *Out-of-plane stress and delamination growth in homogenized (upper) and layer-by-layer (lower) FE modelling approaches. [42]*

2.4 Repair technologies

2.4.1 EDA PATCHBOND II project

The PATCHBOND II, PB II "Certification of adhesive bonded repairs for Primary Aerospace composite structures" project began in 06/2020 under the framework of the European Defence Agency (EDA) R&T Category B projects. Originally scheduled four-year project was approved to be extended for one (1) year due to foreseen delay in the planned flight test campaign, thus the closure of the project will be 06/2025. The overview of the project has been documented by Jokinen et al. [33].

The PATCHBOND II project was also introduced in Chapter 3.2 of Ref. [11] and Chapter 2.5.1 of Ref. [12]. The project concentrates on damage tolerance of bonded repairs for primary aerospace composite structures, and the objective is to set guidelines, to validate developed analysis methods, as well as further development of the SHM systems enabling beyond the Bonding Repair Size Limit (BSRL) repairs. The key element to ensure the damage tolerance for bonded repairs is to understand the damage propagation in composite structures – especially in the bondline. From manufacturing point of view co-bonding and secondary bonding (hard patch) methods together with proper material systems comes into question. Adhesive bonding joint geometries include strap joints and scarfed joints. The NH90 helicopter has been used as a demonstration platform.

Despite the limited number of material systems in question in the project, the EDA PATCHBOND II project includes substantial amount of experimental testing of various scales under different environments, also out-of-laboratory testing. Experiments and analysis have been concentrated on initial bondline defects and barely visible impact damages (BVIDs) to fulfil "analysis supported by test evidence" principle. The primary interest is in no growth (threshold) condition in the bondline. The secondary interest is in the stable/unstable damage propagation. The relevant loading types include static, fatigue and impact loads.

The work has been performed by an international consortium consisting of 15 industrial and scientific partners from six European countries enabled to participate in EDA's projects, countries alphabetically: **Czech Republic**: Czech Aerospace Research Centre (VZLU); **Finland**: Tampere University (TUNI), Patria Aviation, VTT Technical Research Centre of Finland (VTT); **Germany**: Bundeswehr Research Institute for Materials, Fuels and Lubricants (WIWeB), Airbus Defence and Space (ADS), University of Stuttgart (USTUTT); **Italy**: Politecnico di Milano (POLIMI); **the Netherlands**: Netherlands Aerospace Centre (NLR), Fokker Services, KVE Composites Repair; **Norway**: Norwegian Defence Materiel Agency (NDMA), Norwegian Defence Research Establishment (FFI), FiReCo, Light Structures. Project Lead Contractor is NLR (the Netherlands). Tampere University is the national coordinator of the project (see also Chapter 2.4.1.1) and the Finnish Defence Forces Logistics Command (FDFLOGCOM) is the national bill paying authority of the project.

The EDA PATCHBOND II project structure has been divided into five Work Packages:

- WP 100: Management (lead by NLR)
- WP 200: Materials & Processes (lead by NLR)
- WP 300: Design & Analysis (lead by TUNI)
- WP 400: Tests (lead by VZLU)
- WP 500: SHM (lead by FFI)

2.4.1.1 EDA PATCHBOND II activities in Finland

The activities of the Finnish partners supported the certified repair process involving in analytical and numerical analyses, experimental testing, Non-Destructive Inspections (NDI) and Structural Health Monitoring (SHM) based on Acoustic Emission (AE).

Tampere University has been a partner in the project along with other Finnish partners, i.e., Patria and VTT. The work of Tampere University in the project has been related to damage tolerance and the methods for assessing crack onset and propagation in adhesively bonded joints.

The usage of external bonded patches is a common approach for repairing relatively thin structures. In the project, the damage tolerance of bonded repairs was studied using the double strap joint (DSJ) specimen type (see **Figure 27**) and relevant experiments [34]. The DSJ testing included three different specimen series. The two of the series were intact, i.e., without any pre-existing flaw. Then, one of the series was a specimen design with a pre-existing crack. Also, the two intact specimen series differed in terms of the over-lap length. All the specimens' adherends were made of carbon fibre reinforced plastic (CFRP) laminates and bonded with adhesive film (FM 300-2, Solvay).

All the DSJ specimens had 1-inch nominal width. The experiments of the intact specimens provided average maximum forces of 25.7 kN and 38.5 kN with a 0.5-inch and 1-inch overlap, respectively. The specimens with the pre-existing crack had a 1-inch overlap, and one of the straps (against parent laminate) had a 0.5-inch pre-crack. Due to the crack configuration, the specimens basically were unsymmetric. The series with the pre-crack provided an average maximum force of 15.7 kN. This states that the pre-existing crack caused significant reduction in the maximum force of the joint. Part of the pre-cracked specimens were monitored using digital image correlation (DIC) to better understand the time of crack onset and propagation of crack (see **Figure 27**). The failure in all the specimens was sudden, i.e., the crack(s) propagated very fast. The consistency of the failure process between specimens was not possible to be confirmed.

