Structural Integrity – Yesterday – Today - Tomorrow

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Abstract. Early airplanes were designed using purely static conditions and mainly tested only with simple wing tests. But despite the significant advances in design, manufacturing and testing capabilities, structural failures may still occur. Thus new concepts are required to ensure safe operations over the lifetime of an airframe.

In 1952 Juerg Branger developed a concept for a fatigue simulator at the Federal Swiss Aircraft Factory (F+W). The Pilatus P3 trainer became the first airplane to be tested in Emmen, Switzerland to demonstrate the safety of the airframe over a lifetime of 2’500 FH. This first test demonstrated the importance of full scale fatigue tests to ensure the structural integrity of the airframe. Due to the intense usage of the fighters deployed by the Swiss Air Force, further full scale fatigue tests were undertaken on the Venom, the Mirage III, and the F/A-18.

As the complexity of the materials used in modern aircraft design increases, more and more analysis is being taken over by highly sophisticated software and test procedures. Structural integrity is still an important means to ensure safe operations in aviation for all types of airplanes.

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.

The crash of the F-111 bomber of the US Air Force in 1969 after 107 flight hours leads to the development of the damage tolerant design criteria (MIL-83444). Further incidence in the civil aviation (Crash of 707-300 in 1977, incident Aloha 737 in 1988) demonstrated the limit of fail safety and damage tolerance. Full scale fatigue testing was up to 1998 not required in the civil regulation of 25.571 amendments. To ensure structural integrity for widespread fatigue damage the airworthiness requires to establish a Limit of Validity (LOV). In the new part 26 or EASA CS26 even further actions are defined for aging structures which will not only be addressed by the OEM but also by the operators. More challenges will come with the new generation of hybrid structures with weight ratio of 50% composite. The structure and fatigue behavior for composite is very different compared to metals. Today airworthiness requirements are mainly based on metal fatigue experiences. Even further structural tests with the new generation of composite planes will be
necessary to ensure the structural integrity. The loss of a composite rudder on Airbus 310 in 2005 showed clearly the limitations due to fatigue of composite structures. The use of primary composite structures needs special care to ensure the safe operation within the defined LOV based on metal considerations. The design of hybrid structures (metals and composite) needs more research to ensure the service life and extended testing with safety by replacement strategy.

The Fatigue History Simulator

1952 the Swiss Federal Aircraft Factory called F+W Emmen decided to develop a so called ‘Fatigue History Simulator’, because the Swiss Airforce 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 time 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 Juerg Branger (first Swiss national delegate of ICAF) was the iniator, 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 fatigue history applied on the simulator is an extract of the service history which 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.

In conclusion of the report of Juerg 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.’

The Swiss Full Scale Fatigue Tests

Pilatus P3 trainer test

In 1960 the last Pilatus trainer aircraft produced for the Swiss Air Force was tested in the fatigue history simulator for a fatigue life of 2'500 FH, overall 5’000 FH were simulated with a test set up of 19 jacks. Only symmetrical load conditions were applied. It takes 24 hours to simulate 72 FH. At the end of the fatigue test an ultimate test with factor of 1.5 up to 9g was done. The wing failed at 8g at the shear web plate of the main spar.

De Havilland DH-112 Venom test

Astonishingly the venom aircraft was originally guaranteed for a Swiss safe life of 500 FH. The full scale fatigue test has been init iated to elongate the life to 1000 hours, conforming to the aim of Swiss Air Force. This test has been carried out on the Fatigue History Simulator developed by F+W Emmen. The scope of this test was very advanc ed for that time period (phase 1 from 1962 till 1964, see figure 1 of the test). To double the safe life the following requirements were applied:

1. The load of the aircraft in service had to be ascertained.
2. These load conditions must be represented in the full scale test without restriction
3. All reinforcements, modifications and replacements juged necessary for the ‘flying safety’ of the full scale test structure must also be introduced on all service aircrafts.
4. Incipient cracks and their propagation must be observed on the full scale test. On that basis the periodical intervals for inspection of the service aircraft will be done.
5. All aircrafts of this type must be put into service in such a way that all are fatigued in the same manner, forming one population only.
6. The landing gear loads has to be considered even the effect of the rotation of the wheel were considered; taxi loads also showed its impact in the fatigue life

The test speed of the Venom test was slower compared to the P3 test it takes 5 days to simulate one block of 200 FH. Already at 472 FH the wing of the test article has to be reinforced. More than 3 pairs of wing were tested and considered improved. From 1972 till 1976 a new more severe actual usage spectrum was tested to ensure the structural integrity for Swiss service life of 2’000 FH with several qualified repair solutions.

Mirage IIIS Test
The Mirage III S full scale fatigue test took place in F+W Emmen from 1976 to 1985 and brought essential knowledge in the fatigue behaviour of the aircraft in relation with Swiss usage spectrum. Compared to previous full scale fatigue test this one was in an order of magnitude more complex for two reasons:

1. the Mirage III S is a heavy sub- trans- and supersonic aircraft
2. the wing has a delta shape whose lift behaviour is very different from a conventional wing

It is also remarkable to note that this project has been achieved in a total independent way of aircraft manufacturer Dassault. Practically all the data necessary to determine the different forces to be applied through the test rig in a large set of points of the airframe have been elaborated in the company. The aerodynamic loads have been generated through tests in the wind tunnel facilities of F+W Emmen.

