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STRUCTURAL INTEGRITY FOR AGING AIRPLANES

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Abstract

The intense usage of Swiss military airplanes has a significant impact on fatigue life. The Swiss design life based on the OEM design goal is reduced. As a result, special program has to be implemented to ensure the structural integrity over the aircrafts' lifespan. An important task was to perform a full scale fatigue test that reflects the Swiss usage spectrum. The life of the Swiss military airplanes could thus be extended to meet the economic life goals – using fatigue tests – by more than 10 years for the Venom De Haviland DH-112 and the Mirage III.

Today former military planes like the Pilatus P3 (trainer), Venom, Vampire, Hunter and Mirage III are civil registered. During operations in military service, these planes had strict requirements regarding inspection, maintenance and life time. In civil aviation however, there are no such regulations for these planes and their maintenance and operation is only superficially regulated.

The Pilatus P-3 (military trainer in service from 1958 till 1990) was originally built for a design life time of 2'500 flight hours and 10'000 flight cycles. As the aircraft started to reach 2'500 hours in military service, the limit was increased to 3'000 flight hours and 12'000 flight cycles. Although most of the Pilatus P-3 airplanes still in service today have already reached 3'000 flight hours by now, they are still flying around and have been doing so since 1995 as civil airplanes

An initial assessment already demonstrated that the wing of the P-3 required further some strengthening in 1959/60. This part of the wing is still considered to be critical based on the current review.

Following the current risk assessment which was based on ICAO standard, recommendations were made to fly the P-3 till 5'000 flight hours with no constraints but beyond 5'000 flight hours further engineering investigation (damage tolerance analysis) and inspections are definitely needed. The P-3 has real potential for longer usage in civil conditions as the result of the less severe usage compared to the conservative original design spectrum from Pilatus.

1 Introduction

Up to 1958 no formal fatigue requirements exist only static strength considerations plus safety factors were expected to preclude fatigue damages. In 1954 two Comet I De Havilland plane crashed with approximately 1'000 pressure cycles which was well below the anticipated service life. In 1958 six Boeing B-47 bombers crashed. To exchange information among experts get more understanding and improve the fatigue design the International Committee on Aeronautical Fatigue (ICAF) was founded in 1951. Already in 1952 Juerg Branger from the Swiss Federal Aircraft Factory in Switzerland developed the so called fatigue history simulator. In 1959 the Pilatus P3 military trainer was tested in the fatigue history simulator to demonstrate a service life of 2'500 FH. For fatigue life extension special full scale fatigue tests on venom and Mirage III were performed over more than 10 years.

In Switzerland several ex-military airplanes (Pilatus P3, Venom, Vampaire, Hunter, Mirage III are still in private use as annex II planes.

The Pilatus P3 trainer planes are close to the tested life of 5’000 FH. Other planes are close to the demonstrated life of the Swiss Air Force. The use of these old planes may be quite different to the military usage. Nevertheless the safe operation is a demand and has to be approved by experienced fatigue engineers. A further challenge is the documentation of past experience.

For the Venom and Mirage III more information concerning material data, loads data, test results for multiple service life are available. For the Mirage III in the nineties damage tolerance analysis was performed for critical structural components based on the fatigue test results.

In this paper the procedure for the Pilatus P3 will be given to ensure the structural integrity in civil operation.

2 Full Scale Fatigue Test

1952 F+W Emmen decided to develop a so called ‘Fatigue History Simulator’, because the Swiss Air Force was aware of the fatigue problems, that would concern the new fighter aircraft and trainer projects. In 1952 no facility was available in the market to determine the safe life of an aircraft. The essential property of the new test facility is the absolute proportionality of the load distribution and the genuine sequence of loading.

On that time the fatigue testing of an aircraft was not usual, industry pulsators were used for fatigue testing on aircraft components applying an oscillating loading. No specialist of general engineering was available to develop and design the test rig, consequently F+W Emmen had to start itself with the work. It is important to mention here that J. Branger (first Swiss national delegate of ICAF) was the initiator, the moving spirit and at last the father of the fatigue testing in Switzerland. During this time Switzerland had the opportunity to join Holland, the U.K. and Sweden in the ICAF and to share know how and experiences in relation with the fatigue of aircraft structures.

