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EUROFIGHTER
A SAFE LIFE AIRCRAFT IN THE AGE OF DAMAGE TOLERANCE

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Abstract. *For the fatigue design of Eurofighter the participating European A/C industry has not adopted a complete damage tolerance procedure as used by the US industry. The design principles are based on the conventional safe life concept but supplemented with some damage tolerance aspects. This brief overview contains information about the Eurofighter history and industrial organisations. The general fatigue requirements, the fatigue design philosophy as well as the fatigue justification will be described.*

1 INTRODUCTION

With the Eurofighter (Typhoon, EF2000) project an attempt was raised to develop an air superior fighter aircraft which fulfils the apparently contradictory military requirements of different European nations.

The Eurofighter story can trace its roots back to the early 1970's. A colourful mix of various European nations tried with and against each other to define the aircraft for the next century. After endless redefinitions, debates and delays in the year 1985 a final aircraft concept for a single and twin seat variant mainly based on the BAE Systems experimental aircraft programme (EAP) was agreed by the remaining nations United Kingdom, Italy, Spain and Germany. The first prototype aircraft flew on 27th March 1994, the first instrumented production aircraft flew on 5.April 2002 in Italy. On 30 June 2003 the type acceptance certificate was issued and the aircraft was formally handed over to the air forces at national ceremonies [1].

The Eurofighter (Figure 1) is a two engine pitch unstable delta-canard tail-less design. This configuration was found to give an optimal combination of lift and agility. With its large wing area it has a small loading in a typical combat situation. The particular combination and design of both the control surfaces and flight control system (FCS) together with the high thrust output of the engines provide an extremely good manoeuvrability and, over a wide range, carefree handling characteristics e.g. overload and stall prevention.

2 INDUSTRIAL ORGANISATIONS

The Eurofighter Jagdflugzeug GmbH in Halbergmoos close to Munich/Germany was formed in 1986 to manage the European Fighter Aircraft (EFA). Corresponding to the amount of national aircraft orders the structural design responsibility (SDR) was split amongst the four Eurofighter partner companies (EPC). The work share on production aircraft involves BAES (UK) for front fuselage, canards, windscreen, canopy, inboard flaperons, fin and rear fuselage (with ALENIA); EADS-MAS (GE) for the complete centre fuselage and undercarriage; EADS-CASA (SP) for the starboard wing and leading edge slats; ALENIA (IT) for the port wing, outboard flaperon and rear fuselage (with BAE SYSTEMS). Each nation maintains its own final assembly line [1].

This patchwork of general structural responsibilities and interfaces has to be managed by the Joint Structure Team (JST) located at EADS-CASA in Getafe/Spain. For the structural fatigue interfaces the associated Structural Fatigue Working Group (SFWG) was established. Several times per year the fatigue design criteria (usage, load spectra, SN data etc.) as well as the requirements, results and consequences of fatigue tests have been discussed and harmonized by the fatigue & damage tolerance (F&DT) experts of the four EPCs.

3 GENERAL AIRCRAFT DURABILITY REQUIREMENTS

The corner points of the durability requirements are specified within the weapon system performance specification (WSPS). Beside the structural design and justification philosophy the WSPS also comprises the durability relevant basic data such as the required service life, different mission profiles, mission specific aircraft masses, manoeuvre spectra and the safety factors which have to be applied for test and analysis. For Eurofighter these are in particular a 6000 FH / 25 Years inspection free service life with +9g / -3 g manoeuvre envelope.

4 STRUCTURAL FATIGUE & DURABILITY CRITERIA

For the detailed structural design, analysis and structural ground testing the above listed general WSPS requirements were not sufficient. Therefore, detailed customer agreed structural fatigue & durability criteria (SFDC) have been defined by the JST supported by the partner companies. The SFDC summarizes the structural durability requirements and outlines the resulting philosophy for the Eurofighter structure system. It describes the entire route from requirement to qualification as well as the rules for analysis and structural ground testing.

Structural durability was considered as a quantitative measure of the resistance to initial fatigue cracking under specified conditions. This concept, the challenging low mass targets and the "inspection free" requirement led to the structural design philosophy of a safe life A/C equal to the service life of 6000 FH. The safe life requirement should be demonstrated by extensive structural ground testing including a full-scale fatigue test of all major structural items.

The SFDC describes the derivation of the fatigue loading spectra for major aircraft components. These spectra have been subsequently generated under consideration of the general durability requirements, specific MIL requirements [2] and assumptions or in-service experience with other military aircraft. The spectra cover all aspects of the aircraft usage and include both ground and air operations.