The test started in 1976 and ended in 1985 simulating of 21085 flight hours for the fuselage, 4832 for the first wing. At this time happened the first crash of the wing due to a rupture of the main spar. Another already flown Swiss wing has been mounted on the left hand side, and an Australian RAAF wing with 2192 flight hours on the left hand side. Between 1986 and 1994 the test article and the test rig have been reused to achieve the full scale fatigue test of the canard, the KAWEST upgrade program, developed by F+W Emmen.

The full scale fatigue test allowed to discover a crucial weakness at the main spar due to different drilled holes (slan rivets and tooling hole) where cracks have been initiated very soon during the test. A refurbishment has been undertaken to suppress this weakness in the fleet. Here again no more argument are needed to demonstrate the usefulness of the full scale fatigue test on an aircraft.

Swiss F/A-18 Test
The Swiss Air Force requires for the F/A-18 C/D an operational life of 30 years with a service life of 5’000 flight hours (FH). The Swiss design spectrum is generally three times more severe than the US Navy F/A-18 design spectrum [1]. In an early phase of the procurement Boeing, St. Louis IL, performed an aircraft structural integrity study (ASIP) based on the US Air Force MIL-STD-1530 to assess the criticality of the structure. The Swiss design life for the US Navy structure was only 2’000 FH for the wing and center fuselage. As a result of this study the Swiss F/A-18 had to be redesigned to meet the structural requirements. For the Swiss a crack initiation life of 10'000 FH for fracture and maintenance critical parts had to be demonstrated. The Swiss also wanted a crack growth life of 10'000 FH for fracture critical parts to be demonstrated, according to US Air Force damage tolerance philosophy based on the MIL-87221. Overall Boeing has done 833 analyses. The Swiss F/A-18 is reinforced in the center fuselage by material change from aluminum to titanium for the three carry-through bulkheads and the dorsal longerons. Furthermore, in the center fuselage and the inner wing structure a lot of beef up and interference fastener and cold working was introduced. Based on tests for the US Navy the Swiss F/A-18 was only cleared for a usage of 2'000 FH. The redesign has to be qualified for a service life of 5'000 FH of Swiss design usage.

In 1998 RUAG Aerospace (earlier named F+W) at Emmen, Switzerland, was assigned to perform a full scale fatigue test. The test should start no later then in 2003 and 4'000 FH should be simulated by end of 2003. RUAG Aerospace teamed with German company IABG, Munich, in 1999 to develop a modern and efficient test set-up.
For efficient fatigue cycling an automatically operating digital control and monitoring system is used. It was specified by IABG and delivered by FCS Control Systems. In total 77 control channels were implemented to fulfill the following tasks:

- Closed loop force control of all 68 hydraulic jacks
- Control of jacks in “normal fatigue mode”, “strain survey mode” and “maintenance mode”
- Measurement of the reaction loads at the 6 struts of the restraint system
- Pressure control for the cockpit section
- Transformation of the numerical loading program
- Ensure the safety concept of the FSFT to prevent overloading of the test article
- Perform complete start-up, fail-safe and shutdown procedures

The data acquisition system was supplied by HBM, Germany. It was designed to measure 1’720 channels during the static strain surveys and to measure approx. 300 channels simultaneously during the fatigue test with a sampling rate of 10 Hz. The measurements can be initiated via an interface connection (CANBUS) between the control & monitoring and the data acquisition system. The test speed was optimized to simulate the loads within an accuracy of approx. 2%. The simulation of one block representing 200 FH takes about 18 hours. Efficient fatigue cycling is achieved by operating the test in three shifts. That way 1’000 FH can be simulated in less than one week.

The test (see figure 2 for the test) was completed within less than 2 years. Any fatigue critical location showed severe cracking and the test article sustained a residual strength test without any failure.

Military and Civil Requirements for Fatigue

Military Requirements
The Swiss F/A-18 test showed the improvement of fatigue design and test methods over the last 30 years and demonstrated the usefulness of the US Air Force ASIP concept to ensure the structural integrity. The ASIP tasks see figure 3 has 5 tasks which also takes the operation and service usage into account (Task V: Force Management Execution).