The requirements for this simulator can be expressed in 3 main requirements:

1. All applied load on the structure are controlled by a single command
2. The test facility must allow every loading history
3. The test facility must control itself automatically

The fatigue history applied on the simulator is an extract of the service history that contains every element which is significant for the fatigue life of the aircraft structure. The force are produced hydraulically and transmitted by mechanical means to the test specimen, which jacks which are working in tension as well as in compression.

A sophisticated system of a control piston connected by an adjustable scale beam with a servo piston allows to maintain and to control the jack forces, and by shifting the fulcrum of the scale beam to alter the pressure ratio within wide limits.

The oil pressure of 180 bar is delivered through a high performance pump with 120 litters p.m.
The next figure shows an example of fatigue loading upon the time.

Three curves show the working pressure in 3 jacks. The lapse of speed is depending on the time until the test specimen under load has reached its elastic equilibrium. The time which is needed for the pressure build up and drop is dependent from the performance of the load maintainer valves and the connecting pipes to the jacks, and also from the pump performance.
The sequences of the load are written on a 8-holes tape with optic identification allowing to transmit 256 orders. 67 orders are required for manoeuver loads, ground loads and the switching to different weights and load cases, the rest is needed for special load conditions like engine thrust, wheel spin etc.

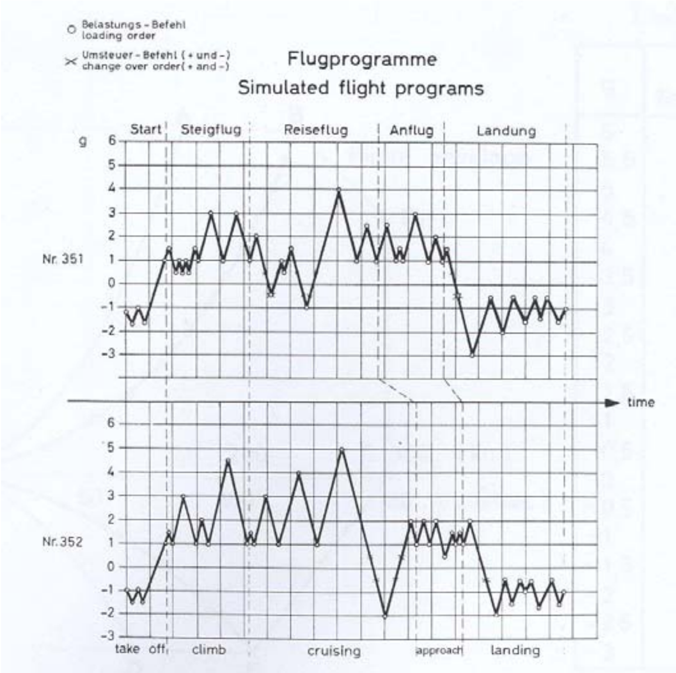
In the conclusion of the report J. Branger states: *'We believe that with the simulator any fatigue history of any aircraft can be simulated, and all the happening follow each other in the genuine sequence which is – until the contrary has been proved, as important as the number and the magnitude of the events .'*

This idea to develop a fatigue facility dedicated to the full scale fatigue test of different aircrafts was very rational and interesting. The reality has nevertheless showed that for different reasons each aircraft full scale fatigue test needs a test rig and an overall facility, which are developed ad hoc for the specific test.

At the end of the fifties the Swiss air Force ordered for the training of the pilots the P3 aircraft of the Pilatus Aircraft Ltd. in Stans. The following clear specifications were required:

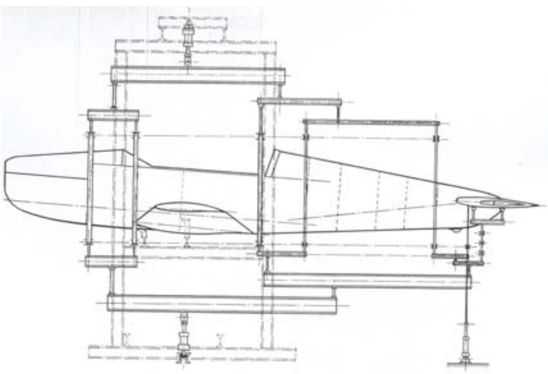
2500 hours safe-life	
1800 times	+5 g
5600 times	+4 g
10400 times	+3 g
3700 times	-2g
370 times	-3g

At this time the 'fatigue history simulator' of F+W Emmen was ready for testing, and thus the P3 was the first test item. After different preparations and some preliminary run the real test began in August 1960.
24 different partial programs, based on v-g-h records, describing take-off, climb, different types of flight, descent and landing, have been combined to generate 1056 different flight, containing about 23'000 cycles. The next figure shows two examples of flight profiles.