For the fatigue analysis of metallic structure, Miners Rule was agreed as the common method of damage accumulation. The generalised fatigue S-N curves used in the fatigue analysis are common design curves agreed by the partner companies. The curves for various materials and stress concentration factors are mean curves i.e. 50% probability of failure and level of confidence. The variation in the fatigue endurance is covered by the application of scatter factors. A scatter factor of 3 on life is used at the low endurance/high amplitude region of the S-N curve, and a scatter factor of 1.4 on strength is used at the high endurance/low amplitude region of the S-N curve. This method (Figure 2) is attributed to the British Def Stan 0970 [3]. Depending on the shape of the considered fatigue spectrum this safe S-N curve approach provides safety factors of SF ≥ 3.0 against mean S-N curves.

For the structural ground testing severe residual strength requirements have been defined. The airframe should be capable of withstanding 100% ultimate load after testing of two design lives and 80% of ultimate load after three design lives. In principal, these residual strength requirements open the door to the damage tolerance philosophy.

For CFC material it has been concluded that the low strain approach in the design will cover the durability requirements. Therefore, fatigue analysis of CFC structure has not been performed. However, extensive structural ground tests have demonstrated the required fatigue life. The effects of different environmental conditions (e.g. hot/wet) are covered by additional factors (knockdown factors) on the test load levels.

5 FATIGUE DESIGN & ANALYSIS

5.1 Metallic Structure

In general the metallic materials were selected under consideration of,

- usage of common (available) materials (aluminium & titanium alloys)
- high strength
- appropriate corrosion resistance
- damage tolerance capabilities (sufficient fracture toughness & crack growth)

In spite of many reservations expressed in numerous publications Miner's cumulative damage rule has been used at the four partner companies, and is obviously still the most widely used analysis method – assuredly due to the simple and universal applicability. A study performed at MBB as early as 1978 [4] revealed an acceptable accuracy for typical fighter aircraft spectra.

A sufficient database of S-N curves has been essential to analyse all types of metallic structure. This was guaranteed by the four partner companies which have provided extensive S-N curves from coupon tests for the standard aircraft materials, various geometric notches, riveted/bolted joints, lugs and manufacturing effects.

The effect of in-service environment on fatigue was considered to be negligible for most of the metallic structure. It has been assumed that the applied surface protection will sufficiently prevent corrosion and, if required during the service life a re-protection will be carried out.

The temperature spectrum due to aerodynamic heating has been based on the predicted mission profiles for the four nations. A degradation of the fatigue properties in consequence of this spectrum is unlikely to be encountered for the typical aircraft materials. However, for areas close to other sources of heating, e.g. engines, a reduction of the fatigue characteristics have been taken into account. Thermal stress cycling as a result of temperature variations on different material joints e.g. metal/CFC has been considered.

In this context the life improvement processes such as shot-peening and cold-expansion of holes should be mentioned. The policy adopted was that these methods would not be used for the initial design but as a cost effective potential to increase the fatigue life of metallic structure that failed during the qualification tests.

Early in the development phase fatigue allowable stress levels were established for various parts of the aircraft. The loading spectra used were either the manoeuvre spectrum for all aircraft structure predominantly loaded in linear correlation to the load factor n_z, e.g. wing box or specific component spectra e.g. undercarriage attachments.

As soon as more accurate loading spectra were available, particularly from computer simulations of typical manoeuvres or prototype flight measurements the fatigue allowables were updated.

The allowable stresses have been usually given in nominal stresses in the net section. They are presented in a graphical form - allowable stress vs. stress concentration factor K_t (Figure 3) or as allowable stress levels for typical joints and also for lugs of various geometries and sizes.

For the major load carrying components, e.g. wing/fuselage attachment lugs, the results of early development fatigue tests have been used for the final design. Wherever possible, previous test results of similar structure have been considered.

Since commonly FEM calculations are performed only for load cases that are defined by static design requirements these have been used also for the fatigue design. To avoid extreme conservatism, those static load cases have been selected for use in conjunction with the fatigue allowables which lie within the envelope of the fatigue design missions. The main parameters which have been considered were the load factor n_z, the roll rate, aircraft mass & configuration, altitude and speed. Exotic cases that are unlikely to occur during the aircraft life of the majority of the fleet have been deleted for the fatigue analysis process.

