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A REVIEW OF RECENT AERONAUTICAL FATIGUE INVESTIGATIONS IN FINLAND UNTIL MARCH 2001

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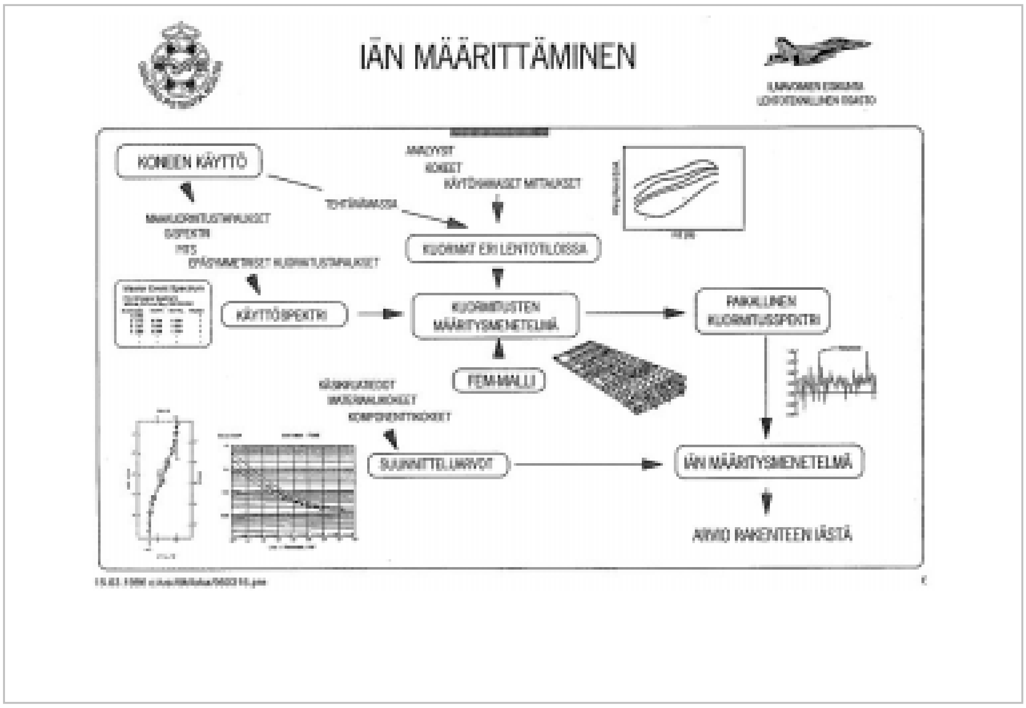

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Summary

This document was prepared for the delivery to the 27th Conference of the International Committee on Aeronautical Fatigue scheduled to be held in Toulouse, France on 25-29 June 2001.

A review is given of the aircraft fatigue research and associated activities which form part of the programs within the Finnish Air Force Air Materiel Command (FAF AMC), Patria Finavitec Oy (PFA), the Finnish Air Force Headquarters (FAF HQ), VTT (the Technical Research Center of Finland), Helsinki University of Technology, Laboratory of Lightweight Structures (HUT/LLS), Laboratory of Applied Thermodynamics (HUT/LAT) and Laboratory of Aerodynamics (HUT/LAD). The review summarizes fatigue related research programs and investigations on specific military fixed wing aircraft up to March 2001.

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Owing to the significance of applied research activities within VTT Manufacturing Technology on aircraft structures, the editor takes this rare opportunity to acknowledge with respect the following gentlemen for their sparring visions, trust and active support in efforts to accommodate the operational strategies of these organizations towards a common goal: Col. Markku Ihantola and Capt. Kari Renko (FAF HQ); Col. Veijo Mustonen and Sr.Lt. Esa Lahtinen (FAF AMC); Jaakko Harjumäki and Jukka Raunio (PFA); Prof. Olli Saarela (HUT), and Prof. Matti K. Hakala, Prof. Heikki Kleemola, Kimmo Oila, Asko Kähönen and Pekka Koskinen (VTT Manufacturing Technology).

Espoo, 21 June 2001

Editor

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1 Introduction

A transition took place within the FAF between 1995-2000, as the older fighter jets - the MiGs and the Drakens which did not have significant structural fatigue issues during the FAF service - were retired and replaced by the Hornets. During the same time period, the Vinkas and the Hawks of the FAF reached their midlife. These jet aircraft (Hawk and Hornet) possess e.g. noteworthy maneuvering cababilities, which are manifested also on the structural side: The era of structural fatigue issues had started. The experience forced the FAF to initiate concrete and systematic efforts on a national level to cope with the structural deterioration effects on the three aircraft types. These efforts are briefly described in this review.

This Finnish review of current aeronautical fatigue investigations up to March 2001 comprises inputs from the organizations listed below.

FAF HQ	The Finnish Air Force Headquarters, Aircraft and Weapon Systems Division, P.O.Box 30, FIN-41161 Tikkakoski; Finland
FAF AMC	The Finnish Air Force, Air Materiel Command, P.O.Box 210, FIN-33101 Tampere; Finland
PFA	Patria Finavitec Oy, 35600 Halli; Finland
HUT/LLS	Helsinki University of Technology, Laboratory of Lightweight Structures; P.O.Box 4300, FIN-02015 HUT; Finland
HUT/LAT	Helsinki University of Technology, Laboratory of Applied Thermodynamics, PO Box 4400, 02015 HUT; Finland
HUT/LAD	Helsinki University of Technology, Laboratory of Aerodynamics, PO Box 4100, 02015 HUT; Finland
VTT	VTT Manufacturing Technology, Maritime and Mechanical Engineering, Aircraft Structures, P.O.Box 1705, FIN-02044 VTT; Finland

2 On the fatigue management policy of the FAF

Fatigue management covers the organization and management of any functions required to keep the FAF aircraft fleet flying until the planned Out of Service Date without a need for major modifications or repairs to the aircraft's load carrying structure, while enabling the operational and training objectives to be met and simultaneously precluding any issues relating to structural fatigue to affect the safety of flight, aircraft availability or costs of operation.

Successful fatigue management requires that the piloting techniques used by the aircrew and the contents of flight training syllabi are brought to a level at which any life expenditure which is not justified by operational or training objectives has been omitted. This further dictates the necessity of gathering detailed information on the usage of the aircraft together with all data which enable the determination of fatigue life expended by the major structural components of the aircraft in different missions and in different flight conditions therein. A summary of the fatigue management policy is shown in Fig. 1.

2.1 Fatigue management goals

The goal for the fatigue management of the FAF can currently be formulated as follows: Adjust the contents of training syllabi and the peacetime operational usage such that operational and training effectiveness is maximized while simultaneously meeting a given Out of Service Date.

2.2 Fatigue management functions

In order to maintain safety of flight, it is required that the fatigue status of the fleet, including all major load carrying structural assemblies of each individual aircraft, can be determined in such a way that any required structural inspections can be carried out and any structural assemblies or whole airframes can be retired from service before or at the cleared life. In case of highly maneuverable military aircraft, e.g. the Hornet (Fig. 2) and the Hawk (Fig. 3), where large differences can exist in the severity of usage between individual aircraft, it is required that the usage and the structural effects of the usage can be tracked individually for each aircraft.

Individual aircraft are assigned to operating units and further to missions based on the expected severity of the usage so that life is expended at an approximately even rate between different tailnumbers. This should result in a replacement window for the fleet which is of reasonable length while simultaneously allowing for the full exploitation of available life of each aircraft. As an example of this is the FAF Hawk wing replacement program: The fleet Fatigue Index (FI) accumulation is planned carefully for each aircraft to get the maximum benefit of the replacement with a minimum amount of new wings.

Adding to the above, individual aircraft may be assigned to "fleet leader" roles to provide early warnings of possible structural fatigue scenarios.

Following to the fatigue management goal of the FAF, the most important goal for any usage recording and analysis system is to identify what types of flying (missions, configurations or flight conditions) cause most damage to the structure, in order to allow:

- to confer with the aircrew to avoid flying in severely damaging flight conditions unless specific training or operational reasons dictate otherwise
- the adjustment of the content of the training syllabi so that flying in severely damaging flight conditions is minimized without compromising training objectives

Data must be collected on occurrences of cracks, etc., found which are to be combined with usage data to produce estimates for the rest of the structure and the rest of the fleet to be used in decision making on pre-emptive modifications. Same type of data can be used in the design of repairs and modifications.

Furthermore, available data and understanding on the fatigue properties of the FAF aircraft structures should be on the level which allows the training of aircrew, technical personnel, planners and managers to meet the objectives outlined above.

2.3 Fatigue management data requirements

Quantitative, calibrated data on fatigue life expenditure rates are required:

- form each aircraft (tailnumber), from the most critical structure (e.g. Figs. 2 and 4), to allow for aircraft retirement decisions and comparisons between pilots and operating units
- from all critical structural assemblies from a large enough sample of flights to allow for the determination of average
  - damage rates / mission type / structural location
  - damage rates / flight condition / structural location

It is required that the flight condition and damage data collected during a flight can be combined with flight log data identifying the mission type, operating unit, pilot, etc.

For the FAF F-18 aircraft, the following can be added: It is also required that the master event spectrum together with loads and material data used in the design are available, together with relevant software, to allow a quantitative assessment of the effects of differences between design and true FAF usages to the lives of all critical structural assemblies. This allows for the identification of highly damaging flight conditions within the training syllabi and allows for the focusing of corrective measures where the payoff is the greatest.

2.4 The scope of the national review

This national review of current aeronautical fatigue investigations in Finland is published for the first time. Therefore, a brief introduction of the aircraft inventory of the Finnish Air Force (FAF) is justified, Table 1. The emphasis of this national survey is on the three most important aircraft types of the FAF, namely the primary trainer Valmet Vinka (VN), the jet trainer Hawk Mk.51 and Mk.51A (HW) and the F-18C/D Hornet (HN).

Finland is willing to seek for the ICAF membership, for which the current review in Finland is collected and delivered. This review also forms a step in Finland towards the international community of aeronautical fatigue research.

3 On the Valmet Vinka's LEP

The Life Extension Program (LEP) of the Valmet Vinka primary trainer, also known as the Valmet L-70 Miltrainer Vinka [Air International 1979] is covered in a more thorough manner by PFA in another ICAF 2001 presentation [Pirtola 2001]. For the sake of the first Finnish national review, however, a brief overview of the program is provided below (Fig. 5).

The most important areas of interest of the aircraft's structures were modeled (FEM) by PFA. Meanwhile at the FAF, the actual sortie distribution corresponding to the FAF use of the Vinka was updated. Fatigue critical areas of the aircraft were also identified and preliminary estimates of their fatigue lives were produced [Pirtola 2001]. Subsequently, more detailed FE analyses of the wing carry-through area were conducted by PFA. Supporting life estimation activities were provided by HUT/LLS [Wallin 1997/1].

A series of flight measurements were performed with one aircraft that was instrumented with a data recorder (strains, normal acceleration, airspeed and altitude) [Vuorio, Teittinen, Siljander 1996]. The purpose of flight measurements was to collect data representative of typical FAF maneuvering and to update the existing flight loads analysis database of PFA. The strain gages were fitted to wings, wing carry-through, tailplane, fin, aft fuselage and engine support structures. To account for all loading conditions of interest (maneuvering and dynamics), all responses were sampled at 3600 samples per second.

Based on the actual sortie distribution of the aircraft in the FAF usage and on VTT's flight measurements during various sorties, the representative load spectrum was generated and fatigue life estimates were made [Pirtola 2001]. The fatigue and damage tolerance analyses of the wing carry-through were made also at Saab in Sweden [Berg 1998; Ansell 1998]. On the basis of the analysis results, some fleet inspections were made within the FAF.

To verify the analysis results, fatigue test components representative of the wing carry-through region were designed and manufactured by PFA [Lahtinen 1999; Pirtola 2001]. The uniaxial and variable amplitude fatigue tests were performed by VTT [Laakso 1999]. Some strain gage locations corresponded to those of the test flight instrumentation. These strain values together with the normal acceleration data of the aircraft provided reliable means to correlate the axial load to the strains and normal acceleration. To allow direct comparisons between the experimental fatigue life to the predicted values, the fatigue test load spectrum was that of previously employed in the analytical and numerical durability assessments. During the fatigue tests, fatigue crack formation and growth from all boltholes were monitored using the Eddy Current technique (ET). In connection with the ET, the roundness of the boltholes, bolt rotation and bolt tightening moments were among the items monitored throughout the spectrum fatigue tests.

As a result of the LEP program, a safe life of 5000 FH of the FAF representative flying was verified. Furthermore, the design effort is underway to extend the safe life to 7000 FH.

4 Hawk Mk.51 and Hawk Mk.51A

4.1 Hawk jet trainers in Finland - overview

A brief structural description of the Hawk aircraft can be found e.g. in reference [O'Hara 1993]. In 1976, a decision within the FAF was made to purchase 50 Hawk Mk.51 jet trainers to replace the FAF's aging Fouga Magister jet trainers. Four Hawks were assembled in England, while 46 aircraft were assembled at Valmet Aircraft Factory (currently PFA) in Kuorevesi, Finland. The tailplanes, fins, ailerons and air brakes of these aircraft were also manufactured by Valmet Aircraft Factory. Finland was the first export customer to the Hawk jet trainer.

The first flight of the Finnish-assembled Hawk Mk.51 aircraft (tailnumber HW-301) took place in January 1981, and the last aircraft (HW-350) was handed over from Valmet to the FAF in October 1985. The FAF made an additional order of seven Mk.51A aircraft in December 1990; these aircraft were all assembled in England by June 1994. Today, there are in excess of 165,000 flight hours with the FAF's Hawk inventory.

4.1.1 First actions triggered by the need

During the years it was observed that the FAF's usage of the Hawk was markedly more severe than that of the original design (Fig. 3). As a consequence, the first fatigue related structural failures were observed in Finland at the end of the 80's. These structural issues were repaired at PFA according to the existing repair instructions made by the manufacturer (then BAe, later BAE Systems) and PFA (then Valmet Aircraft Factory). During mid-90's, a number of Hawk tailplanes were "grounded" for the first time due to certain CSI's (Company Structural Inspections issued by BAE Systems) that came in effect. Additionally, information provided from BAe on their full scale fatigue test results and from other Hawk users on their fleet experience indicated that one should be prepared for various structural fatigue issues (in addition to the tailplane) within a relatively short time. These indications provided additional challenges, since some of the structural-issues-to-come were either such that there were no approved repair schemes, or the life improvement gained while applying some of the approved repair instructions was not acceptable.