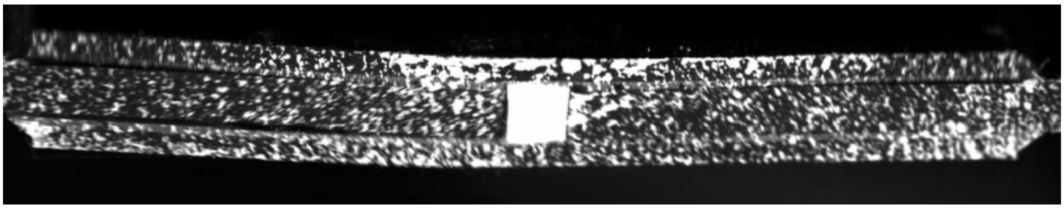


Figure 27: *An in-situ image provided for the DIC analysis of the pre-cracked DSJ specimen. [34]*

The intact specimen with the 0.5-inch overlap and the pre-cracked specimen were modelled using the finite element (FE) method. The adhesive-adherend interface was modelled with cohesive zone model (CZM) based on the contact approach of Abaqus/Standard. The data of the intact specimens with the 0.5-inch overlap length was used as a reference for determining cohesive strengths. The model of the pre-cracked specimen included the intended ply flaw in the CFRP and delamination between the first plies to the bondline, in addition to adhesive damage model and CZM (interface failure) between adhesive and CFRP. The model of the pre-cracked specimen was used for sensitivity analyses. The target of sensitivity analyses was to study the strength of effects of (delamination) parameters and their interaction. The main interest was to find out if the variation between delamination locations could explain the scatter in experimentally observed failure modes. Four different delamination surfaces (interfaces) were chosen for sensitivity analyses. These surfaces were ply-ply interfaces that were likely to delaminate based on the experiments. The values for fracture mode I and mode II related to each surface were varied during the analysis. In total, eight value-sampled sets were developed using normal distribution. Some of the parameters were found to be more important than others, but none of parameters indicated strong correlation to failure mode(s). In addition, negative correlation was found between some of the delamination parameters and the maximum strength. Simulated damage propagation in the modelled pre-cracked DSJ specimen is shown in **Figure 28**.

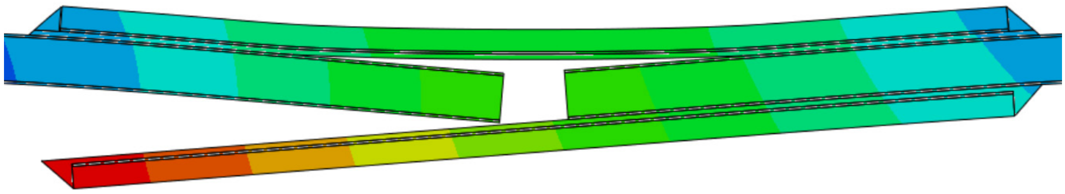


Figure 28: *Simulated damage propagation in the modelled pre-cracked DSJ specimen. 3X magnification of deformation applied for clarity in the image. [34]*

Another focus within the work of Tampere University in the project was the development of a damage assessment method. The new damage model concept for adhesive was developed using the continuum damage (CTD) formulation, with the fundament in the Bazant's crack model [44]. The developed damage model had two damage activation functions with specific parameters. The continuum damage model was expected to model the fracture process zone in the adhesive bondline under mode II dominated (crack) loading yet homogenized by CTD. The continuum damage model especially accounted for local transverse stresses that affect damage mechanisms observed in the experiments. The new model concept was different to the typical approach of modelling damage onset and propagation using CZM, which requires specific elements or contact to be assigned.

The experimental reference for the developed damage model was the end notched flexure (ENF) specimen and related test data. The ENF test specimen in the project included CFRP adherends and two layers of film adhesive (FM 300-2) with pre-crack made between the adhesive layers using a release film. The adhesive film included a knitted carrier. The concept of using the new model relied on dividing the adhesive volume into sublayers of pure adhesive and the carrier (dominated section). A similar conceptualization was adopted for previous work at Tampere University that focused on mode I dominated failure and its modelling with the continuum damage formulation [46].