During the fatigue analysis the allowable stress has been compared with the calculated (applied) principal stress of the considered section. The ratio $\sigma_{allow}/\sigma_{applied}$ has been regarded as a measure for the fatigue quality and has been consequently called fatigue quality factor (FQF). A FQF $\geq$ 1.0 indicates sufficient fatigue life under design conditions.

It was the stress engineers responsibility to apply the allowable stress correctly during the sizing/stress analysis. Advice from the fatigue specialist has been available whenever requested.

5.2 Composite Structure

The primary and secondary structure of Eurofighter has been manufactured from CFC material to a large extent (Figure 4). About 80% of the outer surface has been built from composite materials.

Specific damage tolerance requirements and design criteria for the composite material have not been specified. However, being aware of the impact sensitivity of CFC material, allowable impact energies as design requirement have been defined. The design allowables have been determined to cover the negative effects on strength & fatigue of (non-visible) impact damages and manufacturing defects. Therefore the allowables are significantly below the theoretical material allowables for fatigue.

Specific fatigue analyses of the CFC components have not been performed but the acceptability of the fatigue and damage tolerance behaviour (e.g. growth of delamination) of the CFC structures has been verified by extensive structural ground testing.

6 STRUCTURAL GROUND TESTING

Structural ground tests are essential for the design and qualification of an aircraft. These tests range from simple coupon tests used to collect basic material properties to the full scale fatigue tests (major airframe fatigue tests, MAFT) used to justify the required structural durability and where necessary the damage tolerance behaviour of the complete structure.

For the Eurofighter program extensive fatigue tests have been conducted for the prototype and production aircraft. Production tests became necessary due to changes from the development phase with respect to the previous prototype fatigue test results, enhanced structural design criteria, manufacturing processes or the materials employed and general production improvements.

6.1 Specimen Tests

A large number of material tests were conducted in the early part of the design phase so that the appropriate materials and processes could be selected to meet the design requirements. Based on standardized [5] or in some cases complex specimens, constant amplitude or flight-by-flight tests have been carried out to gather fatigue data for the design and analyses. In addition to tests to establish basic material fatigue properties, tests also covered the effects of heat treatment, manufacturing processes (welding, high speed milling, chemical etching, super plastic forming SPF, etc.), joint configurations (e.g. material combinations, fastener systems) etc.

6.2 Component Tests

The development and production component tests had basically three functions: to support the verification of the structural design, to define those areas of the structure that need special attention and to minimize fatigue induced structural risks. These tests were scheduled so that there was sufficient time to incorporate structural improvements into the full scale fatigue tests as well as the service aircraft.

In general the Eurofighter component tests can be sub-divided into different sections depending upon the specimen type and the test aim as follows:

- Detail – representative of a local structure area of a component or feature (e.g. wing attachment frame lugs) and used to both validate new design concepts and derive design allowables.
- Subcomponent – a specimen functionally representative of a specific structural area (e.g. airbrake structure). These tests were used to validate new structural features and to confirm design allowables.
- Boxes – a specimen typical of a large section of substructure (e.g. centre fuselage - wing attachment box).

All component tests were simplified but representatively fatigue loaded by an adequate flight-by-flight program. Non-destructive inspections have been periodically performed to guarantee the detection of initial cracks in an early stage of development. Marker cycles as used in damage tolerance tests have not been applied.

6.3 Major Aircraft Fatigue Tests

The crowning glories as well as the touchstones of the accuracy and qualification of the Eurofighter fatigue design are the Major Airframe Fatigue Tests (MAFT) on representative airframe build standards. The main purpose of the MAFT test articles is to provide evidence of airframe durability under the required in-service loading by demonstrating a test fatigue life of 18000 test hours. Moreover, these tests also provide basic data for the applied structural health monitoring system as well as strain gauge measurements for the verification of the applied global FEM models for development and production.

The load simulation covers all load variations (aerodynamic & inertia) that are likely to affect the structural fatigue life, including manoeuvres, gusts, wing & fin buffet, airbrake operations, landing impact and ground operations, cabin pressure and also tank and air intake pressure. In Figure 5 an example is shown for the test loading of an asymmetric manoeuvre that is obtained from a computer simulation. The manoeuvre is represented by test load cases defined by the time slices 1 to 4.