4.1.2 The LEP feasibility study

The FAF HQ invited BAe to conduct a LEP feasibility program for the FAF Hawks with a goal to achieve the 6000 FH. To get the longest structural life with minor technical risks, heavy structural modifications were suggested: replacements of the wing, aft fuselage, fin and tailplane. At the same time within the FAF AMC, the FAF squadrons and PFA, some structural damages needed immediate actions. The proposed modifications - if implemented - could have provided structurally upgraded (over 6000 FH) Hawk fleet for the FAF, but without upgrading of the avionics systems. Furthermore, the time and money spent as well as possible training syllabi distraction aspects emphasized more economical and rapid actions. Consequently, the FAF invited PFA to create a repair and rework package for the known and the most probable failure scenarios.

4.1.3 Follow-up actions

Parallel to the LEP feasibility activities described above, the FAF AMC and PFA concentrated their efforts in developing own repair methods and applying them on the FAF's fleet aircraft. Between 1997-1999, there were numerous new (to the FAF) cracking observations requiring immediate repairs. In fact, until the early '98 the repair activities at the FAF AMC and PFA were conducted step by step from the most critical parts to the less critical. Either the repairs were planned and implemented as a structural issue would emerge or where it was known they would emerge soon. The experience of BAE Systems and the United Kingdom Royal Air Force (RAF) on Hawk proved very useful and enabled fruitful discussions and exchange of experience in e.g. analysis methods.

Based on the experience gained along the activities, the solution selected case-by-case was a partial combination of structural analysis using analytical or numerical methods (parallel continuation with the FE modeling and analysis efforts at PFA), flight measurements, modification planning and modifications. Supporting activities included those of VTT (flight measurement and damage tolerance analyses), BAE Systems (structural understanding and fatigue tests results) and the FAF (usage analysis). Today, e.g. an experimentally verified 3D finite element model of the aircraft exists at PFA. Further, PFA and the FAF AMC have developed repair and modification kits for e.g. ventral strakes, flaps, gun pod, aft fuselage frames and wing panels.

The first version of a Finnish repair and rework plan was created during 1999. There was a need for additional studies on the probability of certain failure types. These studies were performed, and by the end of 2000 PFA had completed the design work for all expected structural damage scenarios, e.g. [Raunio 2000; Raunio 2000b]. These scenarios were classified into three categories, of which the most critical scenarios will be repaired or modified in a pre-emptive manner during the routine aircraft maintenance. The second most critical scenarios will be dealt with as they appear. The least significant scenarios will either be ignored or only schematic repair schemes will be considered.

The pre-emptive modification plans for the fin and wing leading edges were developed at PFA at the end of the 90's e.g. [Raunio 1996]. The current investigative efforts on the FAF Hawks are focused on the durability assessments of the fatigue critical areas of the original wing and on the development of the inspection procedures e.g. with the aid of fracture mechanics applications. The existing FE model of the Hawk (Fig. 6) at PFA has been combined from partial FE models which have been created step by step: the tailplane [Keinonen 1997b], the center fuselage [Keinonen 1998], the Mk.51 empennage [Keinonen & Tikka 1999], the fin [Lähteenmäki 1999], the Mk.51 wing [Tikka 2000b] and the forward fuselage [Tikka 2000c]. The aerodynamic loads for symmetric and non-symmetric load cases are evaluated using CFD. Fig. 7 summarizes the most important Hawk activities. In the following, the major aspects are reviewed.

4.2 Tailplane and empennage

The project consisted of the following elements: rework and refurbishment planning and engineering, numerical modeling of the structures, analytical and numerical fatigue life predictions, structural response measurements during test flights, experimental fatigue tests of selected components, as well as the development of a new inspection system and the associated procedures. Some of the activities are described below.

4.2.1 "Mini-OLM I" flight measurements

A part of the plan [Raunio 1997] was the instrumentation of one Hawk aircraft such that the flight maneuvering and buffet induced responses could be captured during selected test flights representing the FAF usage. These test flights and the associated research activities including the tailplane, fin and empennage are termed as a "mini-OLM I" excercise [Vuorio, Teittinen, Aatola, Siljander 1997]. These flight response data, together with the Hawk fleet usage data of the FAF, the maintenance records of the FAF and PFA, and PFA's FE analysis results of the Hawk structural FE model would then be used in subsequent engineering assessments of the economical service life of the tailplane.

The instrumentation consisted a total of 18 channels of response data: 10 tailplane strains, 2 fin strains, 2 wing strains, 2 tailplane accelerations, normal accelerations from the aircraft's center of gravity (N_Z) and from the tailplane attachment main frame inside the aft fuselage. Most of the strain gage channels were instrumented in global net sections such that the response results could be compared to those obtained by the manufacturer from the RAF OLM response results [O'Hara 1993] and PFA's FEA results.

The manufacturer had earlier discovered significant buffet-induced responses of the tailplane within the frequency range of approximately 70 Hz...100 Hz [O'Hara 1993]. Therefore, an experimental modal analysis of the tailplane region was conducted before the flight measurements. The goal was to capture the modal shapes within the frequency range of 10 Hz...100 Hz. A fully functional tailplane, mounted to the empennage at the neutral position, was excited using the impact hammer technique.

To gain understanding of the relation between pilot actions and the responses, all standard flight parameters were captured in a synchronized manner with the strain and acceleration response data. The flight parameters were collected using the TIIKERI+ onboard flight test instrumentation system developed earlier by the FAF and PFA and routinely used by the FAF Flight Test Center. All strain and acceleration response signals (3000 samples per second each) together with the aircraft parameter data from the TIIKERI+ system (20 samples per second) were stored on a digital data recorder. An example of the response data is shown in Fig. 8.

4.2.2 Determination of the aerodynamic loads using CFD

During the rework and rework planning and engineering of the FAF Hawk tailplane, the computational fluid dynamics (CFD) and finite element modeling and analysis (FEM & FEA) were combined for the first time in Finland for aeronautical applications.

The calculations of aerodynamic loads for the Hawk were started at HUT in late 1996 by studying the tailplane at a few maneuvering conditions [Hoffren & Pietilä 1997]. Since the cases were essentially subsonic and no flow separation was involved, the calculations in the Laboratory of Aerodynamics were performed by applying a panel method for the full aircraft. The useful results led to the continuation of the load calculations at HUT, but because of the inherent limitations of the inviscid panel methods, the panel methods had to be abandoned at this stage. To be able to simulate a transonic, viscous flow around the wing with sufficient accuracy, the Navier-Stokes flow solver FINFLO developed at the Laboratories of Aerodynamics and Applied Thermodynamics was employed. However, the use of the FINFLO is very expensive for the whole flight envelope. Therefore, a combination of the use of the panel method and the FINFLO was employed, and the aerodynamic loads were interpolated for a structural model of the Hawk [Tikka 2000]. The calculated wing loads compared favorably against measured data.

Viscous navier-Stokes simulations were performed at 11 different flight conditions using a steady-state assumption. Since the actual state of the flow field is in some cases, e.g. in a case of a pull-up, time-dependent, suitable approximative approaches were utilized. The computations were performed at HUT using a FINFLO flow solver. The flow solver is based on the standard state-of-the-art methods related to structured grids. A compressible form of the Reynolds-averaged Navier-Stokes equations is used. The scheme is cell-centered and based on a multiblock grid topology. The code contains several possibilities for turbulence modeling. In the present cases two-equation k-epsilon- and k-omega -models have been applied. The solution methods of FINFLO are described in more detail in [Siikonen 1995].

At symmetrical flight conditions a half of the aircraft was modeled. The computational grid consists of 3.8 million cells. In asymmetrical cases the whole aircraft was modeled and the resulting grid consists of 7.6 million cells. A surface grid of the aircraft can be seen in Fig. 9.

An example of the unsteady situations simulated using steady-state assumption is a pull-up. The numerical simulation of the pull-up differs only slightly from a simulation in straight horizontal flight, but the effect in the computed flow field is large. In the simulation of the pull-up the aircraft is in an angular pitching motion. As a consequence of the angular velocity, the flow field relative to the aircraft is curved and this changes the pressure distribution and the aerodynamic forces acting on the aircraft's surface. The pull-up condition is modeled by setting the external flow field to rest and putting the grid into circular motion. For this purpose the flow equations are transformed into a rotating reference frame. The computational procedure and some results are described in [Siikonen, Rautaheimo, Salminen 2000]. As an example, a surface pressure distribution and streamlines are given in Fig. 10.

In symmetrical flight conditions the agreement in aerodynamic loads obtained by CFD and test flights was excellent. The same agreement was not obtained in rolling conditions. This was assumed to be due to the difficulties in keeping the aircraft exactly in the desired flight condition during the rolling motion in flight tests.

4.2.3 Fatigue life assessment of fin spar/skin joints

As a part of the HW empennage structural life assessment program of the FAF and PFA, the fin spar/skin joints were analysed by HUT/LLS. The study revealed that it is possible to estimate the fastener load distribution with a simplified FE-model where the fasteners are modeled as beams that are connected to plates with single nodes. An enhanced model of the joint was further constructed using solid elements in plates and in fasteners and a contact was used in all relevant areas. The analyses did not predict the critical location of the joint correctly [Wallin 2001].

Constant and variable amplitude fatigue tests of the fin skin-to-spar structural joints (three-row simple lap joint with Hi-Tique fasteners) were conducted by HUT/LLS [Wallin 2001]. The purpose was to find out whether it is possible to derive the fatigue life of the joint from the fatigue data of smooth and notched specimens. The stress concentration factor of the notched specimen corresponded to the severity factor of the joint specimen. The fatigue test spectrum was generated by PFA [Keinonen 2000] on the basis of the "mini-OLM I - severely biased" flight trial strain responses. The tests revealed that the fatigue behavior of the joint could not be derived from the fatigue data of smooth or notched specimens. Reasonable variable amplitude fatigue life estimates were achieved from constant amplitude fatigue data of the joint specimen.

Round robin style fatigue life prediction activities took place between PFA and VTT [Koski 2000] such that the same test spectrum was employed [Keinonen 2000]. The purpose of the fatigue life predictions was to validate the numerical models and the life estimation algorithms. The fatigue life estimations at VTT were based on the combinations of fatigue crack initiation and fatigue crack growth. An overview of the above is illustrated in Fig. 11.

Additional fatigue tests were performed for specimens representing the Hawk tailplane strap joint [Aakkula, Wallin, Jussila 1997; Aakkula 1998]. Reference data was also established by fatigue testing some generic joints [Aakkula & Wallin 1997/1,2,3].

4.2.4 Fatigue life assessment of the tailplane region

Simplified test specimens simulating the actual butt strap joint of the tailplane were designed and manufactured by PFA, including strength and durability analyses using numerical methods [Keinonen 1997]. Fatigue tests were performed for the specimens by HUT/LLS [Aakkula, Wallin, Jussila 1997; Aakkula 1998]. Reference data was also established by fatigue testing some generic joints [Aakkula & Wallin 1997/1,2,3].

To aid the analysis of the above fatigue test results, the fatigue crack growth characteristics emanating from the edges of fastener holes were emphasized in the analyses. The predicted crack growth rates varied notably, depending on e.g. load spectrum characteristics and on the initial stress state (e.g. degree of the fastener pre-stress) [Keinonen 1999; Koski & Bäckström 2000]. The above investigations are summarized in Fig. 12.

4.3 Center fuselage

After the tailplane and empennage activities, the main interest was focused on the next most important entity, namely the center fuselage. The center fuselage's durability is mainly governed by pressure cycles within the main fuel tank. The first activity at PFA was the design and implementation of the pressure relief valve modification for all FAF Mk.51 Hawk aircraft [Raunio 1998], since even with coarse analytical methods it was evident that the pressure cycle due to the refueling of the aircraft produces significant fatigue life consumption.

Subsequent activities included the center fuselage rework planning and engineering on the basis of known fatigue critical areas. These areas included three bulkhead frames and the main fuel tank's inner sidewall, e.g. [Raunio 1997b; Raunio 1997c]. To support the FAF Hawk center fuselage rework activities of the FAF and PFA, a cooperative concept similar to that described earlier was again conducted.

4.3.1 Strength and durability analyses with and without composite reinforcements

Fatigue life assessments of the original main fuel tank area (i.e. the center fuselage without reinforcements) were carried out. The fatigue life predictions were based on the stress life [Keinonen 1998b, Keinonen 2000d] and crack growth calculations [Koski, Bäckström, Siljander, Wallin; 1999]. VTT's crack growth analyses concentrated on the multi-site-damage (MSD) effects, Fig. 13.

Together with the investigations at PFA using the numerical model of the center fuselage [Keinonen, 1998], various reinforcement techniques within the center fuselage region were studied by PFA and HUT/LLS [Pätynen 1998; Pätynen 1998b; Raunio 1999; Aakkula & Wallin 1999]. The purpose of the reinforcement modification investigations was to reduce operational stresses and to protect the fuel bag from puncture, which could happen if the adjacent structures would experience fatigue damage. A scrapped center fuselage was available for e.g. the mould lining and reinforcement investigations.

Small-scale specimens representing the actual structures were further prepared [Keinonen 2000b; Aakkula & Wallin 1999]. Some of the specimens were instrumented, tested using static loads [Aakkula 2000; Teittinen & Siljander 1998] and fatigue tested [Aakkula 2001; Teittinen & Liukkonen; 2000]. The test specimen geometry and instrumentation is shown in Fig. 14.

A candidate reinforcement structure was manufactured by PFA and HUT/LLS and installed in the scrapped center fuselage which was then pressure tested [Liukkonen, Teittinen, Siljander 1999], Fig. 15. Based on the results, the final reinforcement configuration was fitted to the scrapped center fuselage. A new set of pressure tests was performed to quantify the stresses at critical locations [Liukkonen, Teittinen 2000].

In addition to PFA's strength and durability analyses of the reinforced center fuselage modification, the crack growth analyses will be conducted in near future.

4.3.2 "Mini-OLM II" and "Mini-OLM III" flight measurements

A decision was made to collect center fuselage response data from dedicated test flights. The instrumented test flights were aimed at gaining and providing understanding of the mechanical behavior of the actual structure subjected to the FAF maneuvering, as well as to provide experimental data for the validation of the entre fuselage region's global and local numerical models.