To set up the sequence of flight the ballot box method has been used, it means that one flight after the other has been drawn randomly like in a raffle.

For this test the rig applied the forces through 19 jacks, 16 for the wing in a lying position (see the next figure) and 3 for the fuselage. The chord wise force application is different for the positive and the negative loads, matching on this way the specific pressure distribution on the wing as well on the fuselage. The load applying points have been located along each rib. No side loads were simulated at that time.
With this test rig and its equipment within 24 hours 72 real flying hours could be simulated.



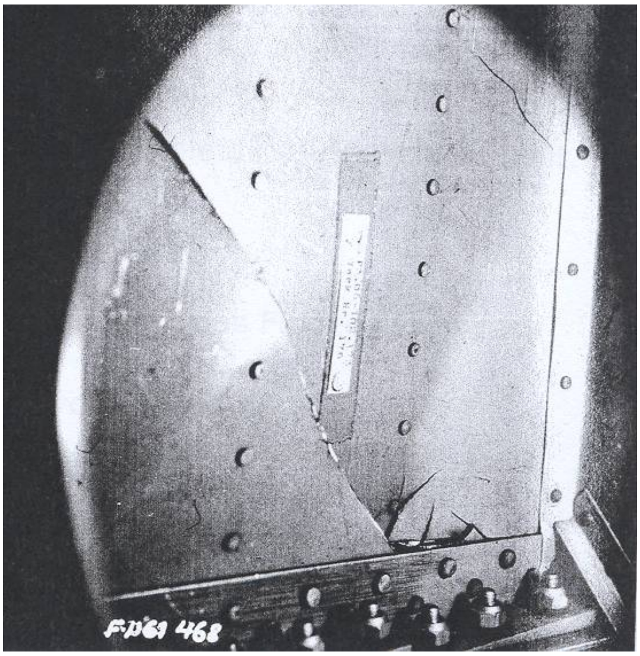
With this arrangement for the P3 test all jacks have acted only in tension.

A simple inspection program has been set up:

1. the structure was inspected visually for defect every day, one day representing 72 flight hours.
2. each reduction of the stiffness of the structure is reported by the wing tip cut out switches at +6 and -3 g due to higher deformation
3. all load peaks from -0.5 to 0.5 g all zero passages were counted and registered
4. the load of 9 selected jacks were measured by precision strain gauges.

For the full scale fatigue test the last aircraft of the production has been selected. By test start the first aircraft has already 500 flying hours, and some loose rivets have be found due to static overloading but sure not due to fatigue cycles. After 1000 hours of fatigue testing a fretting damage occurred. A repair has been done on the test article as well on the aircrafts of the fleet. After 2500 test hours the authority decided to extend the test up to 5000 hours after a static overload test of 7 g. At the end of 5000 hours an ultimate test (factor of 1.5 on max service loads) up to 9 g has been done. The specimen failed at 8 g whilst the design ultimate load target was 9g.

Despite very careful inspecting before this ultimate load test, the fatigue damage that leads to failure was not remarked before. Finally one of the hydraulic people found by chance in a hidden corner a damage can be termed as a classic example for a fatigue failure (see next figure). The failure occurred by shear in a web plate of the main spar in both outer wings, at the attachment to the inner wing. A check of the stress calculation of this part showed, that the web and the riveting did not reach the ultimate factor of 1.5. On all service aircraft the allowed limit was thus reduced temporary to 5 g, and it was possible to strengthen it before an accident occurred.



