FATIGUE LIFE EVALUATION OF CRITICAL LOCATIONS IN AIRCRAFT STRUCTURES USING VIRTUAL FATIGUE TEST

Jarkko Tikka
Patria

Keywords: *fatigue life, finite element method, operational loads measurement*

Abstract

The fatigue life of critical structural locations in the wing of the Finnish Air Force (FAF) Hawk jet trainer was estimated. This was done by using calibration coefficients determined by means of a virtual fatigue test.

The load distribution and load history of the manufacturer's Full Scale Fatigue Test (FSFT) was first reproduced by using an FE-model. The peak through histories of the stresses in the critical structural locations were determined. The calculated histories were then used as an input in the virtual fatigue test calculations.

A fatigue life calibration coefficient based on the ratio of virtual fatigue test estimates versus FSFT results was calculated. It was determined separately to each selected critical location. On the basis of flight measurement data, aerodynamic loads calculation and FE-models were calibrated and the stress histories of critical items in average usage by the FAF were determined.

By correcting the results of the fatigue life analyses using the calibration coefficients produced by the virtual fatigue test, more accurate fatigue life estimates in FAF usage could be made. The calibration of results against in reality detected structural damages improves the accuracy of analytical methods allowing the correction of differences between the actual structure and the idealized FE-model. Since new fatigue tests are not required, it is possible to make reasonable fatigue life estimates at lower costs compared with traditional methods that require fatigue tests.

1. Introduction

Most operational aircraft have been tested for fatigue by means of a full scale fatigue test. The load arrangement of the test specimen is a simplification of the reality and the load spectrum in the test is based on assumptions of the aircraft type's future use. Due to lack of adequate knowledge of loadings in the design phase, surprises can be expected during the actual use of aircraft – the fatigue life of a structure may prove to be considerably shorter than expected. Besides, in the course of the fatigue test or after it the aircraft can be subjected to a number of modifications, which may change stress concentrations in the structure or even the mission-specific mass of the entire aircraft.

Conducting a full scale fatigue test is a very expensive process. This is why it is normally made once only and the fatigue life of the aircraft in each operator's use is assessed, where appropriate, using fairly simple calculation methods. These have traditionally been, for example, flight hours, the number of landings or a computational quantity based on g-level exceedances. As concerns later aircraft types, the monitoring of elapsed aircraft life is typically based on strain gauge or flight parameter analysis. Because large scatter is typical in fatigue life predictions, a rather conservative approach has to be taken to determine the aircraft type's safe-life criteria. If more accurate prediction of the actual service life of an aircraft in the use of each operator was possible, the aircraft operational life could be extended closer to it's real limits. Furthermore, more precise results of analyses decrease the risk of structural failure. The method, presented herein, which is based on the virtual fatigue test, is an attempt to achieve higher accuracy in comparison with conventional analytical life predictions.

2. Hawk Mk 51 aircraft wing fatigue life determination

This presentation describes a research project carried out for the Finnish Air Force to determine the fatigue life for the wing structure of the Hawk jet trainer. Calculations are done for the FAF average usage spectrum. Because the project was about estimating the fatigue life of a 'safe-life' structure in operational use, and not the actual structural certification, it was reasonable to conduct the fatigue life evaluation by numerical analyses without resorting to expensive fatigue tests. The accuracy of the analyses has been improved by utilizing the existing knowledge of structural damages.

The research was initiated partly because of the difference discovered between the actual load spectrum and the manufacturer's fatigue test spectrum, as shown in Figure 1. The actual mass of operational aircraft differs from the 4400 kg used in the fatigue testing. In the majority of the most consuming flights as regards the wing life, the aircraft mass is slightly above 4700 kilos. Besides, already during the manufacturer's fatigue test a lot of cracking was discovered in the wing main structure. On these grounds new fatigue life analyses were well justified. [1,2]

The fatigue life analysis focuses on potentially critical areas, which, when damaged, may risk flight safety and result in the wing retirement or costly repairs. The fatigue life has been determined against the FAF average usage, because the circulation of aircraft in different tasks compensates for pilot and mission related differences in the aircraft usage. For each particular aircraft cumulative g-level targets have also been set to control the fleet life consumption and especially the retirement schedule. In addition to the fatigue life, estimates have been made of crack growth rates and, where appropriate, the critical crack lengths.

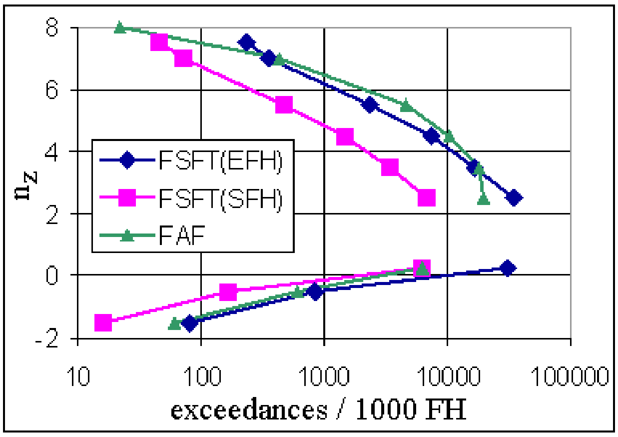

Figure 1 Vertical loading spectra of the operator and the fatigue test. 'FSFT(EFH)' is the spectrum tested in the fatigue test. 'FSFT(SFH)' is the same spectrum with the design scatter factor of 5. 'FAF' is the actual spectrum of the Finnish Air Force.