6.3.1 Development Major Aircraft Fatigue Tests (DMAFT)

For risk reduction reasons a development major airframe static test (MAST, by EADS-CASA, Spain) and a development major airframe fatigue test (DMAFT, by EADS-MAS & IABG, Germany) were performed on prototype single seater build standard airframes from 1993 to 1998. The DMAFT test specimen comprised a complete airframe without equipment consisting of front, centre and rear fuselage, fin and two wings. For the DMAFT a total of 66 hydraulic actuators, 6 struts and 4 pneumatic pressure systems were used to apply the external and internal loads. The required fatigue life of 6000 FH has been proven with a scatter factor of 3.0. The resulting 18000 TH were simulated according to a flight-by-flight test program consisted of 771 different load cases and 3 missions with 17 different flights.

During the progress of the fatigue test a very detailed and extensive inspection program was applied. The object of this program was to detect fatigue damages already in their initiation phase and to monitor the propagation of some cracks and the growths of delaminations. Beside the daily walk around inspections, periodical inspections after every 1000 TH were carried out. Major inspections were performed after 6000 TH, 12000 TH and 18000 TH. In general, visual inspections were specified but more sophisticated methods such as eddy-current and ultra-sonic were required for specific areas. It has to be mentioned that during the daily walk around 50% of all damages were detected.

A total number of 128 different damage locations were found during the DMAFT. Subsequently performed stress and fatigue analysis revealed that 91 findings (62 fatigue cracks) have to be considered as representative. All detected fatigue cracks were unexpected and only in retrospect analytically explainable. Table 1 details the DMAFT test result.

	Damage Classification				
Test Hours	**Fastener**	**Minor**	**Significant**	**Substantial**	**Total**
up to 6000	6	15	10	0	31
6001 - 12001	10	14	3	1	28
12001 - 18000	3	19	7	3	32
Total	19	48	20	4	**91**

Table 1: Representative DMAFT Damage Locations

The majority of the CFC damages were small defects and classified as "Minor", which effectively remained stable and safe, for the entire duration of the test. None of the representative ones (manufacturing defects, impacts, handling damage, etc) needed repair. For the metallic damages, the majority were fatigue cracks with the remainder falling into the categories of migration, play, surface marking, fretting, etc. For the production aircraft, all the relevant DMAFT damages were thoroughly analysed. Under consideration of the advanced production aircraft requirements all critical locations were re-designed to be crack free within 3 life times.

The overall number of damages on the test was very low considering the prototype status of its maturity state. None of the damages have impaired the prototype flight test programme and none led to major changes for the production aircraft re-design.

6.3.2 Production Major Aircraft Fatigue Tests – Twin Seater (PMAFT)

As already mentioned above an additional production major airframe fatigue test (PMAFT) became necessary due to major changes from the development phase to the production phase.

A twin seat Eurofighter Typhoon airframe is currently being used for the PMAFT carried out at the BAE SYSTEMS test facility centre in Brough (Figure 6). To ensure a mature airframe the test specimen has been taken from the production line at the BAE SYSTEMS final assembly in Warton. Equivalent to the DMAFT, the PMAFT test specimen comprises also all major aircraft components and is subjected to a flight by flight loading spectrum at room temperature and without moisture conditioning. Aerodynamic and inertia loads for the various flight profiles are simulated as net airframe monitor station loads. In addition, inertia loads for specific structural items (engines, seat and pilot, undercarriage retraction/lowering etc.) are generated for these load cases. A set of cases was also generated to simulate flight dynamic buffet effects on the wing. Landing and ground operation loads from the undercarriage as well as parachute loading cycles are also included.

The required 18000 TH is simulated in 1000 TH blocks according to a flight-by-flight test program consisting of 28 different flights regarding mission and aircraft configuration. The flights are built up from over 700 different manoeuvres with an average of 4 load cases per manoeuvre.

During the DMAFT, fin buffet loading was simulated as a damage equivalent, quasi-static loading increment superimposed onto a symmetric manoeuvre load case. This method of load application was subsequently considered to be unrepresentative due to the way it is reacted by the overall aircraft structure. Therefore for PMAFT, the dynamic fin buffet loading is applied by a single electro-magnetic shaker driving the fin at resonance to achieve the fatigue relevant bending and torsion modes. The fin buffet increments are introduced in 6 identical blocks at 3000 TH intervals.

The aircraft is situated within a self-reacting test rig, mounted on 6 fixed reactions (three vertical, two lateral and one fwd/aft reaction). Spatial rotation and translation about and along the aircraft axes is prevented by the reactions. 102 hydraulic load introduction actuators are used to apply the aircraft manoeuvre loads, 101 of which are earthed to the test rig, the remaining actuator provides load between the centre fuselage and dummy airbrake rig. The 8 air pressurisation control systems are housed locally on the test rig. Permanent staging is positioned on the test rig around the aircraft to facilitate inspections of the structure and routine maintenance.