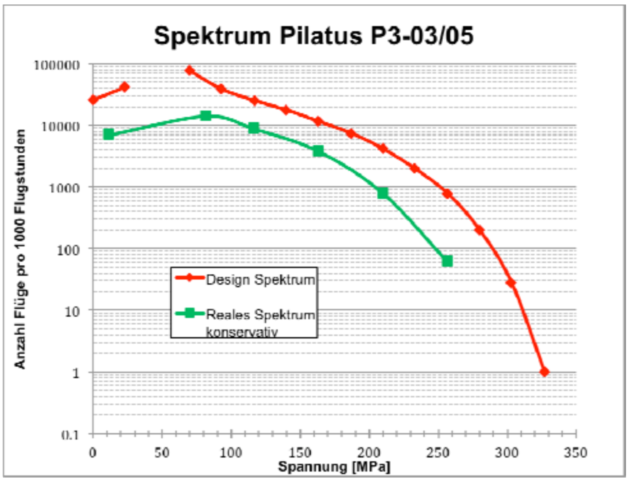
The test simulated two required safe-life and revealed the weak points of the structure reaching on this way the original goal. The original solution of the lying jacks in order to reduce the height of the test rig worked very well, but didn’t set the standard for future tests. In the most full scale fatigue test the jacks are working vertically.

3 Military Usage

3.1 Service Experience

The Pilatus P3 trainers were in service by the Swiss Air Force till 1995. At the end the planes were used for transfer flights and the usage was less severe.

About a dozen airplanes were equipped with Fatigue Meters (Negretti & Zambra Type M.1967) to monitor the Nz exceedance. The data was evaluated every two years and compared with previous Nz cumulative occurrences. The service Nz spectrum is at least three times less severe than the full scale fatigue test. Based on the tests a stress to load ratio was applied to the Nz spectrum to determine the stress at the critical location between inner and outer wing. The data confirms the reduced occurrences of the design (test spectrum, red curve) compared with average usage between 1979 till 1990 (green curve), see figure below.



A Miner fatigue damage calculation was done for the two spectra for stress concentration factors kt of 2 and 4 (material 2024-T3). The Miner sum for kt = 2 is 1.09 for the design spectrum and 0.26 for the average usage spectrum, for kt = 4 10.93 for the design spectrum, respectively 3.08 for the average usage spectrum.

This results in a fatigue life for the military usage four times larger then the design life of 2’500 FH. This seems to be in agreement with the fatigue life of 12’000 FH for the Pilatus PC-7. The structure of the PC-7 is redesigned with some changes on the wing and tail with a more powerful jet engine. Nevertheless the Miner calculations were not proved by a fatigue test.

The P3 full scale fatigue test showed minor damages which were all addressed in modifications for the whole fleet. During the military service life no cracks were discovered during inspections (intervals of 100 FH, 200 FH or once a year) and no special incidence for structural damages were reported.
In 1975 a structural integrity study was done to assess the fatigue life of the fleet. The Swiss fleet was cleared to 3’000 FH and 12’000 flights due to the less severe usage compared to the full scale fatigue test.

The Swiss Air Force retired the P3 fleet in 1995. The P3 were sold as oldtimers to private people.

In Switzerland 17 aircraft received a civil registration by FOCA. The military service schedule was converted for civil usage. The P3 had between 3’000 and 3’400 FH during military usage.
The current fleet leader has accumulated 4’270 FH whereas an other plane has done less FH but reached already 4’872 landings. The P3 full scale fatigue test demonstrated no failure at 5’000 FH and 10’000 landings. This means that the P3 showed a safe life of 2’500 FH and 5’000 landings. According to the structural integrity study of 1975 the fleet leader exceeded the cleared limit of 3’000 FH. Therefore further investigations are needed to ensure the continuing safe operation of the civil P3 airplanes.

4 Assessment for Civil Usage

4.1 Available Data and Information

First the available Nz spectrum from the military usage were analyzed and compared to the full scale fatigue test spectrum. Second two Swiss operators were interviewed to understand the civil usage. As result we can conclude that the P3 are no more flying spins and do not exceed 5g’s most flights are within 1 to 2 g during special displays the P3 flyers of Airolo still fly loopings with higher g but 5g seems to be the real limit. This information is very limited for making engineering analysis concerning the remaining life of civil usage. The civil usage may be depending on the operators.