The instrumentation for the center fuselage mini-OLM test flights ("mini-OLM II") consisted of 17 response channels (15 strains, 1 acceleration and the pressure difference between the fuel tank interior and outside) [Teittinen, Siljander, Liukkonen 1998]. An updated version of the TIIKERI+ flight parameter data acquisition unit with its 59 parameter monitoring feature was also utilized. The strain gage locations and bridge configurations were selected aiming at the commonality and comparability to those of the aircraft manufacturer. All data was again stored on a data recorder installed onboard the aircraft.

The mechanical calibration of the response tranducers on ground consisted of a series of gravity refuelings and defuelings, as well as those with full fuel system pressure. Test flights with a constant aircraft configuration at different altitudes and with different fuel amounts were performed, including individual maneuvers, air-to-air combat, and aerobatics.

The identical reinforced center fuselage configuration as described in the previous chapter was then realized in a Hawk aircraft. The structure was instrumented with strain gages, and the flight-induced responses were captured from test flights ("mini-OLM III") to verify the anticipated mechanical behavior and stress-reducing effects due to flight-induced loads. To allow comparisons of the results with the "mini-OLM II" flight test response data, the "mini-OLM III" flight test program was nominally identical to that of the "mini-OLM II" excercise. The analyses of the results are ongoing.

4.4 The OLM program

The "mini-OLM" programs described in previous chapters were aimed at quantifying the durability and flight safety aspects of certain structural assemblies only, such that the responses were captured only from specific maneuvering events. For fleet management purposes, and to verify the conclusions derived from the limited scope flight tests (the mini-OLMs), and also to gain statistically reliable data of the entire Hawk airframe in routine FAF usage covering all maneuvering possibilities in the FAF training syllabi, differences between operating units and piloting techniques, etc., a separate OLM program was initiated.

The OLM system design and delivery responsibility is with the original aircraft manufacturer, BAE Systems. PFA is responsible for the installation of the aircraft parameter transducers and all cabling and the system maintenance. VTT is responsible for the strain gage installation and their maintenance as well as the response data analyses using the ground stations and software provided by BAE Systems.

Two FAF aircraft have been equipped with over 50 strain gages, accelerometers, aircraft parameter transducers and onboard data acquisition units, Fig. 16. The first aircraft (HW-348) was delivered to the FAF in July 2000 and the second one (HW-319) in March 2001.

The two aircraft are being used in reqular FAF service in such a manner that all training syllabi and other usage will eventually be covered. The use of the aircraft is managed such that the mission types which are considered more damaging to the structure are flown early on in the program.

The OLM program will be a "rolling program", i.e. the OLM-equipped aircraft will stay in service and the recorded data will be analyzed until the retirement of the Hawk from the FAF service.

5 F-18C/D Hornet

The FAF has a total of 64 F-18 Hornets in its inventory (7 D's and 57 C's). The D models were assembled in the USA by Boeing, while the C models were assembled in Finland by PFA. The first D models were flown to Finland in November 1995 and the last C-model was delivered to the FAF in August 2000.

The FAF F-18 Hornet has an onboard fatigue tracking system based on 7 strain gages and a number of aircraft parameters. These data are sampled and stored onboard during each flight. The damage analysis is made on ground by strain life method using the SAFE software. The damage rates (FLE; fatigue life expended) for each flight, including all essential flight information, are attached into the FAF flight log database. Examples of the data extracted from the FAF database are shown in Figs. 2 and 4. From the database, fatigue reports can be made per mission code, pilot, squadron, etc. The FAF Hornet fatigue life usage has been more severe than expected, although the damage accumulated per each year is anticipated to be going to the better direction.

5.1 On investigations preceeding the HOLM program

During the past five years, several small investigations have been conducted within the FAF and PFA to e.g. better understand the operation of the onboard fatigue tracking system, its functions, etc. Further, the ground station environment (SAFE), which is used to analyze the onboard data after each flight, has been continuously developed at PFA and the FAF to better suit to the Finnish needs.

Since 1996 Finland has participated in the operation of two international working groups of the F/A-18 users – IFTWG (the F/A-18 International Fatigue Tracking Working Group) and CREDP (the F/A-18 Composite Repair Engineering Development Program). The information exchange within these working groups with the other F/A-18 user countries (the USA, Canada, Australia, Switzerland) is useful and significant for the future of the structural integrity work of the FAF F-18.

The current fatigue tracking system was evaluated by VTT [Siljander, Liukkonen, Teittinen, Hedman 1999]. As a result of the evaluation, it was found out that the current system does not fully match to the needs of the FAF and it does not provide information from the entire structure.

PFA conducted another investigation on the current fatigue tracking system [Orpana 2000]. Features such as temperature compensation, low sampling rate and absence of antialiasing filtering of the current system on the fatigue tracking results were among the goals of the study. The strains from the onboard strain gages were recorded during selected flights using 3 parallel measurement systems onboard: The current system (20 Hz sampling rate), the ALBUS flight recording system (20 Hz) of the FAF and a commercial system (SWIFT) of PFA (1000 Hz and 2000 Hz were used). The results of the project indicated e.g. that the 20 Hz sampling rate of the current onboard system is adequate for 3 of the 7 strain gages, and for the other four gages the sampling rate should be markedly higher.

5.2 The HOLM program

The experience gained in developing applied mechanics tools to cope with aging aircraft structures of the FAF are being tailored to the FAF F-18C/D aircraft. A decision has been made at the FAF to initiate the HOLM (Hornet Operational Loads Measurement) program in support of the FAF fatigue management principles. The work will contain principally similar elements as described previously for the Vinka and Hawk aircraft.

A research Statement of Agreement (SoA) has been signed between the FAF, PFA and VTT on the HOLM program. The HOLM program is divided in three phases: HOLM research, HOLM prototype and HOLM production. The creation of detailed work packages and the activities therein are underway (Fig. 17). General description on the HOLM research phase is provided in the following.

- Structural information, structural software and possibilities to integrate the HOLM (production) system to the aircraft are being evaluated with the aircraft manufacturer.
- The aircraft related non-destructive inspection (NDI) activities underway at VTT form a step in Finland towards developing NDI methods capable of detecting fatigue cracks from the fatigue critical structural details of the FAF F-18, including the IVD coated and peened aluminum components [Jeskanen *et al* 2001]. The work is being done partially together with the DSTO/AMRL (Defence Science and Technology Organisation/Aeronautical and Maritime Research Laboratories, Melbourne, Australia).
- Structural modeling on the basis of the FEM specification [Lähteenmäki 2000] of the main airframe is underway at PFA.
- CFD analyses, using the FINFLO software are being done at HUT.
- Fatigue critical structural parts assessment corresponding to the FAF usage and the structural modification level is underway at the FAF, PFA and VTT.
- Alternative solutions for the onboard system will be assessed by VTT to come up with a data acquisition system capable of e.g. collecting, preprocessing and storing anticipated quantities with adequate sampling characteristics to capture maneuvering and dynamics induced responses. The avionics integration specification will be done at PFA. This forms the first phase (HOLM research).

During the second phase, a prototype will be designed, which will be installed to a limited number of the FAF F-18 aircraft (phase 3). These response data will eventually be used as with the FAF Hawk OLM.

6 Related Activities

This chapter summarizes investigations of general nature that serve one or more of the FAF aircraft types covered in previous chapters and in Table 1.

6.1 On data acquisition and analysis efforts

Due to the sample rates employed in the flight measurements performed by VTT, the amount of stored response data is noteworthy. Therefore, one of the main activity areas at VTT associated with the flight measurements and the data analysis environment therein has been on developing features related to the management (e.g. postprocessing) of the bulk of the stored data. The analysis environment existing at VTT prior to the flight measurements has evolved over decades of man-years, principally on maritime but also on ground applications. The data management requirements of these applications may be similar to those of the aircraft applications, but e.g. the size and weight requirements of the measurement hardware differ by at least by an order of magnitude. Starting from the response data processing of the Vinka flight measurements, the analysis environment has been continuously developed, as the amount of flight data has increased from a flight test to another.

To gain a thorough understanding of the structural behavior in view of fatigue life consumption of e.g. an aircraft, it is vital to have the ability to study pilot control inputs (aircraft parameter data) and the response signals characterizing the structural behavior (strain, acceleration etc.). Based on the experiences obtained while analyzing the "mini-OLM I" data, methods were investigated and developed to integrate all measured quantities into one software. Within the software developed it is possible to e.g. "zoom" into selected maneuvering/dynamic events such that a reliable synchronization between the anticipated quantities exists [Liukkonen, Siljander, Teittinen, Hedman, Koski 1998]. The data from the "mini-OLM I" exercise were used as an input for the investigative efforts.

6.1.1 WEAG RTP 3.20: "AHMOS"

The project AHMOS (**A**dvanced Structural **H**ealth **Mo**nitoring **S**ystems) is a joint European Research and Technology Program (RTP 3.20) under the Western European Armament Group (WEAG). The participants in the on-going program are: EADS (Germany; the single leading industrial entity); BAE Systems, DERA and Smart Fibres (England); Alenia and CIRA (Italy); CASA, INTA and UPM (Spain); CSL (Belgium); DEMEX and Risoe (Denmark), Fokker Services and NLR (the Netherlands); PFA and VTT (Finland).

The objective of the RTP is to define, develop and demonstrate structural health monitoring systems capable of being applied to military platforms (e.g. military aircraft). The systems will include the necessary sensors, signal processing, data storage, analysis and presentation. Techniques for incorporating the sensors into the structure and consideration on how the system will be integrated into the platform will be considered. The complexity of the system may vary – via modular design - depending on the platform and on the materials used. This varies from a system able to detect and locate impacts likely to cause damage, to a system capable of determining the integrity of the structure at any time. The overriding objective, however, will be to demonstrate practical systems which will reduce the cost of ownership by reducing inspection and maintenance costs, and to extend the life of the military platforms in question. An example of an implementation scenario is shown in Fig. 18.

6.2 Development of fatigue analysis tools

A simple software for Palgren-Miner analyses of aircraft structures was developed by HUT/LLS in 1999 [Wallin & Karttunen 1999]. The work included the integration of VTT's Rainflow counting algorithm into the software. A tool for fitting test data or SN-curves from literature to a numerical format was also developed. The software includes database consisting of SN-curves for most typical materials and mechanical joints found in the literature [Wallin 1999/1]. Typical joints in current fleet of FAF were also identified during the project [Wallin 1999/2].

A literature survey on deterministic life prediction methods was performed in co-operation between VTT and HUT/LLS [Wallin & Koski 1999]. The deterministic models included those published on stress-life (infinite life), strain-life (initiation life) and fracture mechanics (residual life) and their combination methods together with each model's assumptions, limitations and advantages. The main activity was focused on fracture mechanics applications. The most common aircraft joint types, as well as the evaluation methods of the load and stress distributions in the vicinity of the joints were covered by the survey. The work was funded by the Scientific Committee of National Defence (MATINE).

As a follow-up of the literature survey, the applicability of the deterministic fatigue life prediction methods and software was evaluated with two case studies. The work was performed in co-operation between VTT and HUT/LLS [Koski, Bäckström, Siljander, Wallin; 1999]. The first case study was chosen from the open literature fulfilling the criteria:

- any laboratory fatigue test specimen such that its e.g. material, material thickness, hole geometry and loading were similar to those of a "typical FAF structural detail";
- the study should deal with multi-site-damage (MSD) effects;
- availability of experimental test results (e.g. artificially produced pre-crack locations and dimensions, as well as crack growth rates).

With the above criteria, the first case study was chosen (Fig. 19) [Horst *et al* 1997]. The second case study was chosen to be the rivet line of the main fuel tank within the center fuselage of the FAF HW aircraft, Fig. 13**.**

Another literature survey on probabilistic life prediction methods was performed in co-operation between VTT and HUT/LLS [Wallin & Koski; 2001]. The work was a logical continuation of the literature review on the deterministic methods. The survey was focused on methods applicable for fatigue crack growth analyses. It covered the random variable method based on the damage tolerance philosophy and deterministic crack growth models, as well as the method based on the concept of economic life. The effect of NDI intervals on probability was also surveyed and examples of the allowable risk on different application were searched. Finally, software available for the analyses were evaluated and an analysis example of probabilistic crack growth was made with the random variable method. The MATINE again funded the survey. One of the future goals is to apply probabilistic life prediction methods to on-going and new aircraft projects.

While working on fracture mechanics applications focusing on durability assessments of aircraft structural details, a need to improve certain areas of the analyses has emerged at VTT. The following describes some of the topics that will be investigated in the future:

- The stress intensity factor solutions for cases with a complex geometry and loading and the MSD;

- The utilization of global FE model results in local BE/FE models;
- The interface aspects between local and global models;
- Generation of crack models within the local models;

The above topics will be screened and eventually applied to the analyses of suitable case studies. Further future areas of interest include the probability based methods applied to the above scenarios. The progress and results of these activities could be reported e.g. in the national reviews subsequent to the ICAF 2001.

6.3 Cold working of holes in Al-plates

The effect of cold working of holes was studied by HUT/LLS in 1997 [Karttunen 1997]. A literature survey was accomplished to get theoretical background. Additionally, some experimental, analytical and numerical methods were reviewed to estimate residual stresses due to cold working. Finally, some models for predicting fatigue life and crack growth in cold worked materials were studied.

Fatigue tests were conducted to investigate the efficiency of cold working in two aluminum alloys (2024-T3 and 2014-T6). Three types of specimens were investigated: open hole, crack arrest hole and a riveted joint. The thickness of the specimens varied from 0.6 to 2.3 mm. The test program included 14 test series each containing 4-8 specimens. The specimens were tested using constant amplitude sine wave loading (R = 0.1, f = 10-15 Hz). Depending on the test specimen the maximum stresses varied from 25 MPa to 175 MPa.

Cold working increased the fatigue life of the open-hole specimens by factor of four. The life improvement factor of the crack arrest hole specimens was 3.8-14.2 depending on the material thickness. With riveted joint specimens the life improvement factor was 3.3.