The development work included studies about the strength properties – especially their effects on damage onset and propagation. The results showed that the normal and shear strength values of the model influenced both onset and propagation. An example of the results is shown in **Figure 29**. The figure presents damage indexes (1 means failed material and 0 intact material) in the bond line for computed normal (d_n) and shear (d_{sh}) damage evolutions. The simulations (designated: a*, d and e) have strength values preset at 35 MPa, 90 MPa, and 200 MPa in the normal direction, per designation. The results remark that the normal strength influences damage localization and evolution in the model. This is an interesting result, which shows that the normal strength influences when the (homogenized) crack tip is experiencing mode II loading. In the experiments, transverse cracks towards upper interface were observed. Based on the modelled spatial damage evolution, model a was shown to be accurate. The highest strength value governs the damage at the specimen midplane. The crack tip regime has the stress localization from where the crack is propagating under shear loading. In addition to damage onset and propagation, the experimental force-displacement curve and the maximum force were compared with the model's results. The model was shown to somewhat underestimate the maximum force during a (ENF) test.

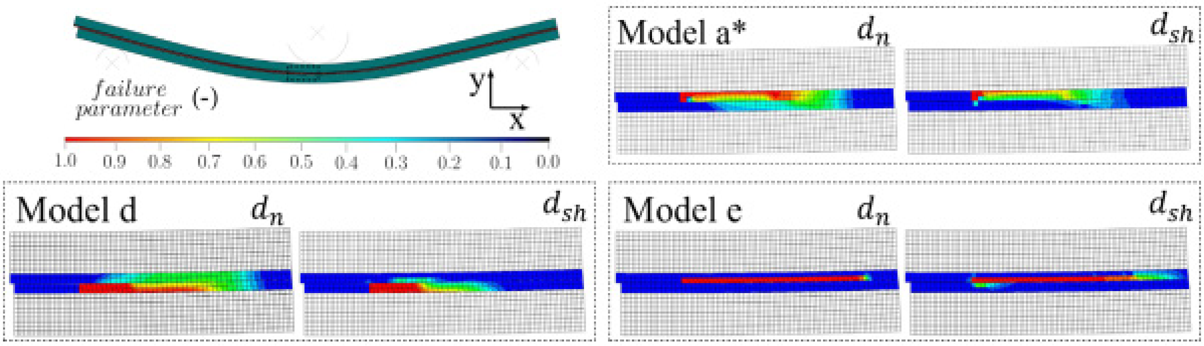


Figure 29: *The influence of strength (i.e. different input parameter values) on damage at the bondline of ENF specimen. [44]*

The layered configuration of the concept was also investigated. In the concept, the adhesive was divided into sublayers (matrix (M) and carrier (C) dominated sections). The matrix dominated section was modelled using the CTD model. The continuum damage model was used for the whole adhesive section (thickness direction) for comparison. The sublayer sequence was also switched between comparison (CMC and MCM) and related results are shown in **Figure 30**. Based on the results, the CMC-III model was shown to provide the best outcome. This model and concept of sections had large (180 MPa) shear strength value input. Another (MCM) model did not provide similarly good correspondence due to switch of domination in sublayers.

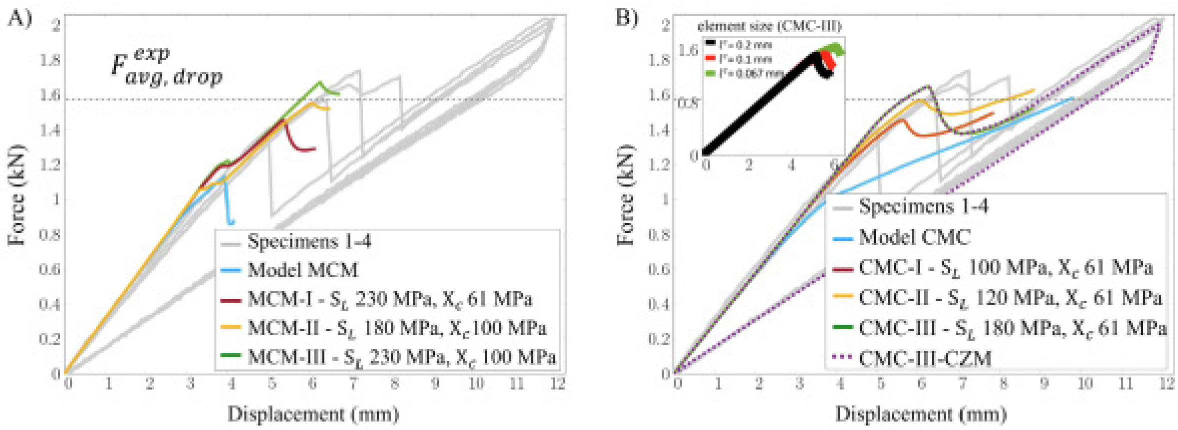


Figure 30: *Force-displacement curves of ENF test simulations using different sublayer configurations, i.e., MCM (left) and CMC (right). [44]*

Another strand of the EDA Patchbond II project involving the Finnish partners is the WP 500 regarding Structural Health Monitoring (SHM). In the WP 500, VTT has been evaluating the performance of the selected Acoustic Emission (AE) + real-time Ultrasonic Testing (UT) + strain sensor (SG) -based SHM system and various algorithms therein in a small-scale cyclic test program together with our national test partners: Tampere University (TUNI) and Eurofins Expert Services (ES). The purpose of the constant amplitude (CA) cyclic test program was not so much to provide fatigue test data, but to provoke a laminated artificial debond to grow in controlled manner such that anticipated stable debonding could be monitored with the SHM system.