Strain gauge sensors have been fitted during the manufacturing stage by each partner company. The number of strain gauges has been scoped to be commensurate with the requirements of the PMAFT, SHM and also the static load cases that are undertaken in support of the FEM validation. The specimen has a total of 2139 strain measuring channels fitted. The dynamic strain gauge output from the complete flight-by-flight spectrum is used by the structural health monitoring system (SHMS) to define the test correlation factors.

The test status of PMAFT is currently about 5500 TH. The number of significant damages is very low. All the previous conducted fatigue tests and detailed fatigue analyses show now a positive impact. But nevertheless it should never forgotten that fatigue surprises can still happen.

6.3.3 Single Seater Fatigue Test (SIFT)

Parallel to the PMAFT a single seat Eurofighter airframe is currently being used for the single seat fatigue test (SIFT) carried out at the BAE SYSTEMS test facility centre in Brough, too. This test became necessary due to the partially non-common structure compared to the twin seat variant. The test article comprises the single seat front fuselage, the centre fuselage and a dummy rear fuselage.

The SIFT flight-by-flight test program is based on the PMAFT test program but considers the specific single seat front fuselage loads and load cases.

The test status of SIFT is currently about 9000 TH. The number of significant damages is also very low.

6.3.4 Other Qualification Tests

Besides the major airframe fatigue tests (PMAFT, SIFT) a number of component qualification tests were required for those items which are not embodied in the airframe test specimen, or replaced by a dummy, or not representatively loaded. The reasons for this are manifold and range from economic and technical restrictions to risk reduction reasons. For Eurofighter separate qualification tests have been conducted for the nose and main landing gear and for the control surfaces such as foreplane, slats and flaps. The qualification tests have been subjected to individual flight by flight loading spectra covering the specific component (system) fatigue requirements.

7 STRUCTURAL HEALTH MONITORING SYSTEM (SHMS)

The In-Service Usage Monitoring is an important airworthiness requirement to handle military aircraft safety. In contrast to civil aircraft the fatigue load spectra are changing frequently due to different tactical requirements, new missions, advanced aircraft configurations (e.g. higher masses) and different environments.

During the last decades the usage monitoring has grown from a simple g-counter to a highly complex and intelligent onboard system with the ability to monitor in real time various locations.

For Eurofighter BAE Systems has developed a high-capacity Structural Health Monitoring System (SHMS) consisting of an on-board system for the data acquisition and an off-board system for the data handling, analyses and storage. Each individual aircraft does have the complete functionality of the SHM and is monitored relative to the qualification tests.

8 CONCLUSIONS

For the fatigue design of Eurofighter the safe life philosophy has been adopted. Since the requirements are specified by the customer, i.e. the Ministry of Defence or Air Force, a generally good confidence in the "safe life" design may be presumed. Nevertheless, some customer driven damage tolerance aspects expand into the structural fatigue and durability criteria. Particular consideration to the material selection as well as an appropriate structural accessibility has been the answer from industry side. The required residual strength properties are covered by the structural "crack free" design for 3 life times.

From the analysis point of view, the fatigue damages which occurred on the DMAFT clearly show that a large portion of the fatigue critical sections were not recognised in the design process. The reason is that the stress analysis was not sufficient, whether it was not detailed enough, or the FE model inaccurate, or for whatever reason. Another considerable portion has to be categorised as "bad detail design" or "assembly induced".

Therefore, as an obvious conclusion it has to be stated that the comprehensive full scale fatigue testing as well as the subsequently performed tear down inspections are essential parts of the Eurofighter Fatigue Safe Life verification process. All fatigue sensitive locations were and will be re-designed to give a maximum confidence in the fatigue behaviour of the Eurofighter airframe.