3. Fatigue life calculation

The fatigue life calculation is implemented analytically without new fatigue tests. Information on structural behavior accumulated in the course of FSFT has been utilized whenever possible. The most central parameter for the fatigue life of the wing is the Fatigue Index (FI). It is a non-dimensional quantity used when defining the wing operational life according to the 'safe life' principle. The cumulative FI value is calculated after each flight on the basis of g-counter exceedance levels.

3.1 Full scale fatigue test results

The most important source data used in the presentation are the results of the manufacturer's full scale fatigue test.

The results led to the selection of six structural locations critical to the wing life. For each item, the crack observation moment and data on its exact location and size were recorded during the FSFT. In operational use, cracking has been found in one of these critical locations only.

3.2 Other source data

3.2.1 Contents of the training program

The Finnish Air Force has defined the principal contents of the Hawk training program. It contains a categorization into different types of missions and describes, among others, the average duration of flight depending on the mission type, the number of missions per 1000 flight hours and the mission-specific FI consumption per 1000 flight hours. On the basis of the description, it was possible to generate the FAF average usage spectrum measured by means of strain gauges in the course of a small number of flights.

3.2.2 Flight measurement data

The Finnish Air Force has instrumented some aircraft with strain gauges. During so called Mini-OLM flights strain gauges were installed in certain areas only, such as the tailplane or the centre fuselage. The instrumentation of two so-called "full-OLM" aircraft is more extensive and they are in normal flying service at the squadrons. Figure 2 shows the strain gauges installed in an OLM aircraft. This study utilizes the flight measurement data received from OLM aircraft during a small number of flights which represented typical flying. Also data from one Mini-OLM installation was used. The Mini-OLM installation consisted of three axially measuring strain gauges [3], fixed on the most critical locations on the wing. The strain gauges installed in the OLM aircraft were of full bridge type [4].

Both aircraft instrumented with strain gauges performed certain calibration flight manoeuvres, which typically included constant-g turns. On the basis of these manoeuvres it was possible, with certain limitations, to compare the results received from the above mentioned types of instrumentation.

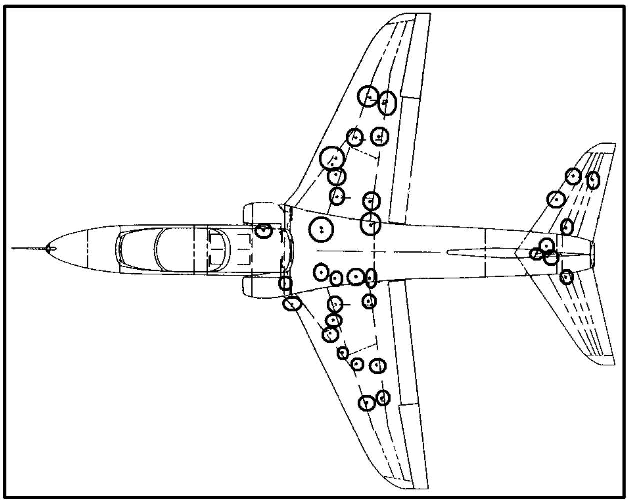

Figure 2 OLM strain gauges shown circulated

3.2.3 Aerodynamic model

An aerodynamic model of the Hawk aircraft for the FINFLO Navier – Stokes flow solver has been developed by the Helsinki University of Technology. Figure 3 shows the grid of the model on the aircraft surface. The grid of the half model is comprised of 3.7 million cells. With this model both symmetrical and unsymmetrical stationary flight conditions were calculated [5].

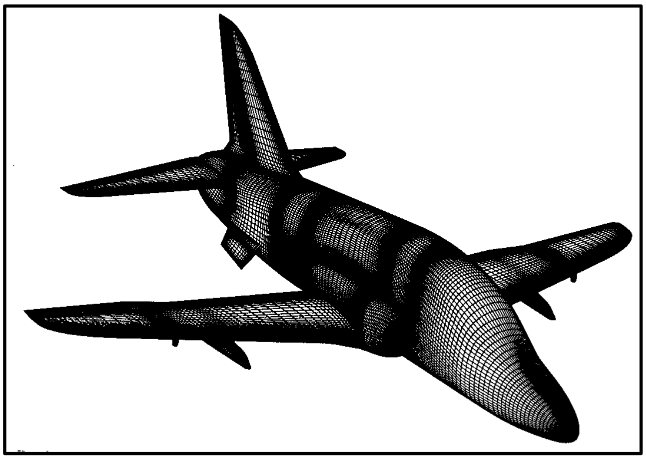

Figure 3 The grid of the aerodynamic model on aircraft surface [5]

Thanks to this advanced aerodynamic calculation method a realistic load distribution could be produced. Furthermore, it was possible to examine how realistic the manufacturer's fatigue test loading was. It was found out to be fairly representative especially at higher g-levels. Figure 4 shows the wing shear force distribution at 7.5 g normal acceleration under FSFT and FINFLO loads.