6.4 Repair of fatigue cracks with composites

HUT/LLS, the FAF and PFA have investigated composite repair since 1989. As a part of the work, the effect of composite reinforcements on the crack growth rate of center-cracked 1.6 mm thick 2024-T3 aluminum plates was studied [Aakkula & Saarela 1995]. The reinforcements investigated were wet laminated carbon/epoxy, carbon/epoxy-prepreg and boron/epoxy-prepreg. An alumina grit blasting followed by the silane treatment was used as a surface preparation method prior to the bonding with the vacuum bag technique. Residual thermal stresses were tailored by constraining the thermal expansion of the aluminum plate during the curing of the adhesive, by lowering the curing temperature, and/or by raising the testing temperature.

The repaired plates were fatigue tested at room temperature or at 70°C. The single-sided repairs were supported against secondary bending with edge supports or with a sandwich construction. The variable amplitude loading with the maximum tensile stress of 140 MPa was extracted from the FALSTAFF-spectrum.

The fatigue life of 120 000 cycles was measured for the edge-supported cracked plate without a reinforcement. This increased to 500 000 cycles with a 1.2 mm thick carbon/epoxy-prepreg reinforcement, when the thermal expansion of the Al-plate was constrained. The corresponding cycles were 600 000 and 980 000 for the 0.8 mm thick boron/epoxy reinforcement and for the 2.2 mm thick wet laminated carbon/epoxy reinforcement, respectively. An increase in residual thermal stresses significantly decreased the fatigue life of the specimen. Drilling of the crack arrest hole before the repair improved the fatigue life, as well as the use of the sandwich test specimen instead of the edge supported specimen.

A pilot application of the composite repair within the FAF was a wet laminated carbon/epoxy-repair of fatigue cracks in the upper wing surface panel of the MiG-21 BIS. Several panels were repaired since 1990 without further crack growth or bond failure. Another application example is a wet laminated repair of a fatigue crack developed in the front edge of the engine cowling of the Vinka. Fatigue cracks developed in the edges of the chemically milled pockets in Hawk's integrally stiffened upper wing skins have also been repaired by stop-drilling the cracks, by cold working the stop-drilling holes and by bonding carbon/epoxy-prepreg patches over the cracks [Aakkula 1996].

6.5 Fatigue of composite plates with an impact damage

The behavior of the impact damage in composite laminates in fatigue and static loading was investigated experimentally and theoretically by HUT/LLS in 1994-97. The purpose was to find out the main factors affecting the delamination and impact damage growth in simultaneous compression (or tension) and shear loading. A test fixture was designed to apply the loading to a plate specimen [Wallin 1994].

The materials used in the tests were glass fiber/epoxy and standard modulus carbon fiber/epoxy. Circular and elliptical single delaminations were simulated with Teflon inserts. Different orientations of the elliptical delamination in respect to the loading direction were studied. The impact damages were produced with different impact energies using a drop weight impactor. The specimens were tested with different compression to shear ratios [Wallin 1997/2].

Delaminations and impact damages of the glass fiber/epoxy specimens did not grow in the tests with load levels that are typical in the design of the GFRP structures. Tests of CFRP specimen pointed out that the load for onset of the impact damage growth is significantly lower than the load for the onset of the delamination. The impact damage can grow with relatively low loads that are common in practical structures. The shear loading significantly reduces the strain level needed for the crack growth. The crack growth rate in tests was generally slow and it is possible that crack growth slows down and stops. However, it is also possible that a sudden failure occurs because of an overload only about 30% higher than the load used in fatigue tests.

7 Summary

The transition within the Finnish Air Force from older jet aircraft to newer ones with e.g. notable maneuvering capabilities forced the FAF to initiate systematic efforts to ensure the aspects related to the flight safety and economy of the most important aircraft types of the FAF. These efforts, which are aimed at improving the national capability to cope with the many structural fatigue effects are reviewed. The fatigue management functions described herein have formed a solid co-operative base and this know-how will be further developed to meet the structural challenges ahead.

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9 Tables

***Table 1**. The current aircraft inventory of the Finnish Air Force. The aircraft types considered in this national review are highlighted in grey.*

Aircraft	FAF type ID (on tailnumbers)	Role	Number in use
F-18C/D Hornet	**HN**	**Fighter**	**64**
Mk.51 Hawk	**HW**	**Jet trainer**	**52**
Learjet 35A/S	LJ	Target towing, reconnaissance, surveying, transport	3
Fokker F.27	FF	Transport	3
Valmet L-90 TP Redigo	RG	Liaison aircraft	9
Piper Chieftain	PC	Liaison aircraft	6
Valmet Vinka	**VN**	**Primary trainer**	**28**
Piper Arrow	PA	Liaison aircraft	7

10 Figures

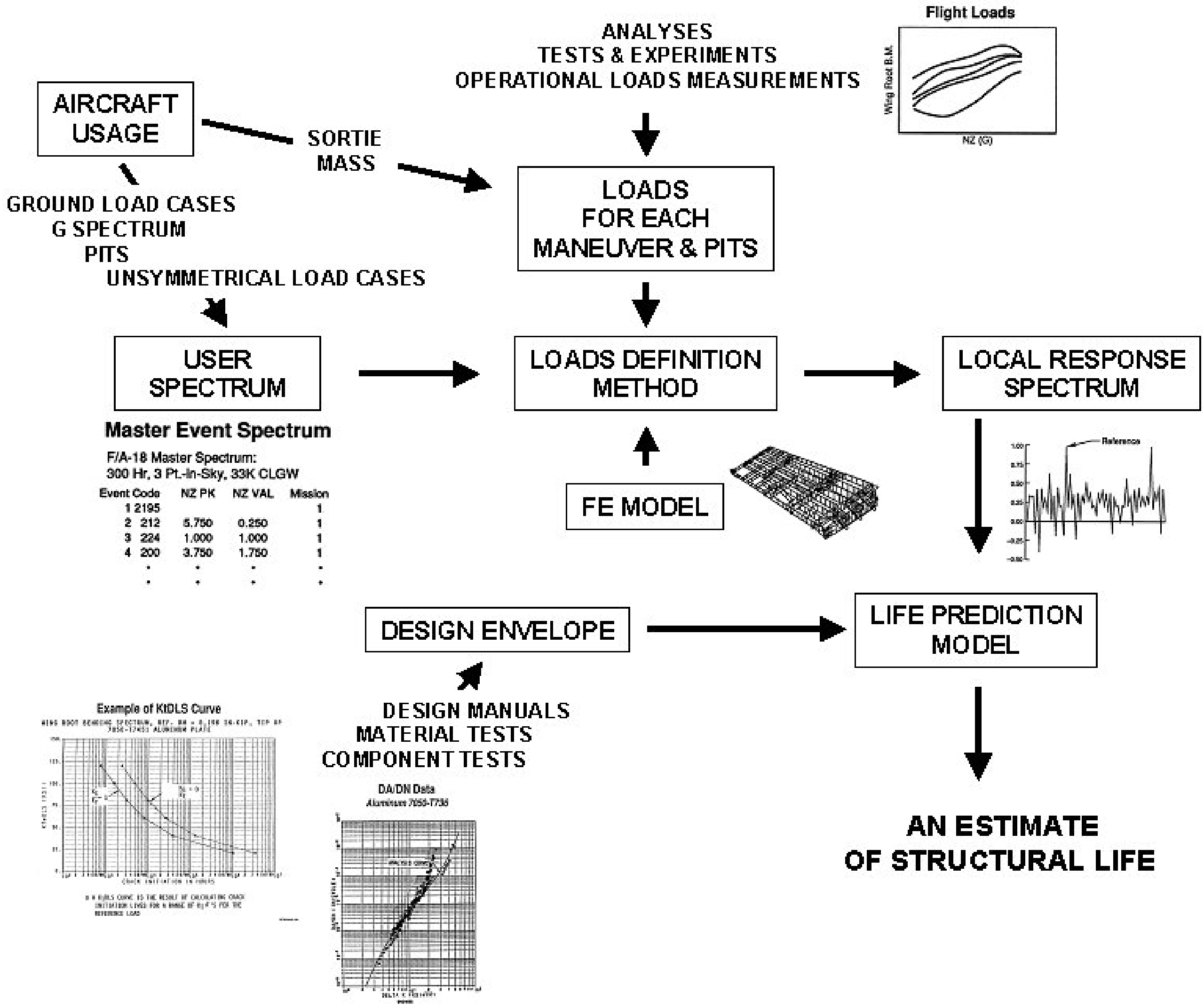

Figure 1. *Schematic of the lifing activities as used by the FAF. Courtesy of the FAF HQ.*

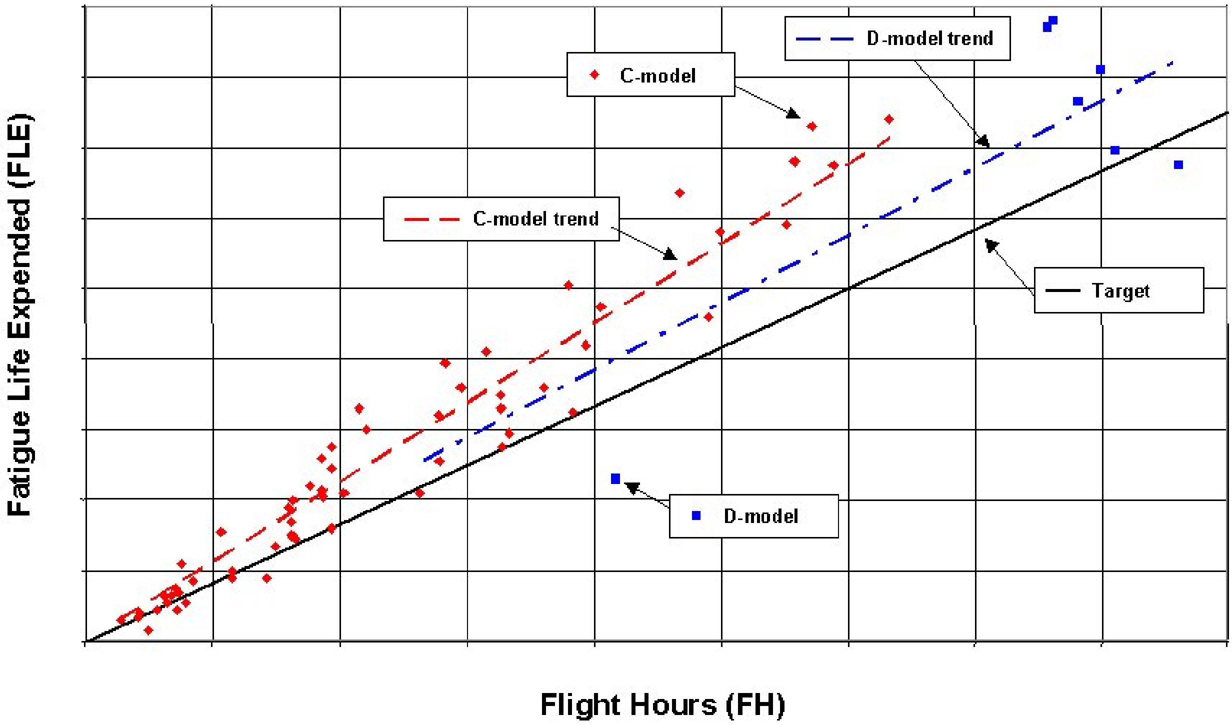

Figure 2. *Summary of the wing root fatigue life expended (FLE) of the FAF F-18 fleet as ranked according to the data obtained from the current onboard strain recording system. Courtesy of the FAF.*

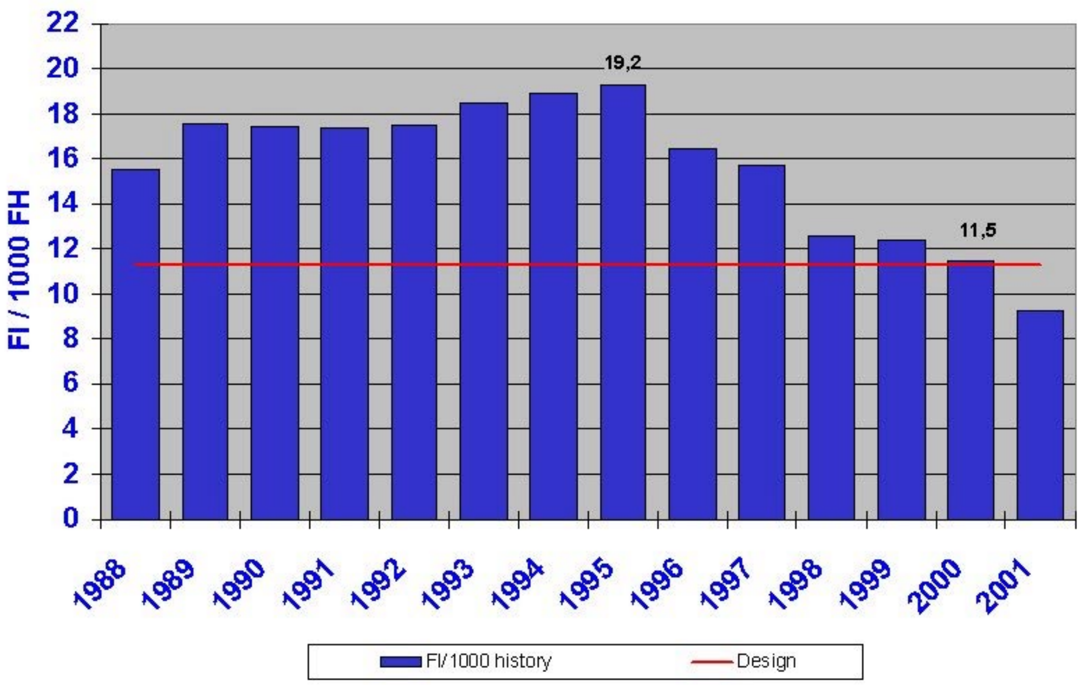

Figure 3. *FAF Hawk Fatigue Index (FI) development: Summary of the benefits gained by conferring with the aircrew on the fatigue management principles of the FAF. The figure depicts reductions in the fatigue consumption (fleet average). Courtesy of the FAF.*