Nevertheless an assessment was done collecting all the data from the military usage and review the information.

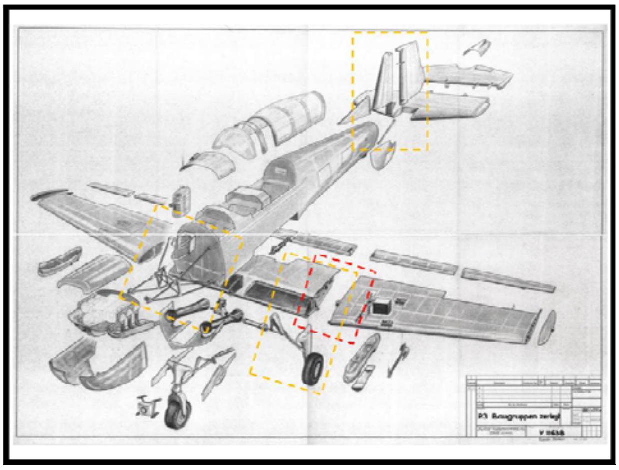
The risk matrix of ICAO was used to rank the status of the P3 structure regarding safe operation.
In general the structure of the P3 has hazardous risk severity with improbable risk probability, see graphic below (blue box).

Risk probability		Risk severity				
		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5					
Occasional	4					
Remote	3					
Improbable	2					
Extremely Improbable	1					

The critical areas were found to be:

- engine mount fairing; not tested
- landing gears; not tested
- vertical tail, not tested
- connection between inner and outer wing; high loads transfer, bolts were already replaced in service

The critical areas are shown in the figure see below.



No service failures or cracks were reported and document. After the changes due to residual static test in the fleet no modifications were done.

In a review with the Federal Office of Civil Aviation it was decided to do a static analysis and fatigue investigation on the engine fairings. These fairings were never tested but are safety relevant. A crack could lead to fata failure which mast be avoided under all conditions.

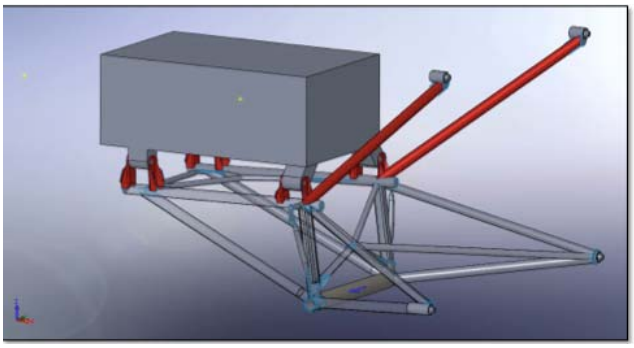
5 Analysis of Engine Mount

5.1 Static Investigations

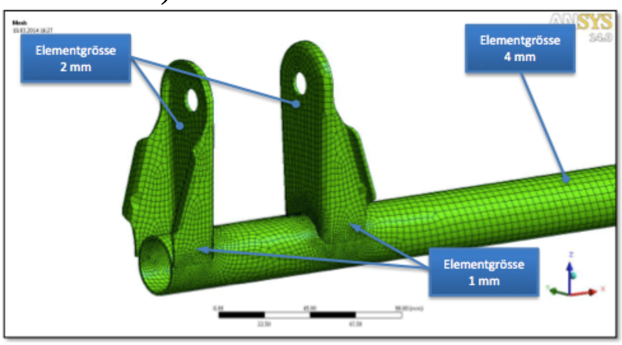
For loads selection the EASA standard CS23 was applied:

- Steady state maneuvers CS23.361
- Gust load CS23.361
- Side load maneuver CS23363
- Horizontal spin maneuver CS23.361
- Side load on ground CS23.485
- Ground load condition as reference for fatigue analysis (weight on wheels condition)