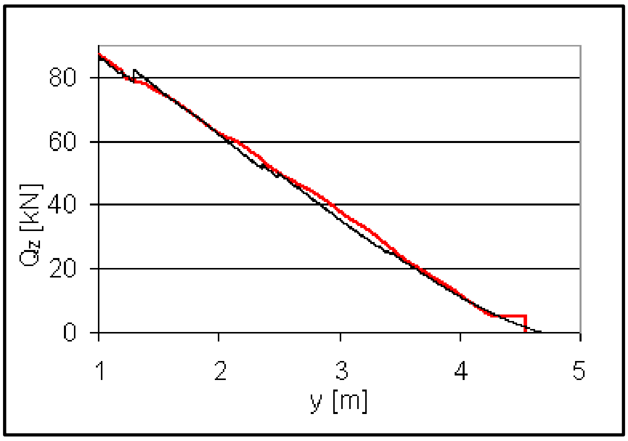

Figure 4 Wing shear force at 7.5 g normal acceleration. The black line indicates FINFLO and the red line FSFT [2] loads.

3.2.4 Finite element models

A global FE-model (Finite Element model) of the complete aircraft has been constructed (Figure 5). The global model is comprised of approx. 55.000 elements. The accuracy of the model does not yet suffice for actual fatigue life estimates, but it can be used to determine realistic translational boundary condition for more accurate sub models. A sub model facilitates the determination of transfer functions from the nearest applicable strain gauge to the critical structural detail. The global model can be used to assess the stress levels of structural locations defined as critical by fatigue tests and make assumptions on whether severe stresses exist in that area in reality as well.

The sub-models have been used in an attempt to describe the stress concentration in the critical item with adequate accuracy as to the fatigue life analysis. One of the sub models used is shown in Figure 6. Sub models are calibrated to correspond with strains measured during Mini-OLM calibration manoeuvres. The Mini-OLM strain gauges have been used because they measure only one strain component as opposed to OLM instrumentation with full bridge strain gauges. In that case, the transverse strain component does not complicate the interpretation of the results. The difference between sub-model strains and flight test results was in this study between –13 percent and +5 percent.