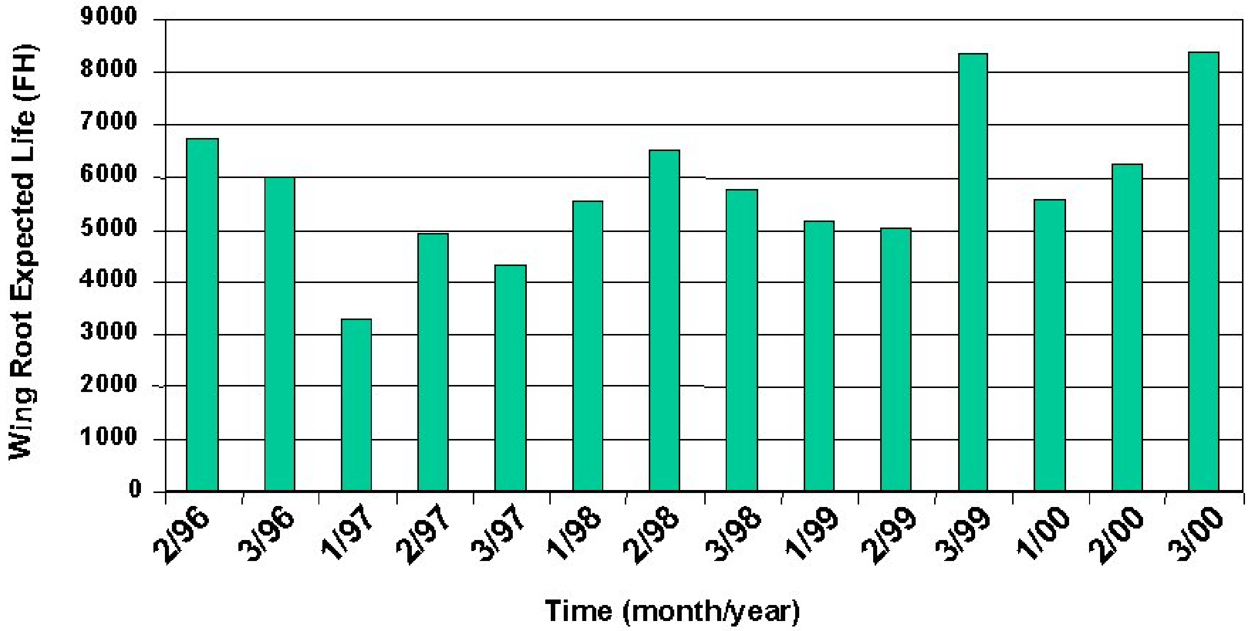

Figure 4. *The average wing root expected life development of the FAF F-18 aircraft as described by the left wing root strain results (each column represents a 4-month prediction average including all flights and the entire F-18 inventory of the FAF). Courtesy of the FAF.*

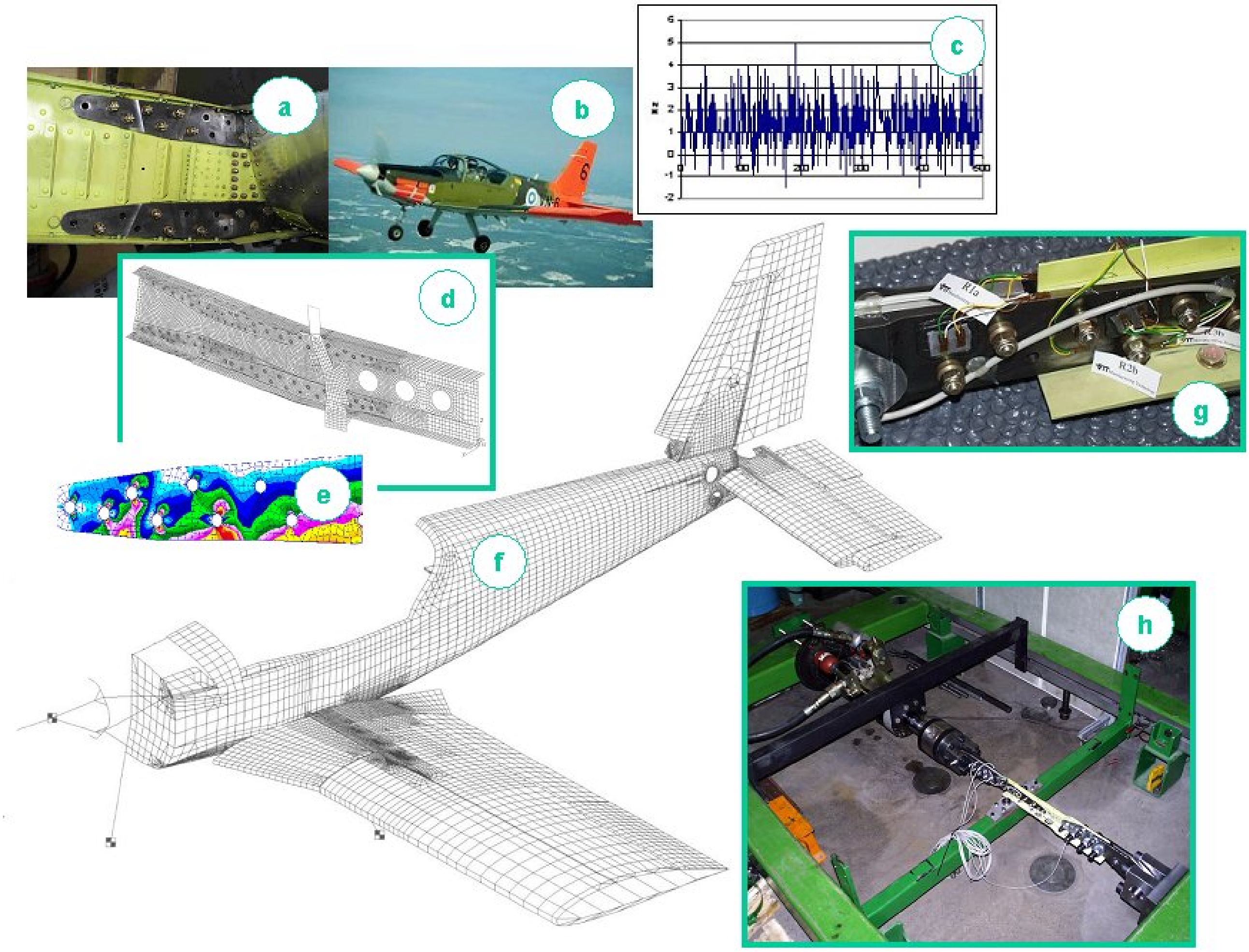

Figure 5. *An overview of the Valmet Vinka Life Extension Program: The wing-to-fuselage double-lap knife joint (a) was among the areas of interest, from which response data were collected by VTT on test flights (b). The load spectrum was generated by PFA and the FAF (c), which PFA employed in the strength and durability assessments using their numerical models of the wing-to-fuselage joint (d, e) and of the primary structure (f). The spectrum fatigue test specimen (g), designed and manufactured by PFA, was subjected to experimental proof tests (h) on the strong floor of VTT Building and Transport.*

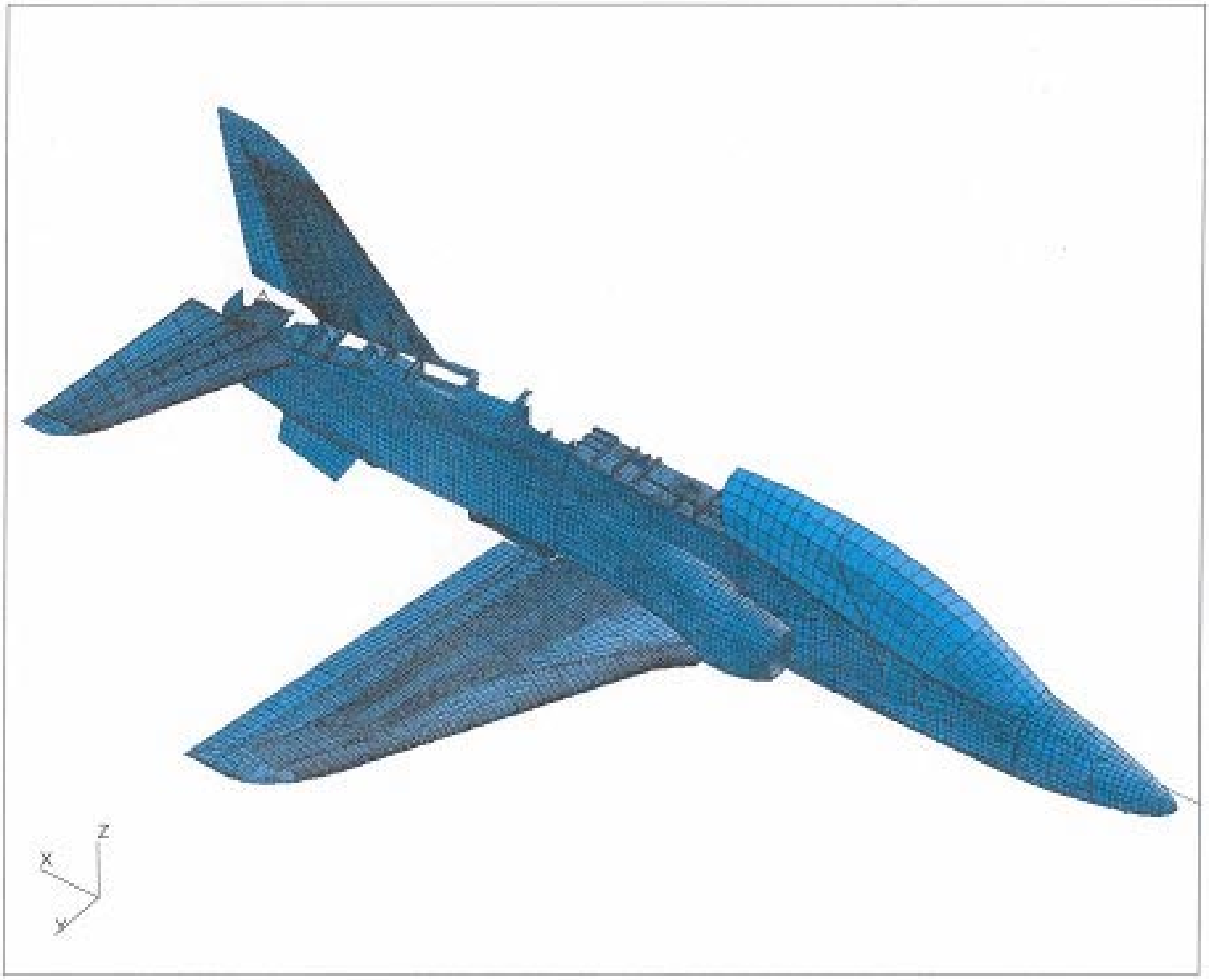

Figure 6. *The FE model of the FAF Hawk. Courtesy of PFA.*

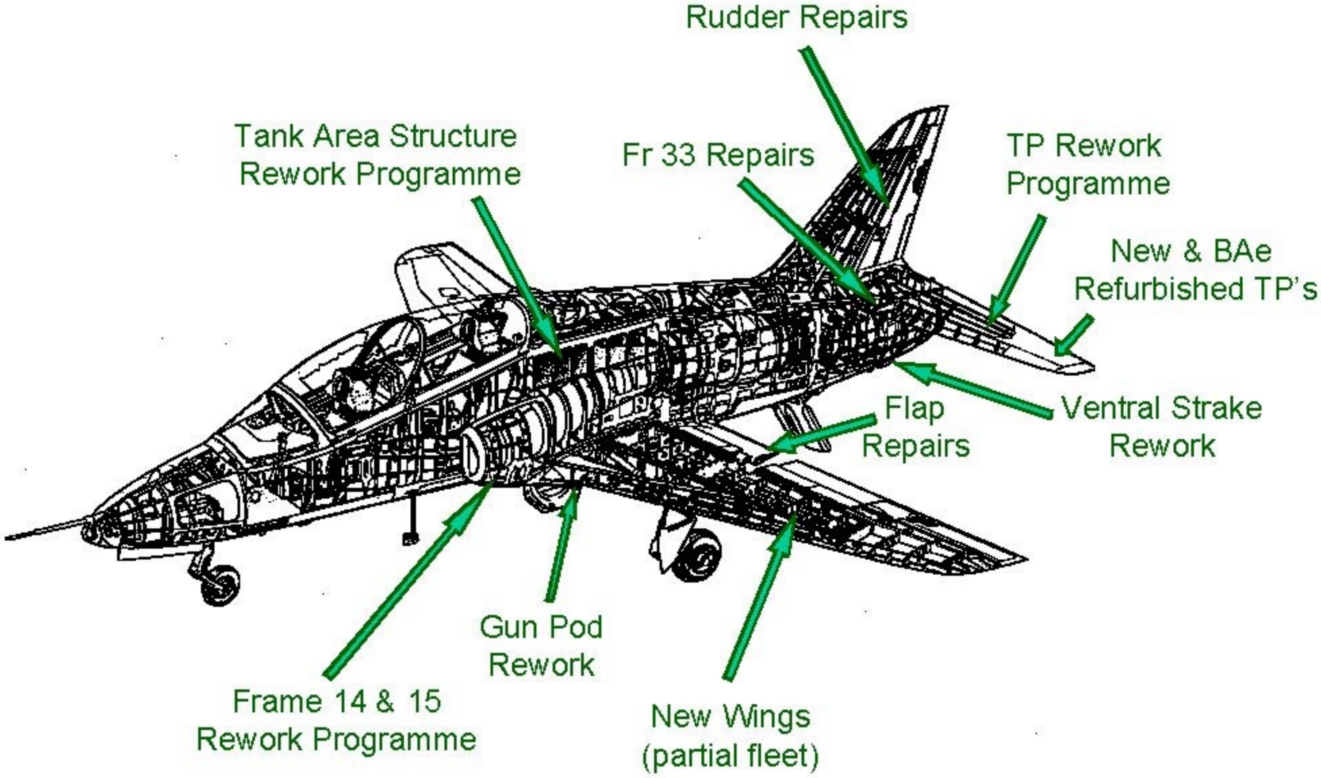

Figure 7. *Examples of the rework and reworkt activities as realized at the FAF and PFA. Courtesy of the FAF.*