The experimental cyclic test campaign was carried out by End-Notched Flexure (ENF) test in 3-point bending (presented in Chapter 2.5.1.1 of the ICAF2023 National Review [12]) and by Cracked Lap Shear (CLS) test. The CLS test is a relevant choice for characterizing fracture toughness and damage growth behavior in adhesively bonded joints. The CLS test coupons were manufactured from Carbon Fiber Reinforced Polymer (CFRP) fabric prepreg, with a quasi-isotropic stacking sequence. Two 8-ply laminates were bonded together with two layers of film adhesive. A zig-zag-patterned artificial defect was inserted between the two adhesive layers on the other end of the bondline to initiate the debonding. Two short or “standard” (length 250 mm), and two long (length 275 mm) CLS specimens were tested under constant amplitude (CA) loading (F_{max} = 7 kN, R = 0.1, *f* = 5 Hz) up to approx. one million cycles. Dimensions and instrumentation of the CLS specimen are depicted in **Figure 31**.

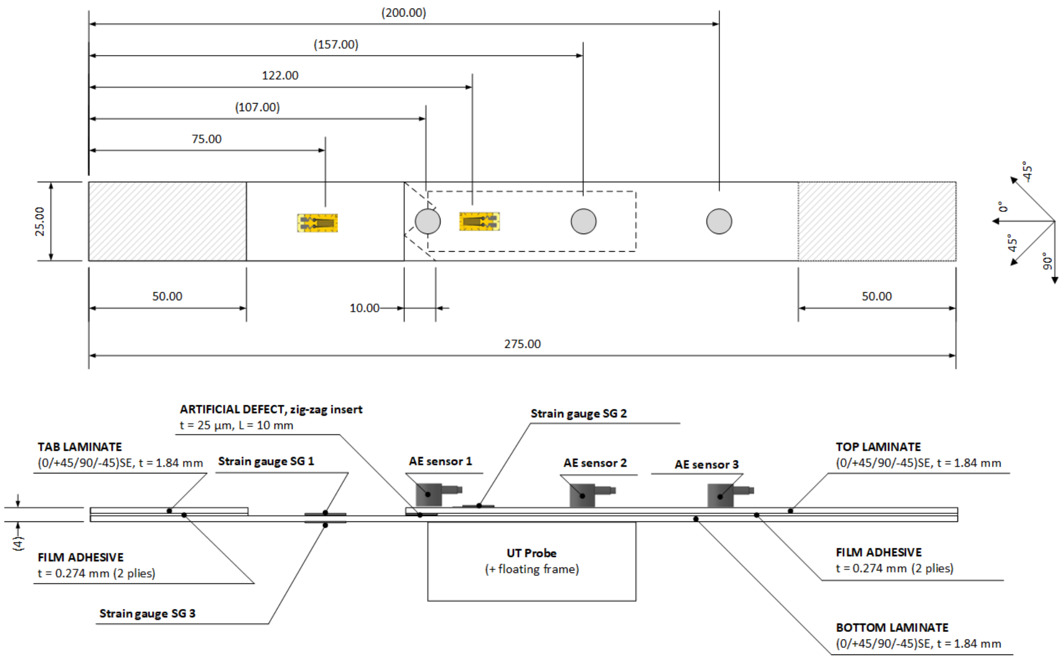


Figure 31: *CLS coupon dimensions [mm], lay-up and instrumentation. The UT probe in a floating frame was shifted along the debond growth. The test specimens were manufactured by Netherlands Aerospace Centre (NLR). [50]*

As all (even microscopic) failure mechanisms in composite structures generate acoustic emission, the focus here was to map the AE system capabilities to discover/separate the structurally important events. During the test, real-time Phased Array Ultrasonic Testing (PAUT) was used to validate the AE findings, complemented by visual inspections. Final debond lengths were defined by the post-test ultrasonic C-Scan inspections using through-transmission technique in water immersion. Installed strain sensors allowed to control sufficient strain levels during the test, enabled evaluation of mechanics of the test coupons and facilitate the interpretation of the results. Strain data was also used in validation of the conducted FEA activities. Experimental test set-up is presented in **Figure 32**.