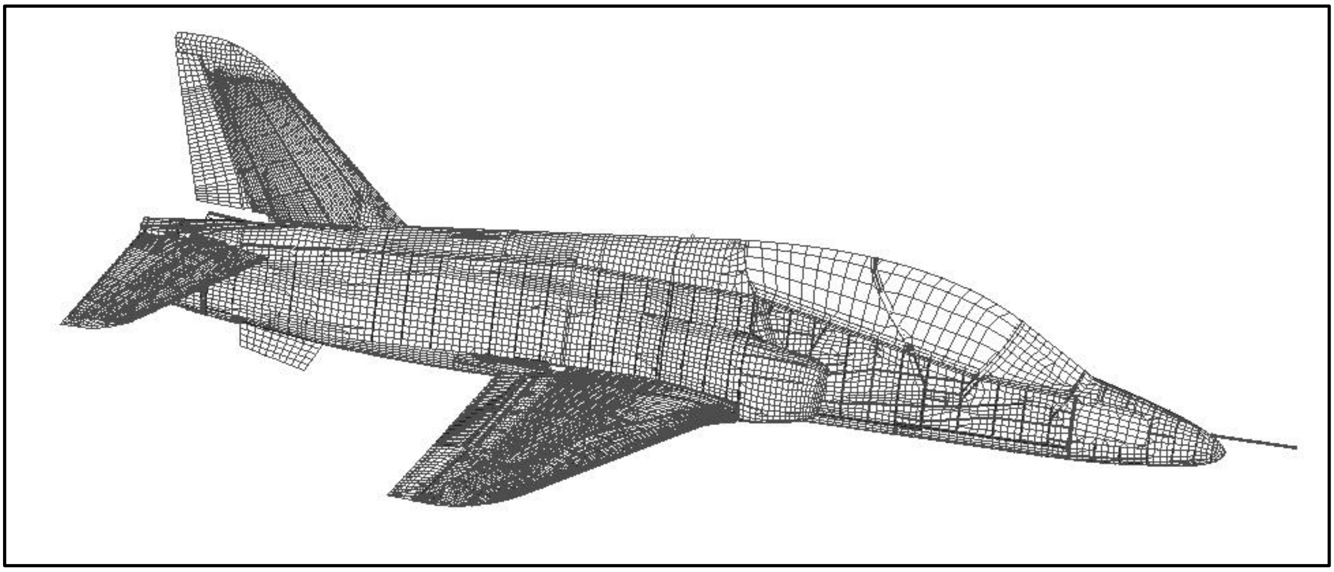

Figure 5 The global FE-model for the Hawk Mk 51

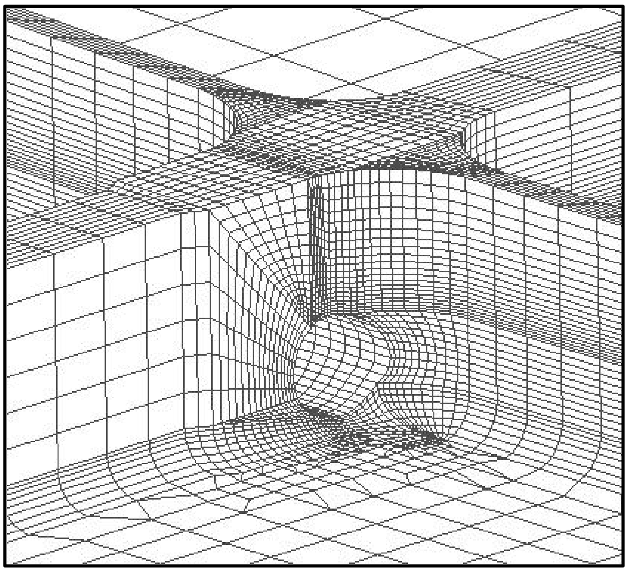

Figure 6 An example of a sub-model
(hole diameter 8 mm).

3.3 Virtual fatigue test

The load history of the original full scale fatigue test at the wing critical locations was reconstructed as the so-called virtual fatigue test. The FSFT load history comprised a block of 25 equivalent flight hours (EFH), which was repeated. The block consisted of 27 flights, representing 19 different missions. Each flight involved individual flight manoeuvres or gust loads, each of them starting and ending at level flight. The flights were started from “ground” and ended as well. The time history of a particular flight by manoeuvres is shown in Figure 7. The flight manoeuvre loads were applied to the aircraft by hydraulic cylinders and fuel tank pressure.

The FSFT loading arrangement was reconstructed on the finite element model. To achieve an enough realistic boundary condition the fixed points were located at the fuselage. The whiffletrees of the original test between hydraulic jacks and pads attached to the wing were statically determined. Since the hydraulic jacks were force-controlled, the FE model loading could be implemented with point forces. Figure 8 shows a part of the original loading arrangement and Figure 9 of its reconstruction on the FE model.

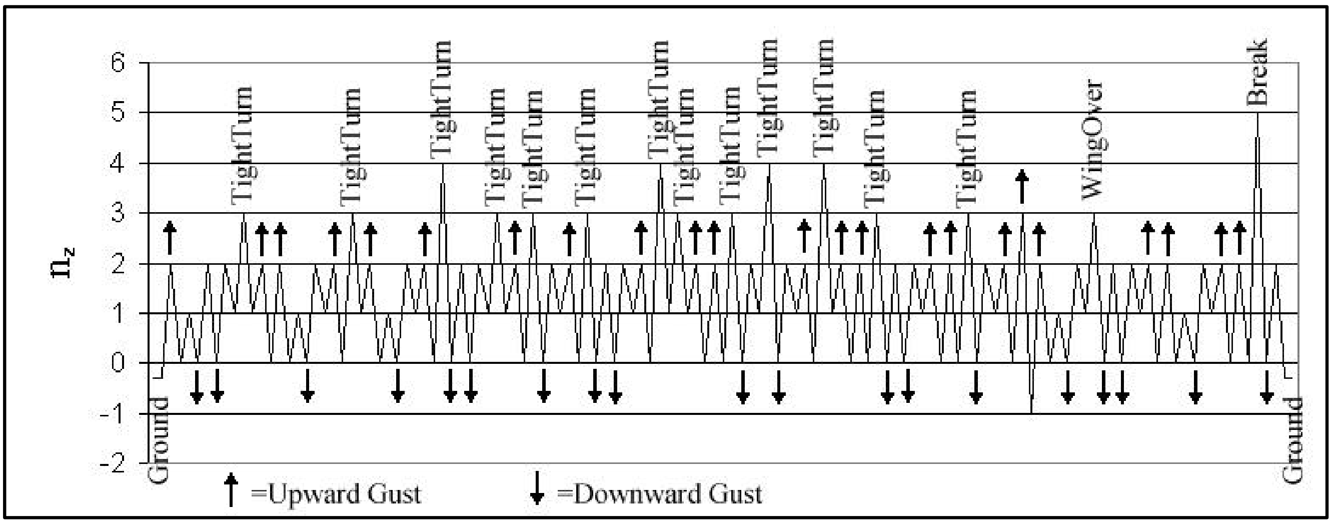

Figure 7 Loading history by flight manoeuvres during one flight [2]