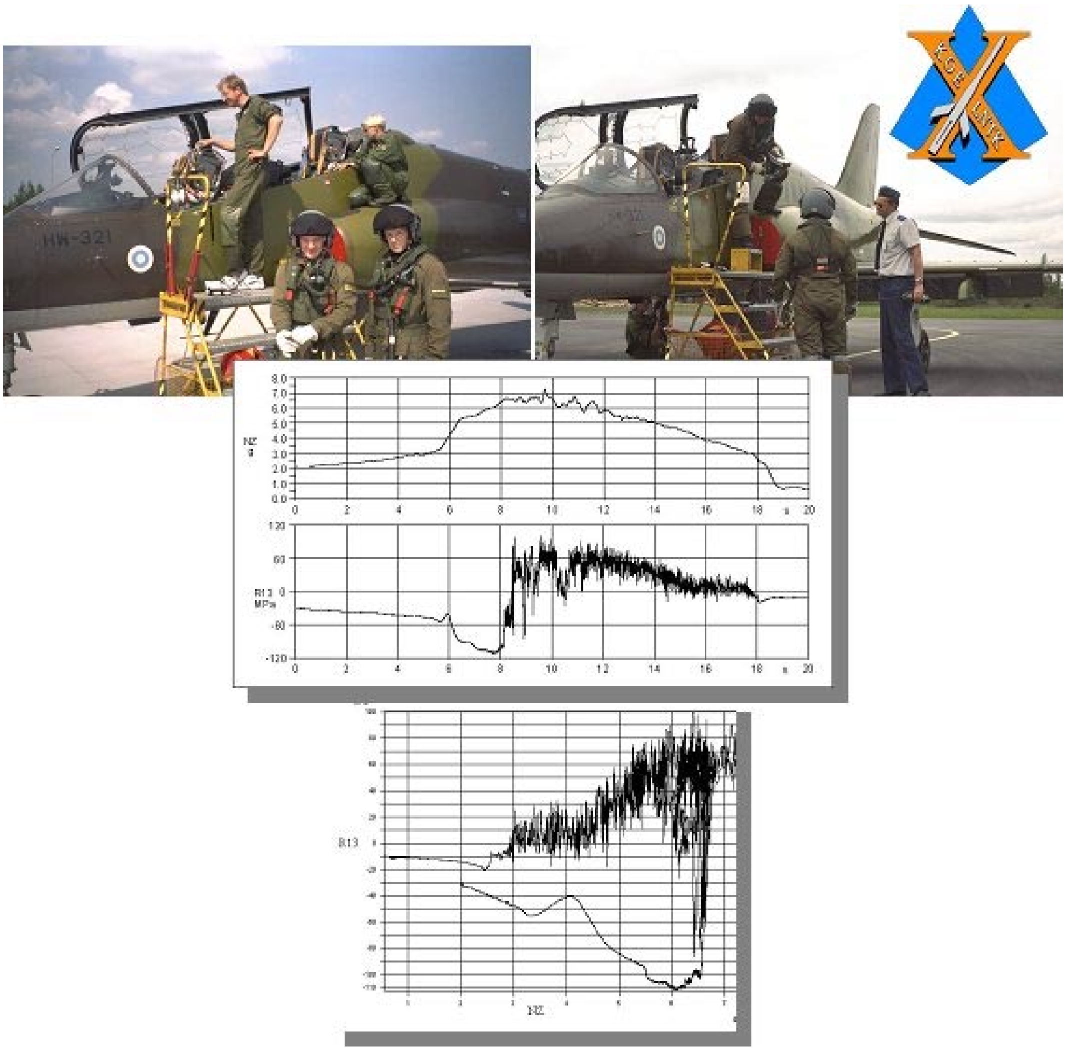

Figure 8. *An example of flight measurement response data: Time histories of a flight parameter and a strain and an XY presentation. With adequate sampling parameters the dynamic effects can be captured. The accurate synchronization of the aircraft parameter and strain data allows the "zooming" into the more interesting dynamic events.*

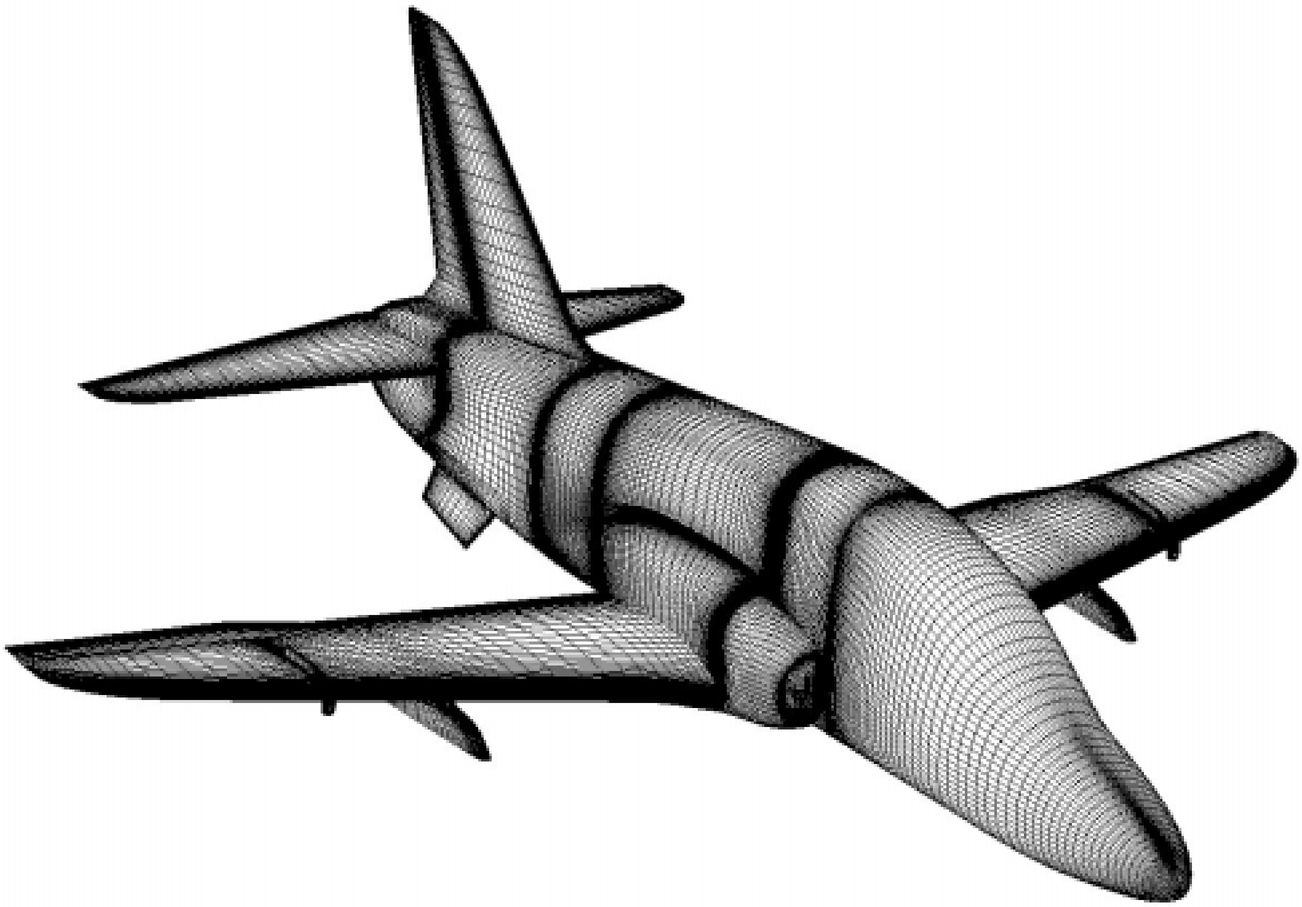

Figure 9. *The surface grid of a BAe Hawk Mk.51. The aileron deflection is 11.3° representing a rolling condition. Courtesy of HUT/LAT.*

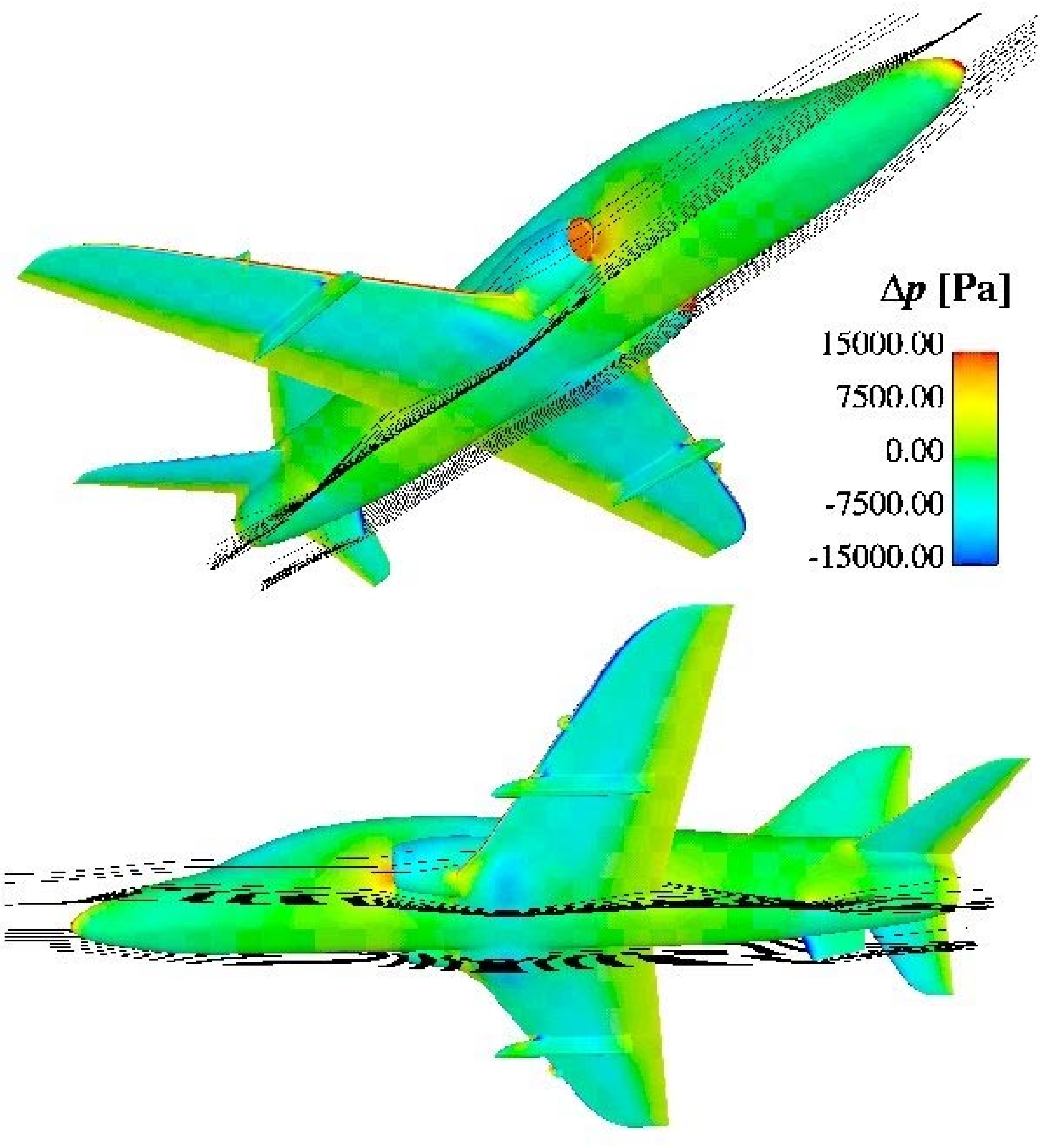

Figure 10. *The surface pressure distribution and streamlines hitting the ventral fins at a 50°/s roll. The Mach number is 0.646 at 2500 m altitude. Courtesy of HUT/LAT.*

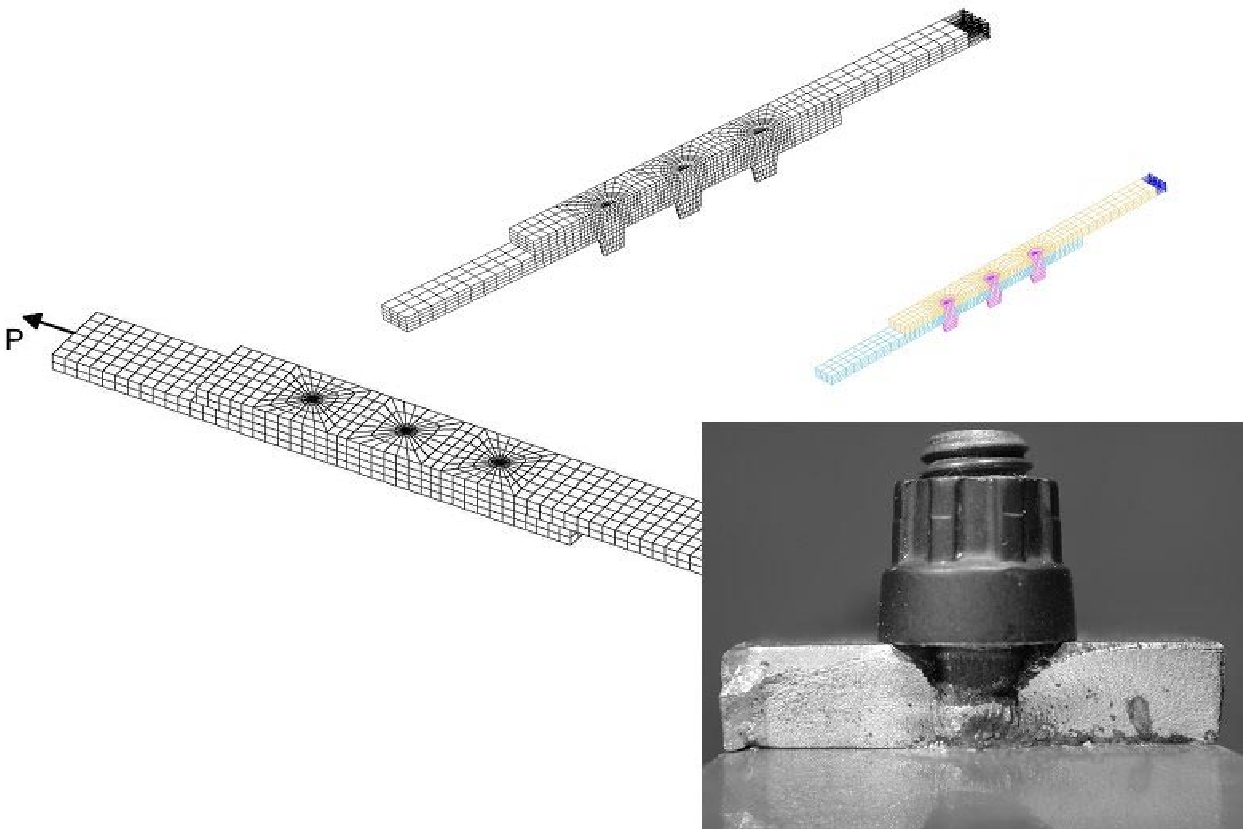

Figure 11. *A schematic of the prestressed fastener joint (Hi-Tique) representing the fin skin-to-spar joint used in the round robin analyses: The model by HUT/LLS (upper two with fasteners) and the model by VTT (lower left). Fracture surface of a fatigue test specimen by HUT/LLS (lower right).*