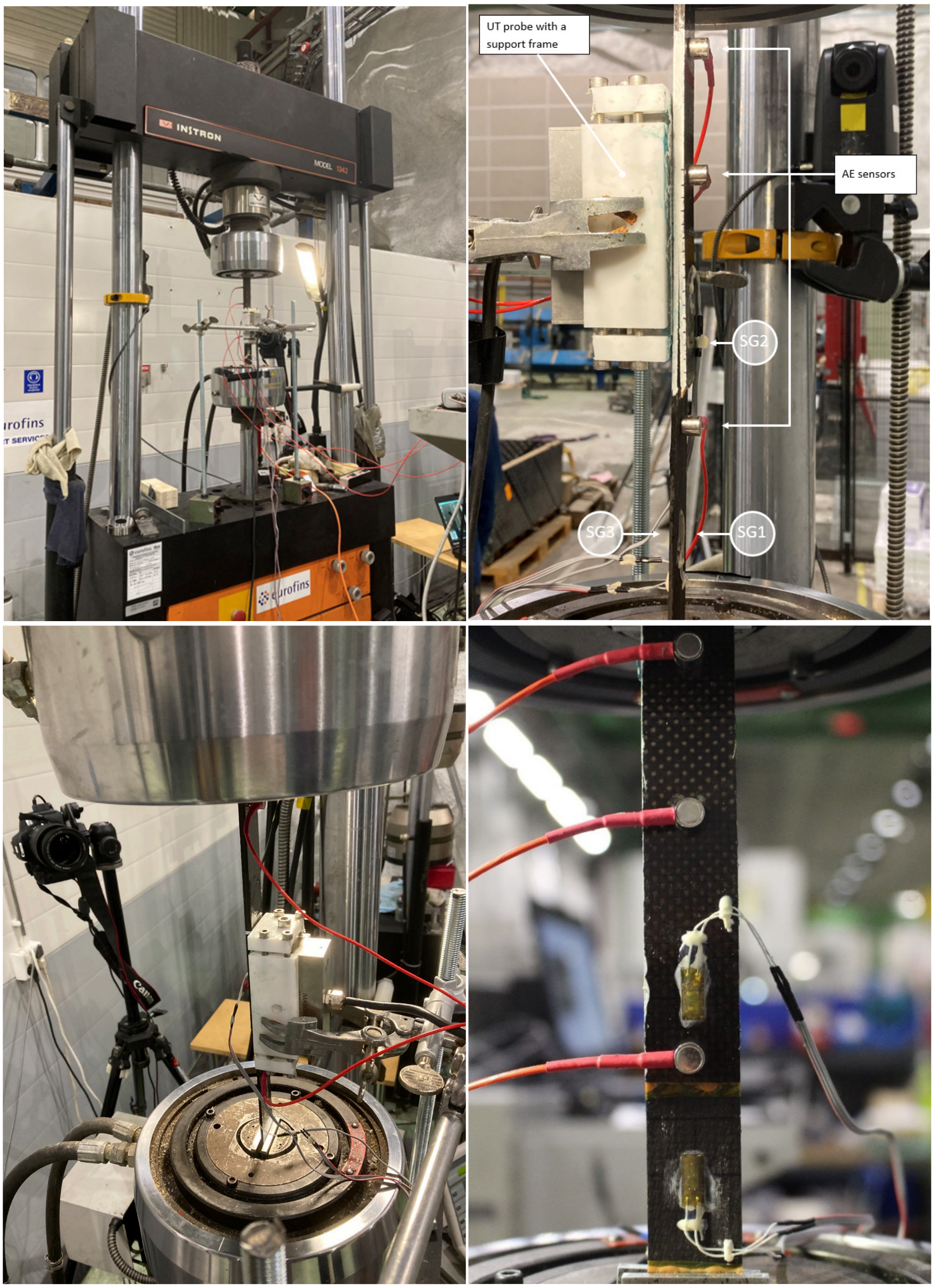


Figure 32: *Experimental test set-up in the Cracked Lap-Shear (CLS) coupon tests at Eurofins Expert Services. Instrumentation consisted of three PAC Nano-30 AE sensors, a 2 MHz 64 elements Imasonic 5486A101 linear array probe attached to a 15 mm thick plexiglass wedge installed into a (white) floating support frame on a bottom of the specimen, and three axial strain gages. One edge of the test coupon was also painted with typewriter correction fluid and reference marks to facilitate visual debond growth observations. [50]*

Real-time ultrasonic measurements were carried out using the Verasonics Vantage™ 64 LE research ultrasound system. The system offers software tools encapsulated within Matlab® structures that allow precise specification of ultrasound parameters controlling both acquisition and data processing aspects along with image display functions.