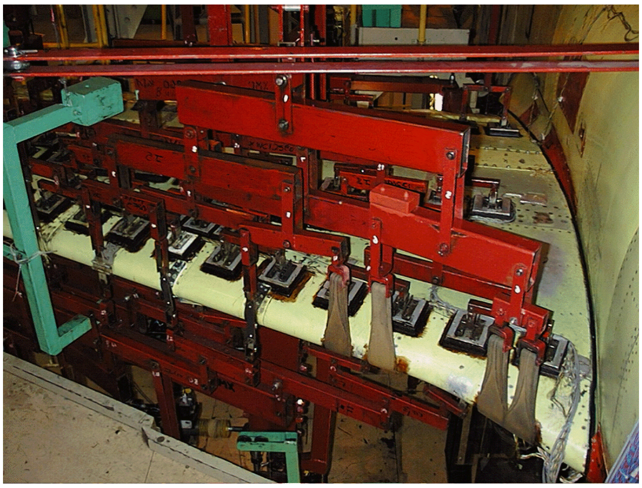

Figure 8 Loading arrangement of FSFT. ® Bae Systems

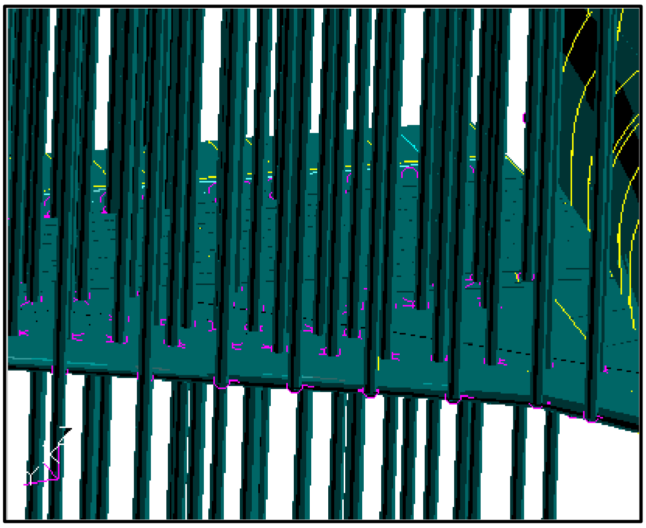

Figure 9 FSFT arrangements reconstructed on an FE-model

The wing structure behaves linearly at loads below design limit loads thus enabling the use of the superposition principle and linear static solutions. When reconstructing the FSFT load spectrum, a unit load was separately applied to each hydraulic jack position, and by using sub-models the stress state generated by the load was determined at the critical locations. The loads applied by the hydraulic jacks during each flight manoeuvre were established and by superimposing the results of the unit load application the stress state by flight manoeuvre was calculated for the critical items.

By locating the stress states generated by flight manoeuvres into a 25-flight-hour block, the peak through history of each critical item could be simulated in the fatigue test. Figure 10 shows the peak through history of one critical item in the 25 EFH block.

On the basis of the generated peak through histories, a calculated fatigue life was determined for each critical structural item during the virtual fatigue test. In each location, the calculated fatigue life was determined by the total life (S-N) and crack initiation (ε-N) methods. The calculations were based, where appropriate, on various material data. Crack growth rates were also estimated.