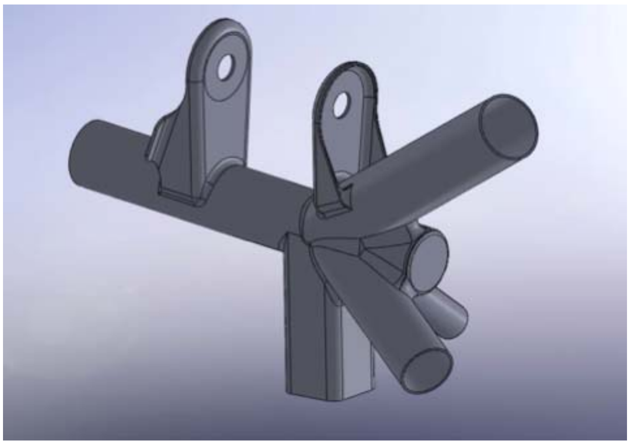
For engine conditions also CS23.423 and AMC23.371 was used. To get all the loads the flight manual was necessary with the data from the Lycoming engine model GO-435-C2 and the propeller information from Hartzell.
The engine mount is a tube structure with welded connection with steel material 4130 [1], see figures below; general simplified layout and detailed picture (aft connection to engine = Motorlasche).



All the required loads could be calculated without any problems.
The FE code from ANSYS was used to develop a finite element model. First s simple model was done and afterwards a more complex model was designed. The engine itself was simplified as quadratic bloc. For details see the FE model below. To determine the correct size for surface FE model a grid converge study was done which results mesh size 2.0 mm and 4 mm for tube diameter of 15 mm.
In this FE model the welds were not modeled. For the connection of the tubes ANSYS Workbench ¨bonded¨ approach was used. In the connection area the mesh size was further reduced to 1 mm. For details see the figure below (forward connection to engine = Motorlasche).



To improve the model especially at the connections and interfaces the FE model was locally refined using a submodel using volume elements. Weld were simulated as radius, see details below.

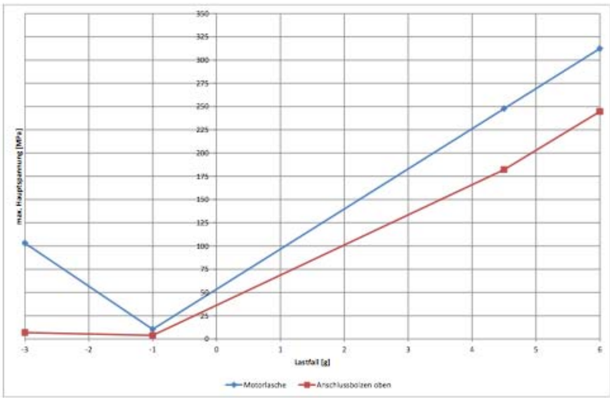


The results of the FE model showed larger deformations of 4 to 4.8 mm at left hand forward engine mount fairing. The static analysis was based on the FKM requirements, see ref [2]. Based on the static strength analysis it could be concluded that all load access have smaller load factors than one, except the case with tailspin movement.
At the critical connections the CAB process ref [3] was used to perform the static analysis on the weld.
The equivalent van-Mieses stresses at some locations were in the range of 87 ksi. Also the upper bolt connection to the fuselage had very high stress levels as well.
A lot of effort was spent to determine the impact on local yielding at the high stress areas in the detailed analysis. The safety factors at critical locations showed values above 1 for all load cases up to Nz = 6g (limit load) with exception of the horizontal spin condition. This load case will no more be practice in the civil operation. This has to be included in the flight manual.

5.2 Fatigue Investigations

Based on the spectrum information from the test and the Nz exceedance data for the Swiss Air Force usage a Rainflow Counting Matrix was developed. A lot of knowledge of the period of Mirage III test development has to be applied to determine the 32 by 32 Rainflow Counting Matrix.