Acoustic Emission and real-time ultrasonic signals partially operated within overlapping bandwidths and would have interfered with each other without adjustments. This unwanted feature was resolved by generating a test-specific trigger signal i.e., square pulse from the force output voltage signal of the Universal Test Machine (UTM) and slightly offset the AE and UT scans from each other based on it. The trigger delay was adjusted to send the UT burst once in a load cycle at the time when the specimen was least deformed.

The AE workflow consisted of following steps: continuous data acquisition at 1 MHz, detecting hit candidates, evaluating AE features, and locating the AE source. Due to high attenuation of the AE events in the CFRP material, three AE sensors were used in the CLS tests. Optimal positioning of the sensors was crucial to locate the source of the AE event. In this case, time-of-arrival (TOA) -based source location provided sufficient results.

The positioning of the UT probe on the specimen was determined based on the debond front location, allowed continuous monitoring throughout a full day's cycling. The progress of debonding was tracked visually as well. The PAUT system collected the data from the entire test duration, thus approx. 1.3 GB of raw data and 128 GB of real-time inspection images were post-processed. An example of post-test UT results is illustrated in **Figure 33**.

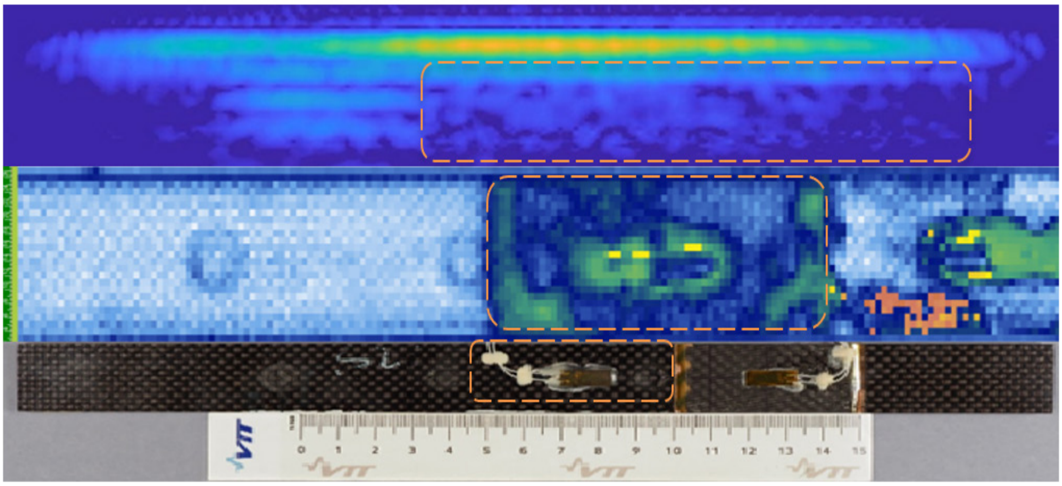


Figure 33: *Post-test results of the short CLS specimen in which the final debond length of 57 mm was determined. Up: The last PAUT image of real-time monitoring via Verasonics. Signal attenuation due to debonding is marked with a dashed line; Middle: Through transmission ultrasonic C-Scan image in which the debonded area is surrounded by a dashed line. Inevitably echoes from the installed strain gauge and its wiring slightly impedes the interpretation. The circular traces resulted from the AE sensor installations; Below: A dashed line highlights the debonded area on the CLS specimen. [52]*

As a reference, the final debond lengths were also estimated by stereomicroscopy from the side of the specimen which was earlier painted by typewriter correction fluid and reference marks for better visual interpretation in debond growth monitoring during the test.

The results obtained from the ultrasonic monitoring of four CFRP specimens were found to be consistent with the trend observed in Acoustic Emission (AE), C-scan images, and visual inspections. The summary of the results can be seen in **Table 1**.

Table 1: *Final debond lengths [mm] after cyclic loading determined by Acoustic Emission (AE), Phased Array Ultrasonic Testing (PAUT), Visual inspection (VIS), and ultrasonic C-scans utilizing the through-transmission technique. [50]*

Specimen	Total Cycles	AE	PAUT	VIS	C-scan
Long Specimen 1	715 115	31	23	23	25
Long Specimen 2	469 900	69	74	74	76
Short Specimen 1	1 260 270	39	43	41	44
Short Specimen 2	1 086 725	69	57	55	57

Figure 34 illustrates the complete collection of data points obtained from UT and AE tests for all specimens. The final assessment of debond growth was conducted using through-transmission (TT) C-scan images in the water immersion system. Rapid debond growth observed for the LCLS 2 specimen was most likely due to manufacturing-induced porosities, which were already detected with C-scan images prior to testing.