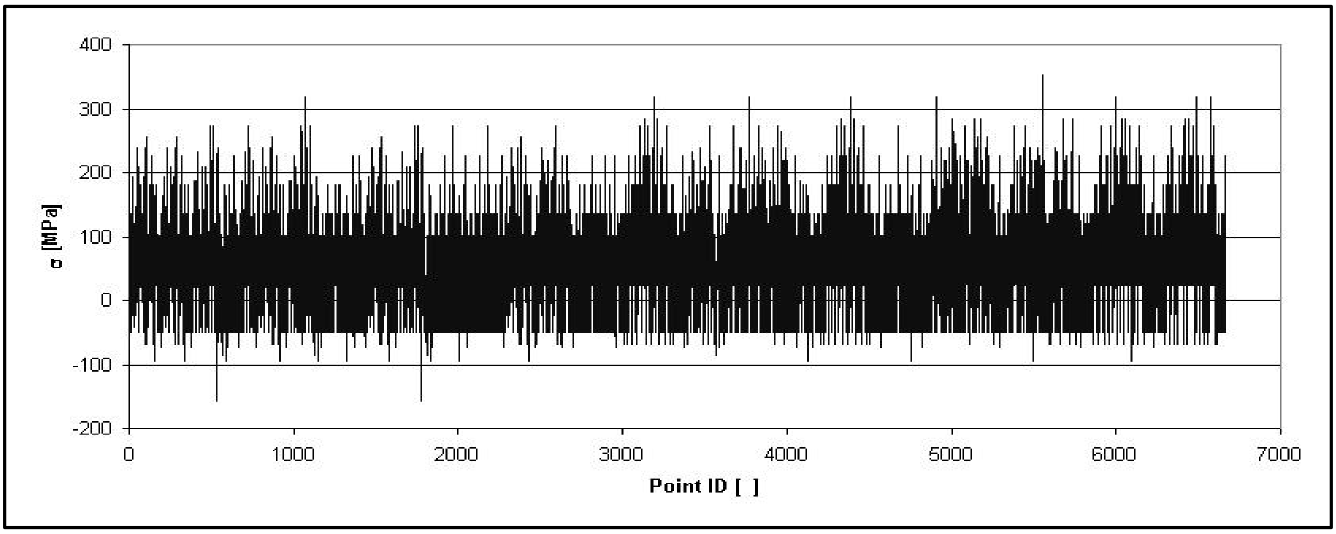

Figure 10 The FSFT peak through history of one critical item in 25 EFH block

By comparing the actual fatigue lives of critical structural items with calculated results, the calibration coefficient K for each critical item was determined using the following formula:

$$K = \frac{Measured\_FSFT\_Fatigue\_Life}{Calculated\_FSFT\_Fatigue\_Life} \qquad (1)$$

In calculations with crack initiation method the crack growth time from initial crack length (normally 1 mm) to the crack size measured in FSFT was taken into account. Depending on the material data used, the calibration coefficients were typically between 0.5 and 2.

3.4 Air Force usage

On the basis of the training program content definition by FAF, a block of flights representing various mission types was determined for an aircraft instrumented with OLM strain gauges. Each of the most consuming mission type was represented at least by one flight. The rainflow data representing FAF average usage was produced for the necessary strain gauges of the OLM installation. The FI-consumption per mission type was set to correspond with the actual usage.

Owing to the fact that the strain gauges of the OLM installation were not located in the critical structural locations, their stress state had to be determined as a function of the strain gauge measurement results. However, this transfer function is dependent on the aircraft flight condition, and since the applied strain gauge data was in rainflow format, flight parameters corresponding to the strain gauge stress values could not be known.

To define the transfer function and its flight condition dependent content, i.e. the transfer function's range of variation, the FE-model was used to simulate a variety of flight conditions. Transfer functions were determined for each flight condition from the strain gauge simulated by the FE model to the peak stress of the critical location. The flight conditions involved are presented in Table 1.

Table 1 Flight conditions used to determine transfer functions

Condition	n_z	Note
symm. pull up	-2	
symm. pull up	2	
symm. pull up	5	
symm. pull up	5	zero fuel pressure
roll start	1	aileron design case
roll	1	50 deg / s
roll	1	100 deg / s
roll	1	150 deg / s
landing	-1	undercarriage design case
refueling	-1	81 kPa fuel pressure

Because several of the critical items were located in the integral fuel tank area, the effects of the tank pressurization and refueling on the stresses were checked. They were found to be insignificant. Rolling maneuvres and the aileron design case were used to determine the asymmetric loading content. Based on the undercarriage design case, the effects of the ground–air–ground cycle (GAG) were studied. Figure 11 shows the stresses encountered by one critical detail and the nearest strain gauge in the simulated OLM installation. Figure 12 presents the transfer function values for the same item under different load conditions.

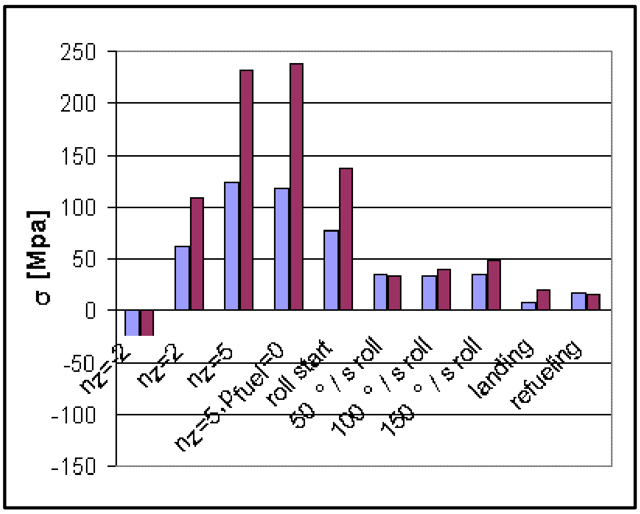

Figure 11 The maximum stress on one critical item (red) and the stress in the nearest OLM strain gauge simulated on the FE model (blue) under different flight conditions.