In the ASIP Us Air Force MIL-STD-1530 very detailed engineering actions are specified in each task, see figure 3. Not only safety factors are defined but also initial crack sizes, probability of failures were categorized. Civil authorities and Us Air Force fatigue and damage tolerance requirements use similar words, but have significant differences.
As a fact the US Air Force fatigue requirements do not leave much room for interpretation [3]. In 2007 a F-15C fighter of the US Air Force crashed due to the failure of the upper cockpit longeron. The fleet of 441 airplanes were grounded and inspections showed that additionally 9 airplanes had already cracks and 176 were not built to the specification. The longeron showed undercuts, rought surfaces and the thickness was partionally below acceptable limits. Such incidences demonstrate the importance of quality control during the full life cycle. In the task V an important action is to monitor the fatigue usage to compare the fatigue life consummation compared to the full scale fatigue test. The advanced technology in sensors and non destructive inspection provides further progress to maintain the structural integrity. At the end the economic life is dependent on the costs of inspections and replacement of damaged structures. The environment also contributes to the degradation of the structure. Even for metals impact damages during daily operation has an influence on the structural life.

Civil Requirements
The first Civil Air Regulations (CAR 4b.316) were published in September 1949. The structure shall be designed to avoid points of stress concentration where variable stresses above the fatigue limit are likely to occur in normal service. This means to design the stress level below the endurance limit and to retire the structure prior to the fatigue life. The philosophy could be summarized as safety by retirement.

The disintegration of 2 Comet I in 1954 first jet planes clearly showed the limitations of the fatigue requirements at that time. The CAR 4b.270 addressed the safety by design strategy. Up to 1978 there was no requirement to evaluate the structure under repeated loads. But there was growing concern over the reliance on the safety by design strategy as an effective fatigue management. At the ICAF symposium in 1973 several authors expressed their concern and proposed a finite life for fail safe structures regarding the development of defects and cracks which may lead to structural failures. The CAR’s were recodified in 1964 and CAR 4b.270 became FAR 25.571 without any significant changes.

Shortly after the Lusaka crash of the Boeing 707 due to horizontal stabilizer separation the FAR 25.571 amendment 25.45 was introduced. The main changes were the replacement of safety by design by the perspective of the safety by inspection. The safety by retirement was retained to cover that contingency. The amendment 25.45 requires to perform fatigue and damage tolerance analysis of all structures that could contribute to catastrophic failure.

The ALOHA decompression of the Boeing 737 fuselage showed clearly that widespread fatigue damages known as multiple side damage (MSD) and multiple element damage (MED) has to be addressed in the requirements [2]. This was addressed in the amendment 25-96 which the important statement of “Damage at multiple sites due to prior fatigue exposure must be included where the design is such that this type of damage can be expected to occur”. Special considerations for widespread fatigue (WFD) have to be considered with sufficient full scale fatigue testing.

The FAA took further action to address WFD in certain existing and future airplanes. The new rule come into play in 2011 which required to establish a limit of validity (LOV) of engineering data that supports the structural maintenance program, for more detail see reference [2, 4]. Additionally, the LOV must be included in the ALS of the ICA for the affected type design as an operational limit that can not be overruled, current status see reference of Continuing Structural Integrity AMC 20-20 [4].
Fatigue and Damage Tolerance of Composite Structures

Composite structures offer some advantages as weight reductions, lower production cost and less fatigue sensitivity. The experience with new models of Boeing 787 and Airbus 350XWB will show us the benefit in real operation in the next 20 years.

The loss of the composite rudder stabilizer of the Air Transat flight 951 in 2005 on an Airbus 310 showed that also composite structures have some limitations in fatigue and damage tolerance [5]. In 2008 an airworthiness directive AD 2008-0012 was released for inspection/repair for Airbus 310, 300-600, 330, 340-200/-300 rudder stabilizer.

In July 1978 the first Advisory Circular covering composite structures was published by the FAA under reference AC 20-107. This document should support the certification of damage tolerance fail safe evaluation. The text was basically a copy of the metal philosophy of the slow crack growth concept. The revision of AC 20-107 A in 1984 recognized that slow growth principle is not practicable with composites and that a no growth concept would be the foundation of the damage tolerance evaluation [6]. Of equal importance is the introduction of the specific concern of low accidental impact damage with composites. Airbus showed in an IATA meeting in 2006 that more than 35% of the structure damages was due to ground handling and that around 70% of the structure repairs concerned the fuselage. For composite it would be very important that structural damage capabilities must be considered even for severe events. Still in the fatigue domain, the development of unified full scale fatigue tests procedures for hybrid structures are very important and a subject of further investigations.

Summary

The safe operation of aircraft structures evolve over time in military and civil aviation. The airworthiness standards are more strict for military than for the civil certification. The US Air Force ASIP program addresses the whole life cycle. The certification standards are mainly based on the metal fatigue experience and on the lessons learnt from fatal failures.

Today the performance of full scale fatigue test is mandatory to ensure the structural integrity. Also in civil aviation the aging of structures during service is addressed in the part 26 requirements. To ensure the structural integrity for hybrid structures (metals and composites) the strategy of retirement/modification for normal fatigue and inspection for anomalous fatigue has to be adopted. For redundancy further full scale tests at half time of the approved life (LOV in civil aviation or design life in military) has to be done. With this supplemental tests the influence of real usage spectrum and impact of accidental damage as well as the environmental condition (corrosion and structural degradation) can be taken into account.

More research needs to be done to ensure the structural integrity of current airplanes and future designs.

References