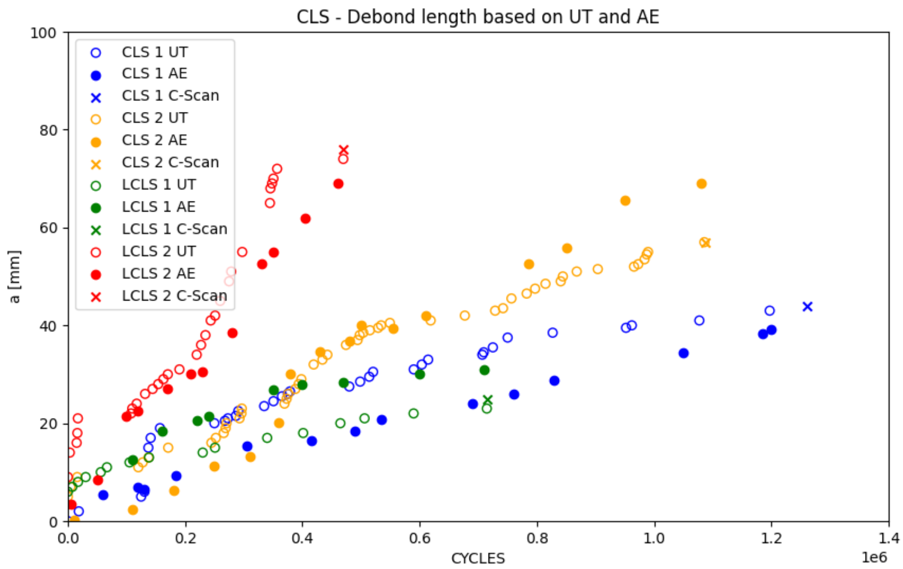


Figure 34: *Debond growth in the CLS tests determined by AE measurements (AE) and real-time UT measurements (UT). The final debond length (ground truth) was defined by the post-test C-scanning (C-scan). CLS# results represent the short coupons' results and LCLS# the long coupons' results. [50]*

Finite Element Analyses were carried out separately for the long and short CLS specimens. The 3D FE model for the short CLS specimen consisted of 37 700 continuum shell elements (linear hexahedral SC8R elements). Mesh size for the adherends (8-ply laminates) was approx. 1 mm (2 elements/thickness) and 1 element/thickness for the adhesive layer. The FE model was simplified with respect to the real-life specimens such that the debond initialization insert in between the adhesive layers which originally had a zig-zag profile, was idealized as a straight profile. An example of the FEA activities is presented in **Figure 35**.