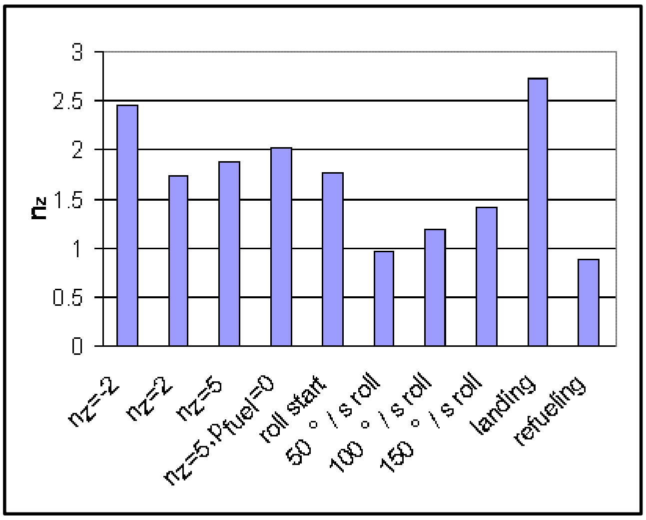

Figure 12 A transfer function derived from the nearest strain gage to the critical location under different flight conditions

As shown in Figure 12, the transfer function is not constant but depends on the flying condition. Because the flight parameters were not included in the flight measurement data, a constant value was determined for each transfer function. If the flight parameter data had been included, the transfer function could also have been determined as depending on it. Transfer functions were selected within the most life consuming flight envelope area of 4 to 5 g. Should the transfer function values be significantly higher in other areas, a slightly higher transfer function was selected to maintain conservatism. The biggest differences in transfer function values compared with the symmetrical 4 - 5 g pull-ups were caused by low stress flight conditions. Consequently, an error in the transfer function regarded as constant does not create major difference in the results of the fatigue life analysis.

As regards FAF usage, the fatigue life calculations were made using the same material values and calculation methods as in the FSFT analysis. The critical location stress data consisted of the strain gauge rainflow results multiplied by the transfer function. As a result, calculated fatigue lives and crack growth rates in FAF average usage were established.

3.5 Calibrated fatigue life in FAF usage

The calculated fatigue lives of the critical structural items in FAF usage were corrected by the results from the virtual fatigue test. Owing to the well-known loading history and load levels in the virtual fatigue test, it can be assumed that the differences between the fatigue life calculations and those measured in FSFT can be primarily contributed to an error in the material data and the FE-model

Since the calculated fatigue lives in FAF usage were determined using the same material data and FE-model as in the virtual FSFT, it is reasonable to assume that the relative error in the calculated fatigue life estimates is congruent with the virtual fatigue test. Consequently, the calibrated fatigue life for critical items in FAF usage can be calculated using the following formula:

$$Calibrated\_Fatigue\_Life = K \cdot Calculated\_FAF\_Fatigue\_Life \quad (2)$$

where K has been determined by means of the virtual fatigue test.

Table 2 gives an example of the calculation of the calibrated fatigue life of one critical structural item using the S-N analysis.

Table 2 An example of the calibration of the fatigue life analysis

SN-analysis for U / C attachment				
Material	Mat. 1		Mat. 2	
	25 FH Block damage	Fatigue life [EFH]	25 FH Block damage	Fatigue life [EFH]
FSFT calc.	1.04E-03	24131	9.01E-04	27744
Crack detected		12625		12625
Damage	0.52		0.46	
OLM flight	Damage	Fatigue life [flight]	Damage	Fatigue life [flight]
1	5.54E-05	18067	1.97E-05	50839
2	1.72E-05	58241	3.93E-06	254518
8	6.33E-09	1.6E+08	2.00E-10	5.0E+09
9	1.41E-04	7117	4.91E-05	20358
10	1.10E-04	9132	4.97E-05	20105
12	5.63E-04	1776	7.50E-04	1333
Calculated fatigue life [FI]	171		233	
FSFT correction	0.52		0.46	
fatigue life [FI]	**89**		**107**	

4. Results from the fatigue life calculation

As a result of the fatigue life calculation, fatigue life estimates for critical structural items were established using S-N and ε-N methods. Furthermore, estimates were made of the crack growth rates and critical crack lengths. A summary of the results from the fatigue life calculation is presented in Figure 13. As shown in the figure, the scatter of results using materials from different sources, is moderate even with calibrated calculation. According to the results, the achievement of the certified 68 FI life is not excluded, but it is possible that some cracking will occur before that.

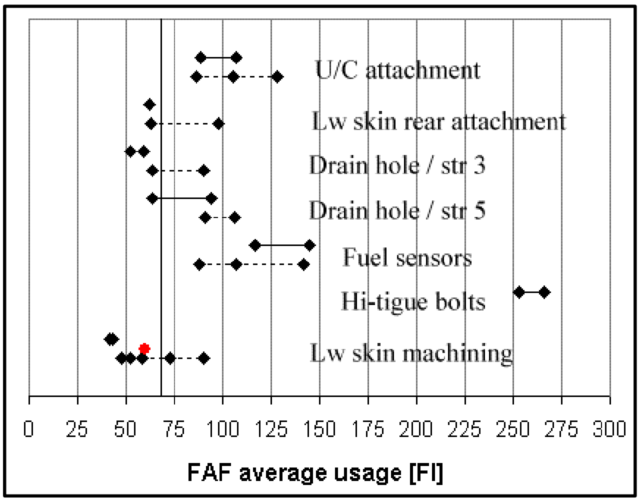

Figure 13 A summary of fatigue life calculation; the solid line represents S-N analysis results and the broken line the combined results from ε-N analysis and crack growth rate calculation. The red dot indicates the only damage on the bottom skin panel detected so far. The vertical line at 68 FI is the certified safe life for wing.