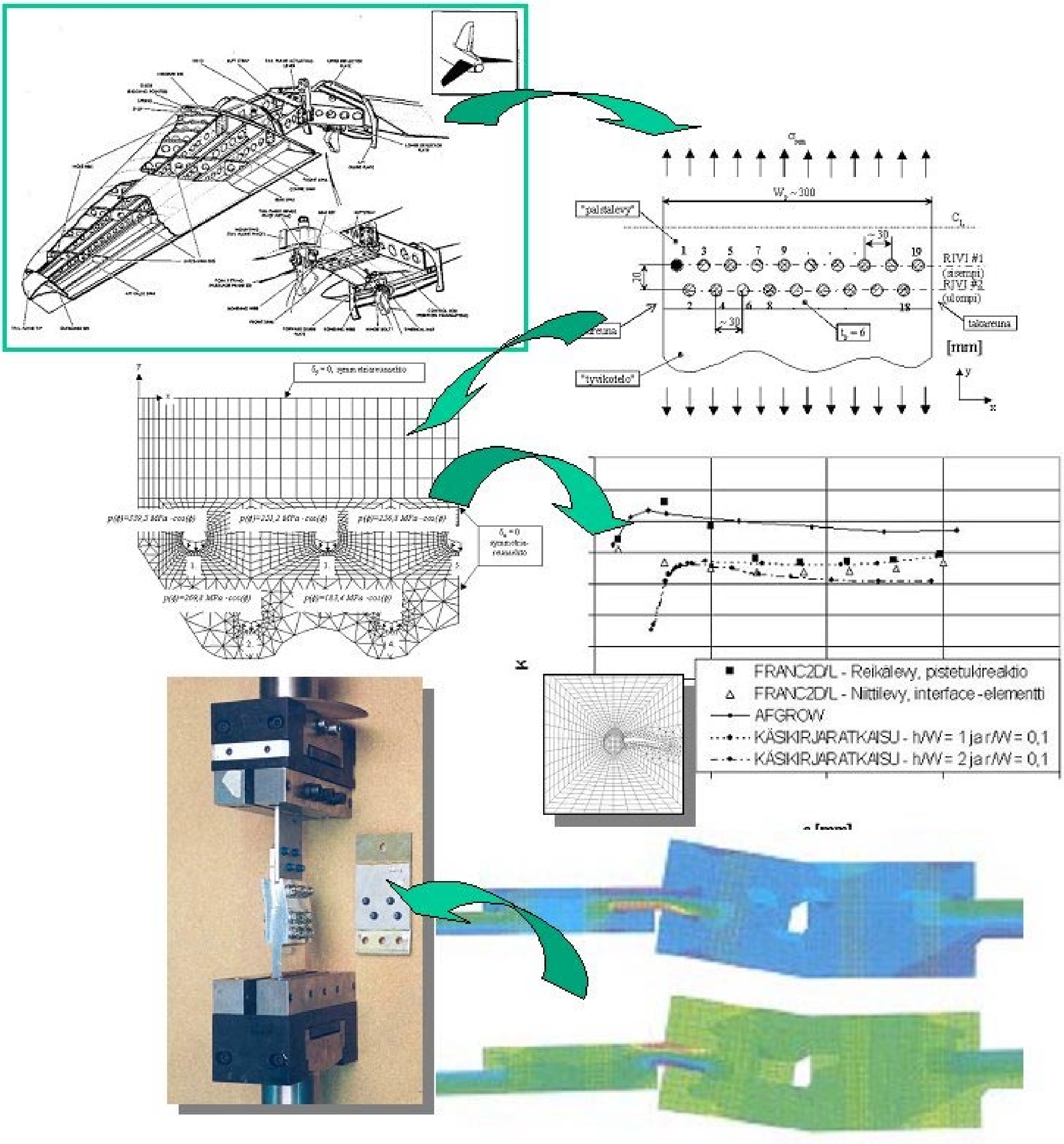

Figure 12. *A schematic of the Hawk tailplane (upper left) and its detail (upper right) for VTT's fracture mechanics analyses: An element model of the detail (center left), estimated stress intensity factor (K) values as the function of the distance from the hole edge using various solutions, e.g. [Harter 2000; FRANC2D/L] (lower right). The simplified fatigue test specimen of the tailplane butt strap tested by HUT/LLS (bottom left), which was analyzed by PFA (bottom right).*

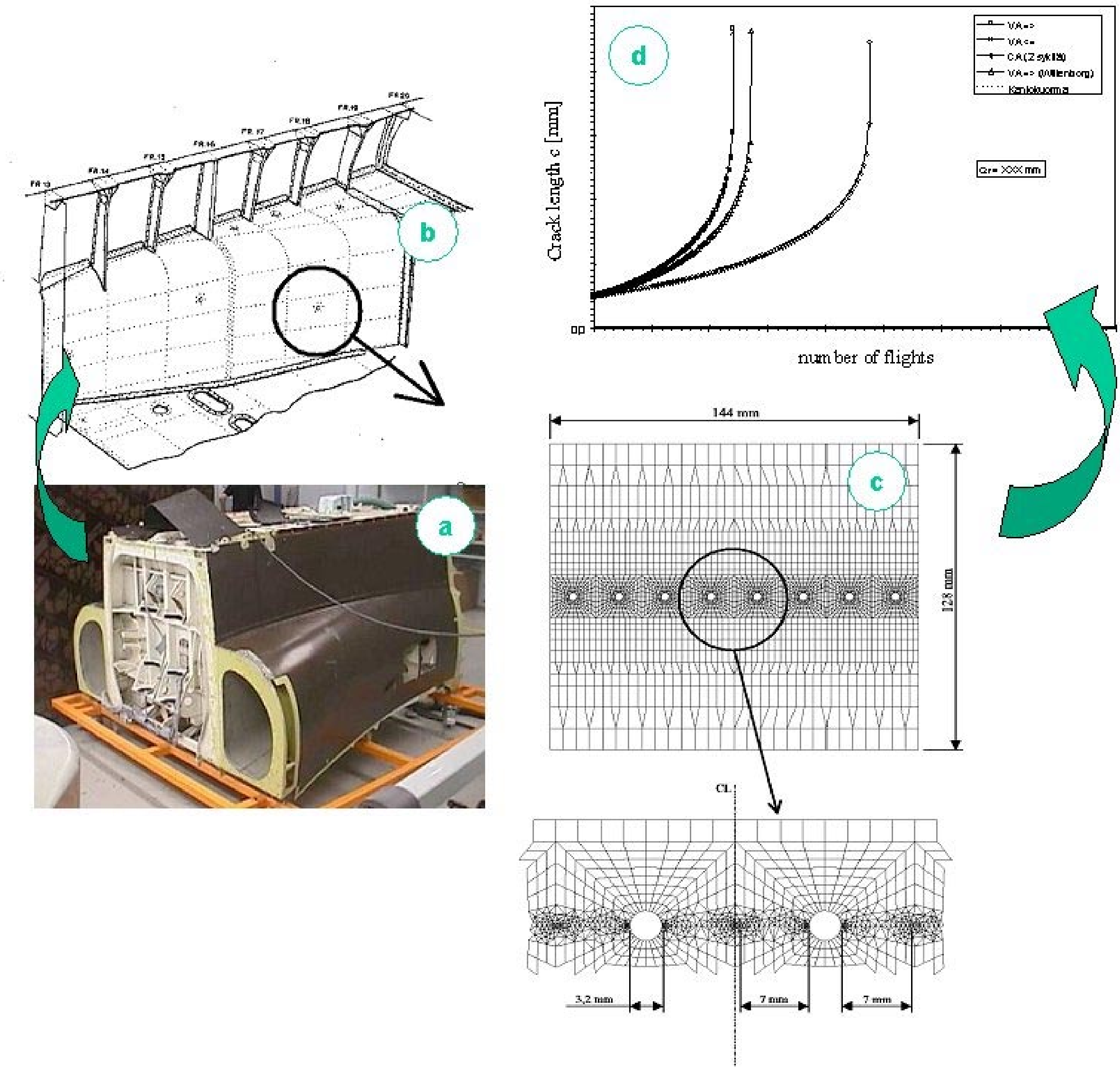

Figure 13. *A scrapped center fuselage of the FAF Hawk aircraft (a) which was employed as the full scale test article subjected to static pressurization tests, and a schematic of its inside (b). The same test article was employed in original structure evaluation (i.e. no composite reinforcement) as well as with the composite reinforcement. An FE model of the center fuselage region for the MSD crack growth simulations and analyses (c) and examples of predicted crack growth rates (d).*

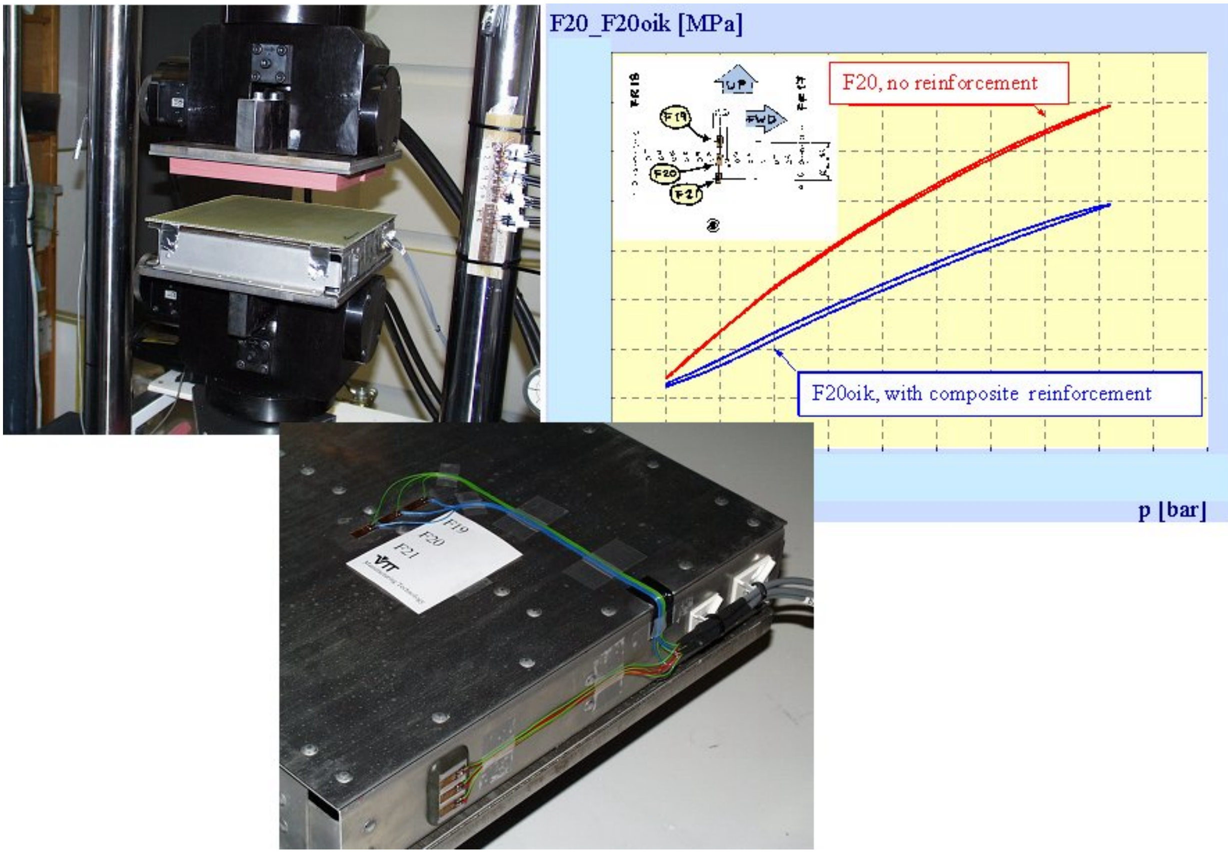

Figure 14. *The simplified, small-scale specimen (design by PFA & HUT/LLS, manufactured by PFA) representing the center fuselage detail of the FAF Hawk (lower left and right: instrumented by VTT prior to protection). The specimen was employed to study candidate composite reinforcement techniques: Test set-up at HUT/LLS (upper left) and example of VTT's results (upper right).*

Figure 15. *Pressurization test set-up of the scrapped center fuselage of the FAF Hawk. The same test article was employed in the pressure tests of the original structure and the reinforced structure. The flight tests ("mini-OLM III") followed the pressure tests.*