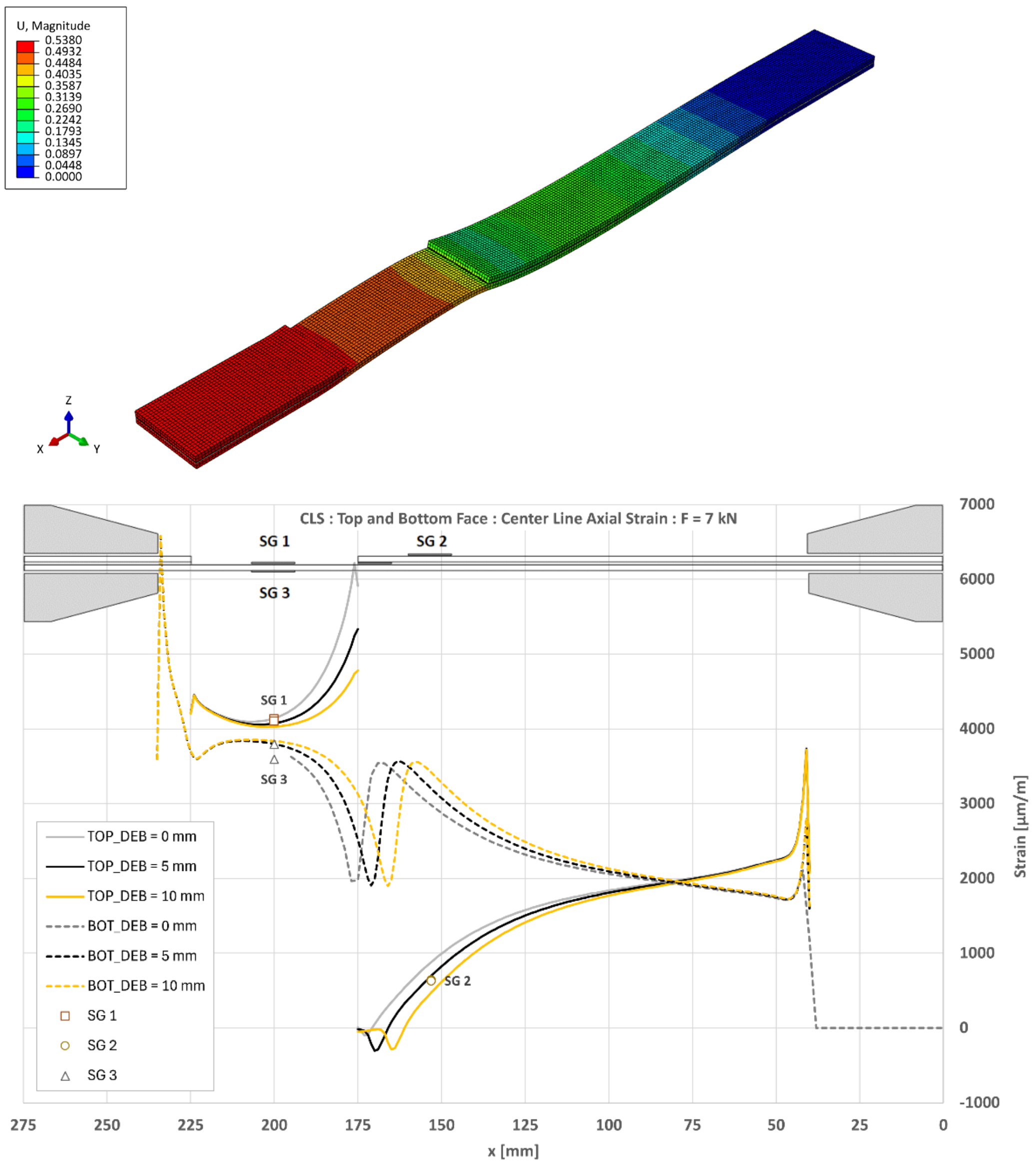


Figure 35: *FEA of the CLS test and comparison of numerical results with axial strain measurements (SG #) with various debond lengths (0 mm, 5 mm, 10 mm) when applied loading F = 7 kN, resulted approx. 4000 µm/m axial strain at the control point (strain gauge SG 1). The left end grip was intentionally adjusted to alleviate the critical hot spot strain of the laminate at the grip during the cyclic loading. Axial strains on the top face center line are presented in solid lines and on the bottom face in dashed lines. [50]*

UNCLASSIFIED
Based on Foreground Information received under EDA Contract No. B.PRJ.RT.670 covering the Ad Hoc Project entitled “PATCHBOND II”. The work was supported by the European Defence Agency (EDA) within the “PATCHBOND II project”.

3 Related activities

3.1 EDA Scorpenes project

European Defence Agency (EDA) project Scorpenes aims to establish a Condition-Based Maintenance (CBM) system focused on corrosion management on aircraft level. The project also aims to enhance the reliability of corrosion testing.

The aircraft level CBM intends to proactively target the maintenance actions through monitoring and predicting equipment failures, so that the maintenance is performed when needed rather than on a strict schedule. The project works through linking the obtained environmental data with corrosion risks by tracking the initiation and progression of the corrosion process. Monitoring allows for the detection of early warning signs, the identification of trends and parameters associated with the onset of corrosion, and to define the effectiveness of corrosion prevention methods. A main outcome for corrosion monitoring would be the ability to define the corrosion rate through corrosion or environmental sensors. This would enable the prediction of critical moments for the application during its lifetime – and for this, real-time corrosion monitoring is crucial.

The project involves several partners Europe-wide. From Finland, the VTT Technical Research Centre of Finland Ltd and Patria Aviation participate in the consortium. VTT leads the work package on modelling and prediction which aims in building a model that links the corrosion risks and environmental aging. Moreover, it aims to validate the model in real conditions. Patria is primarily involved in the test flight data gathering and analysis work as well as concept work related to CBM implementation.

UNCLASSIFIED
Based on Foreground lnformation under EDA Contract No No B.PRJ.RT.905 covering the Ad Hoc Project entitled "Solutions for Corrosion Optimized Repair and Prediction with Efficient Network of Environment Sensors (SCORPENES).

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Report's title	
A REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND MAY 2023 – APRIL 2025	
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Summary

This document was prepared for the delivery to the 39th Conference of the International Committee on Aeronautical Fatigue and Structural Integrity (ICAF) scheduled to be held in Xi'an, China, 9-12 June 2025.

A review is given of the aircraft structural fatigue research and associated activities which form part of the programs within the Air Force Command Finland (AFCOMFIN), the Finnish Defence Force Logistics Command, Joint Systems Centre (FDFLOGCOM JSC), Air Systems Division; Army Command Finland (ARCOMFIN); Arecap Ltd; Elomatic Ltd; Emmecon Ltd; Eurofins Expert Services Oy; Patria Aviation Oy; Tampere University; Trano Oy; Trueflaw Ltd; and VTT Technical Research Centre of Finland Ltd (VTT).

The review summarizes fatigue related research programs and investigations on specific military aircraft since the previous Finnish National Review compiled for the 38th Conference of the International Committee on Aeronautical Fatigue and Structural Integrity (ICAF), 26-29 June 2023.

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