Figure 14 shows the results of the crack growth calculation for one critical item. Since there is not much information about initial crack dimensions or growth rates in FSFT, the crack growth rate calculations were made based on initial cracks of different depth per length ratios.

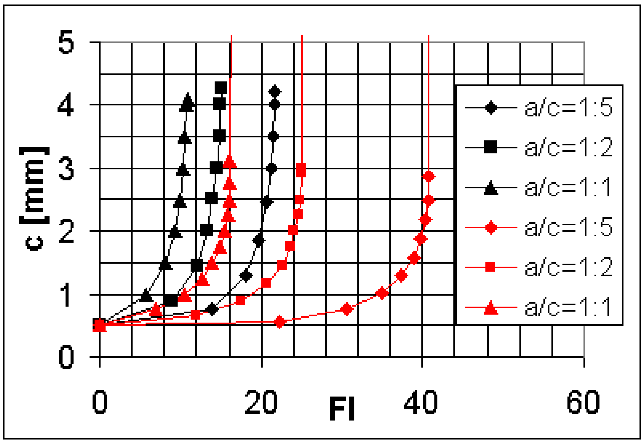

Figure 14 An example of the crack growth analysis results, where 'a' is the depth of a semi-elliptic crack and '2c' the crack length. The black color represents the results calculated with the material data used by AFGROW [6] and the red by VTT [7] accordingly.

4.1 Analysis of results

The order of magnitude of the results received from the fatigue life calculation is reasonable in comparison with the 68 FI design life. The results shown in Figure 12 do not involve scatter factors, and therefore the achievement of the design life can not be fully ascertained. As a whole, the results from S-N analyses are slightly more pessimistic in comparison with the ε-N calculations. The trend is expected, since the calculated life expectations fall between the low-cycle and high-cycle areas. Compared with the S-N analysis, the local strain method gives smaller damage at certain very high load cycles.

As concerns in-service experience, the only observation of calculated critical locations is made on the machined radius of the bottom skin panel. It is within the scatter of ε-N results and supports the calculations. At that location, the S-N analysis seems to give pessimistic results.

5. Summary

This presentation determines the fatigue lives for the critical structural locations on the wing of the Hawk jet trainer in the Finnish Air Force (FAF) average usage.

The manufacturer's full scale fatigue test (FSFT) was simulated by means of an FE-model. On that basis, the calculated fatigue lives for the critical structural items were determined in FSFT. By comparing the resulting calculated fatigue lives with the damage observation moments recorded during FSFT, a correction coefficient was determined for each critical location. Using aircraft instrumented with strain gauges, the wing loading spectrum in FAF usage was determined and fatigue life estimates were calculated in the average usage. The FSFT correction coefficient was used to correct calculated fatigue lives in FAF usage. As the outcome of the work presented herein are the calibrated fatigue lives in FAF usage.

With the procedure used in this presentation it is possible to achieve considerably higher accuracy than in fatigue life estimates based solely on the results of the finite element method and computational fluid dynamics. The increased accuracy is contributed to the use of experience from the FSFT and the correction of the idealized structural model to correspond to the actual structure. Because the whole procedure can be carried out without new fatigue tests, the costs from the analysis will remain at a reasonable level.

Owing to the fact that the test results did not fully ascertain the achievement of the original wing design life, the most critical locations will have to be subjected to component level fatigue tests. With increasing flight measurement data from the OLM installation, it would be worth repeating the fatigue life analysis of the most critical structural items by utilizing the measured total usage instead of the average usage defined by the training program.

References:

[1] Cotton J. *Hawk T.Mk.1. Fatigue Test Loadings*, HSA-KST-N-HAW-661, Hawker Siddeley Aviation Ltd., 1975

[2] Henley K. *Hawk Fatigue Test Loadings*, Bae-KGT-D-HAW-01114, British Aerospace, 1982

[3] Liukkonen S., Teittinen T. ja Siljander A. *Komposiittivuoratun HW-keskirungon lennonaikaiset mittaukset*, VAL33- 012358, VTT, Espoo 2001 (in Finnish).

[4] Liukkonen S., Teittinen T. ja Laakso R. *HW-348: OLM-lentojen erillinen analyysi*, VAL37-012012, VTT, Espoo 2001 (in Finnish)

[5] Salminen E. ja Siikonen T. *Hawkin siiven aerodynaamiset kuormat III*, Raportti T-13, Espoo 2000 (in Finnish).

[6] *AFGROW: The crack growth life prediction program. Version 4.0001.11.8.* (http://fibec.flight.wpafb.af.mil/fibec/)

[7] Koski K., Bäckström M., Siljander A., Wallin M. *Lentokonerakenteiden särönkasvulaskentaohjelmien testaus yksinkertaistetun ja todellisen case-tapausten avulla*, VAL37-992177, VTT, Espoo 1999 (in Finnish).