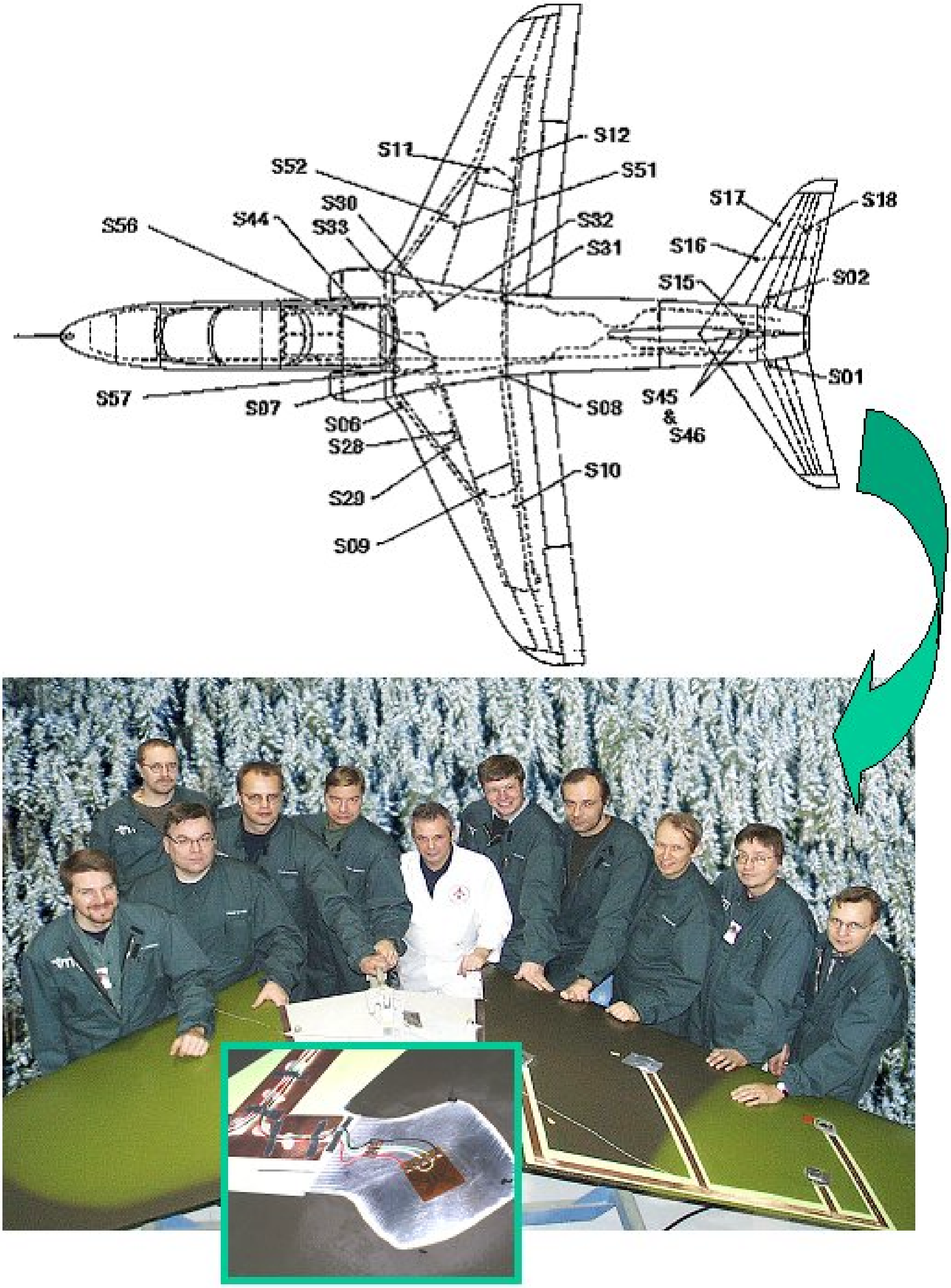

Figure 16. *A schematic of the OLM Program of the FAF Hawk jet trainer (only a part of the strain gage channels shown). The system is designed by BAES in England and installed by PFA and VTT in Finland.*

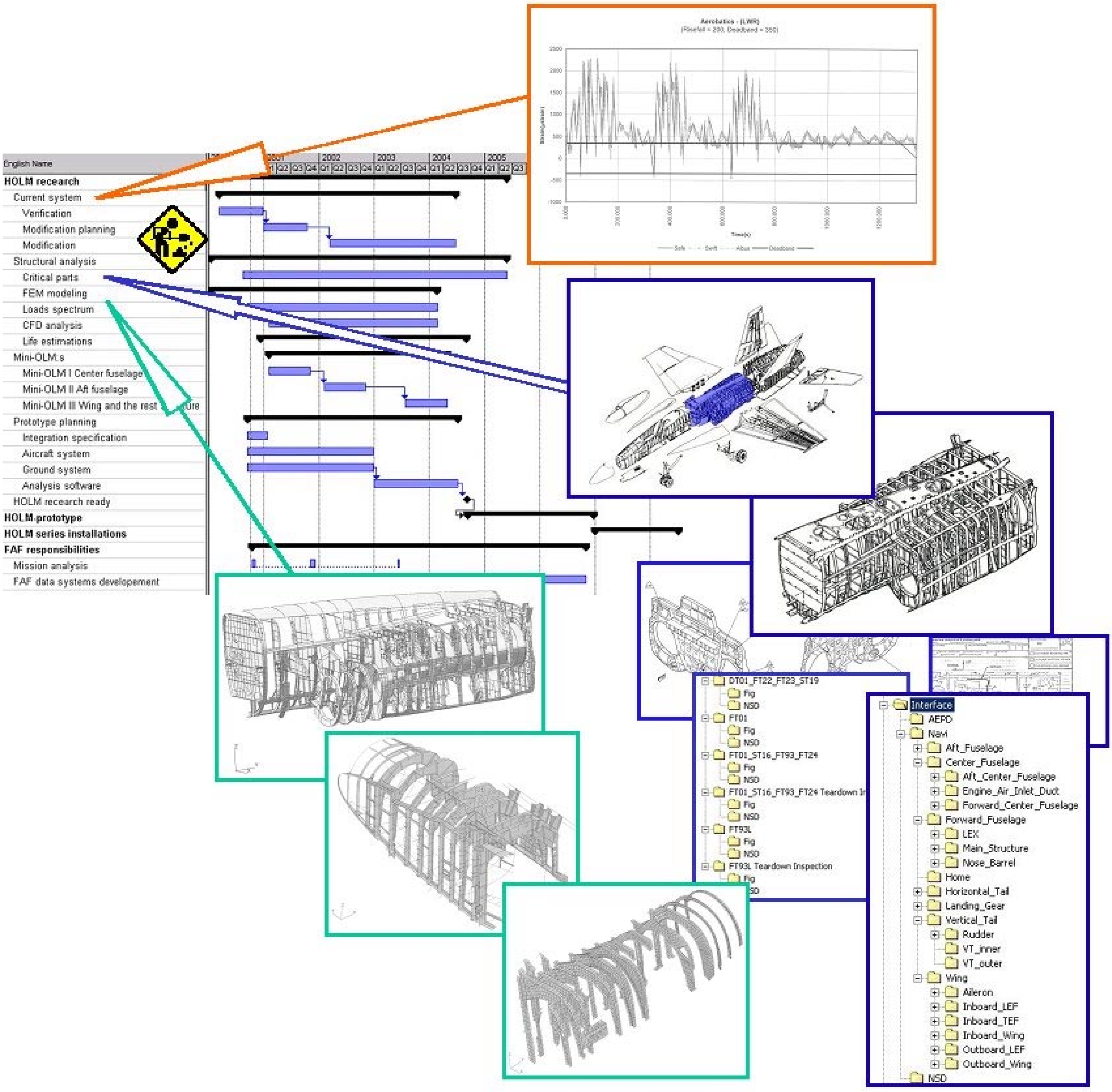

Figure 17. *A schematic of the HOLM Program.*

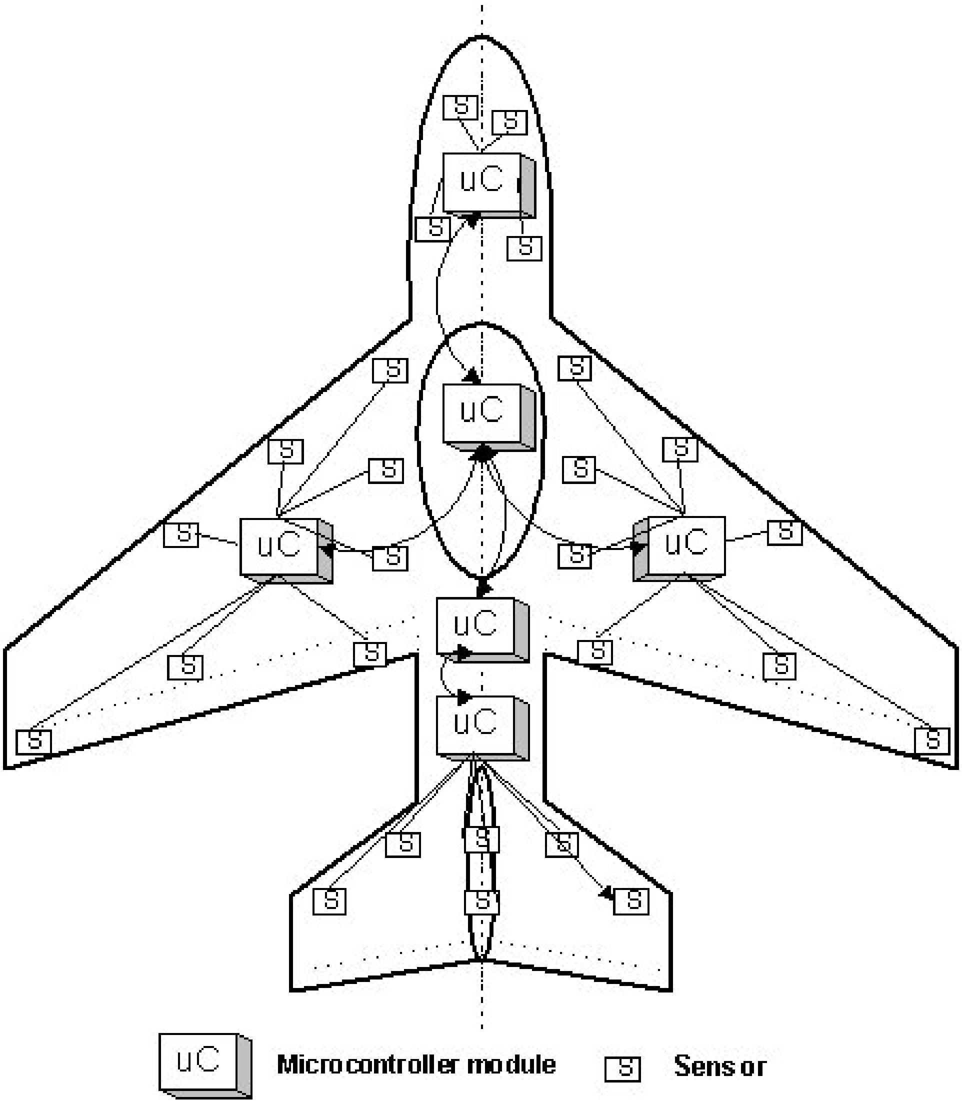

Figure 18. *A schematic of a modular and distributed (e.g. signal sampling and analysis locally) structural health monitoring system concept under consideration within the WEAG RTP 3.20 AHMOS program. Signal sampling and analysis may be realized locally within each module. The data transfer between the modules may be realized with application specific field buses. Different types of modules (each with different function and technology) can be connected to the same network.*

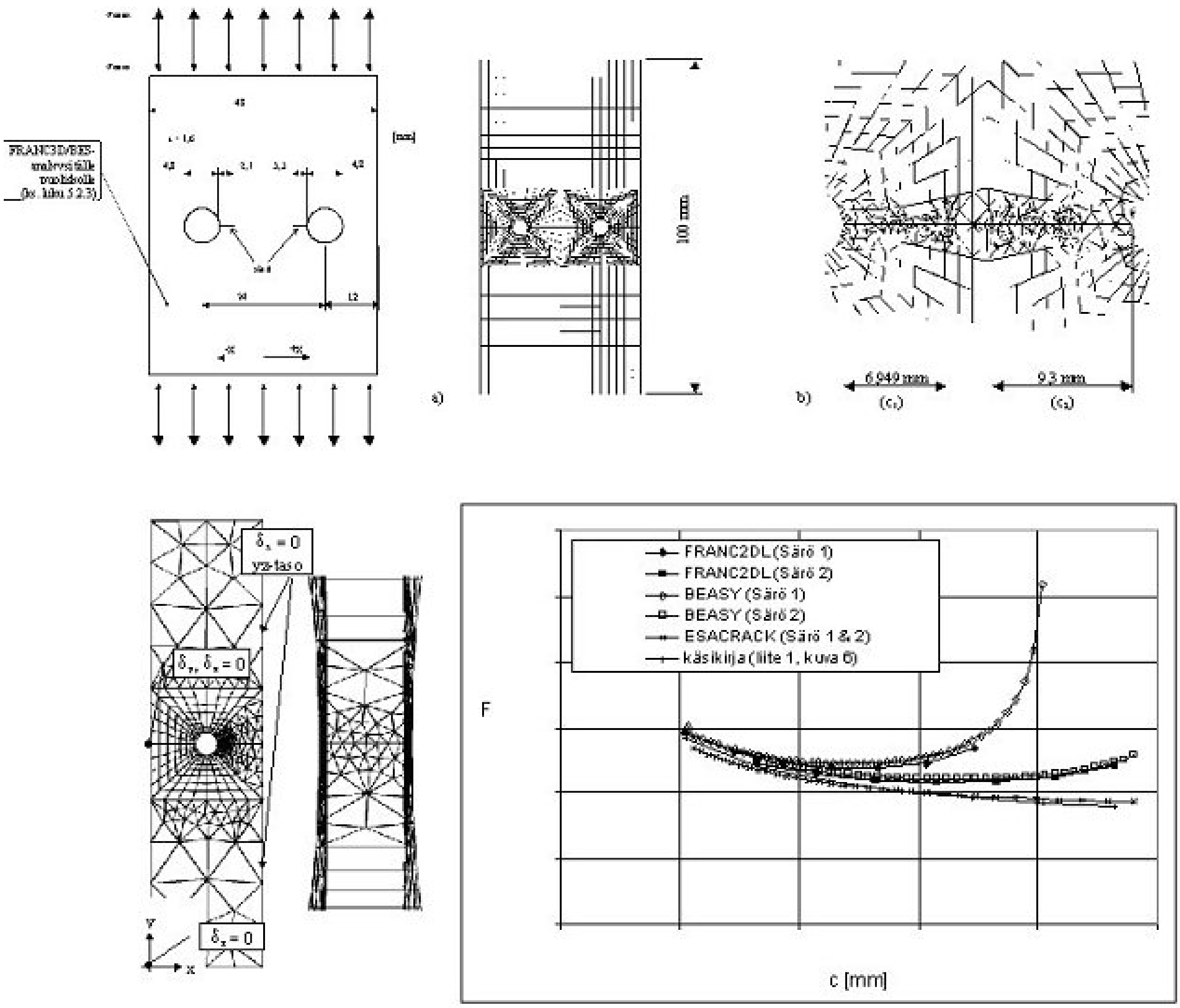

Figure 19. *A schematic of the first case study from literature (upper left), a finite element model of a crack-free configuration (upper right), a boundary element model of a cracked configuration (lower left), e.g. [FRANC3D, 1998] and an example of comparison results: The crack shape factor F as evaluated with various methods [FRANC2D/L 1998; BEASY; ESACRACK] (lower right).*