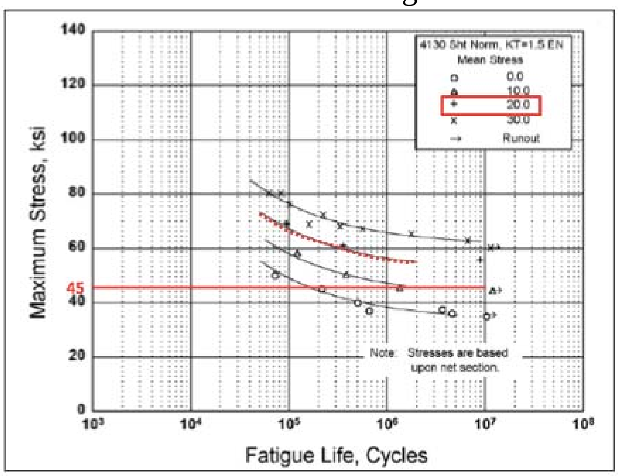
With the corresponding FE results for the Nz values the spectrum could be converted to stresses at the critical locations based on principal stresses of the sub model FE data. For the critical locations (engine connection aft = *Motorlasche* and upper bolt connection to forward fuselage frame = *Anschlussbolzen*) the stresses in function of Nz are shown below.

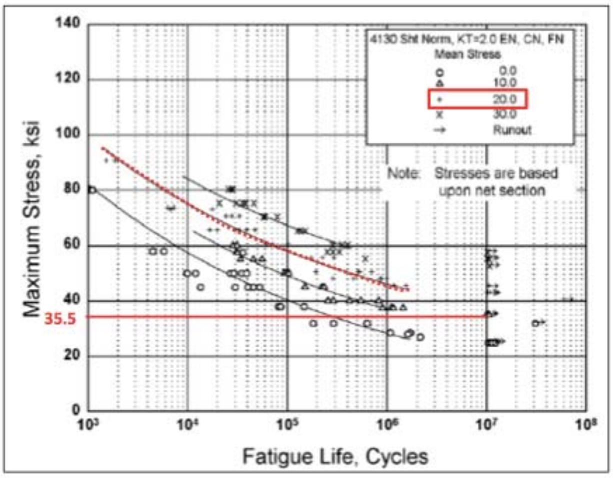


For fatigue investigations the flying steady maneuver loads are contributing to the fatigue damage.

In the first approach MIL-HDK-5J data [4] for steel 4130 at kt = 1.5 and kt 2.0 was used for max min stress level to see if the fatigue life is in the area of durability life. This kt values are considered because the *Motorlasche* has the kt of 1.25 and the *Anschlussbolzen* a kt of 2.0. The max stress for the *Motorlasche* was 35.5 ksi respectively 45 ksi for *Anschlussbolzen* at mean stress of 20 ksi. Both values are below the red dotted curve at 10^7 cycles. This confirms that the two locations have a durability life.

The two curves are shown on figures below:





To get more confidence in our analysis we also used the local strain life approach with strain life curves. Therefore the strains from the detailed FE models at the two critical locations (*Motorlasche* and *Anschlussbolzen*) were taken into account. Using strain life data with stress ratio of -1 we observed strain amplitudes of 0.14% (*Motorlasche*) respectively 0.23% (*Anschluss-bolzen*). The strain amplitude of 0.23% showed 100’000 cycles up to failure whereas 0.14% showed infinitive life. The stress ratio of the real cycle is about 0.4 which yields a higher number of cycles up to failure.

Due to aging of the P3 airplanes in civil operation careful inspection at the critical areas in the engine mount is absolutely necessary.

We recommended the inspection of 5 locations in the area of the *Motorlasche* (engine connections) and *Anschlussbolzen* (upper and lower bolt connection to fuselage frame) every 100 FH or once a year.

6 Conclusion

The Pilatus P3 military trainer was designed in the fifties and operated from 1959 till 1995 for pilot training and transfer flights in the Swiss Air Force. In that period no structural problems were reported which lead to repairs and redesigns. The usage was much lower than the test spectrum which was tested at F+W in Emmen Switzerland for 5’000 FH. Since 1995 17 P3 are in civil operation in Switzerland. The fleet leaders reached close to 5’000 FH. An assessment showed that some locations needed

to be investigated in more detail to ensure the structural integrity.
The engine mount was never tested and so no information regarding fatigue life and critical locations was available. In this paper a detailed FE study with fatigue investigations is presented. The fatigue life calculations showed that the life is in the area of durability life. It is recommended to use at least two methods for fatigue analysis to better understand the sensitivity of the fatigue life. Keep in mind that the fatigue life curves belong to 50% probability rate of failure. Five locations should be inspected every 100 FH to ensure a safe operation.

7 Acknowledgements

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