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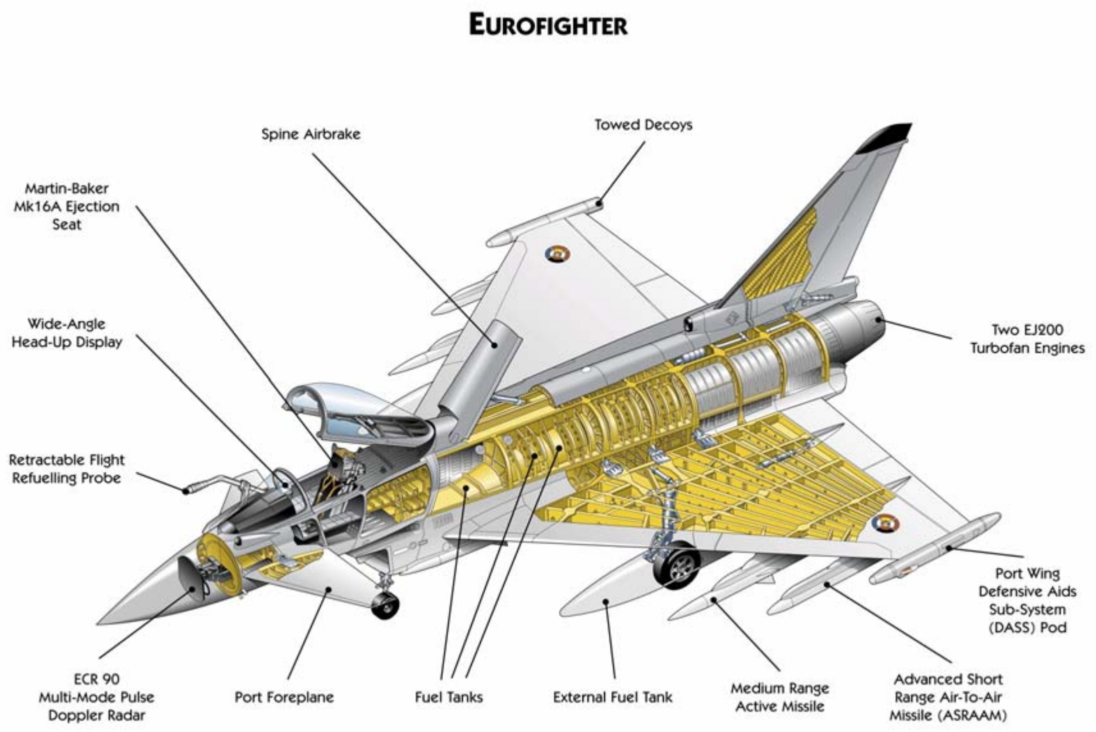

Figure 1: Eurofighter – General View

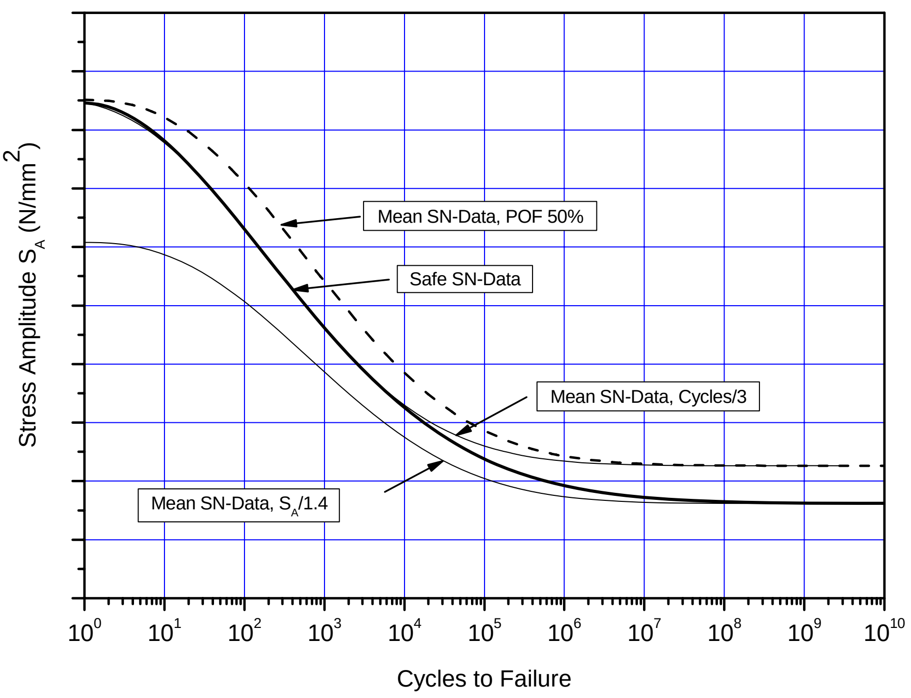

Figure 2: Generation of Safe S-N Curve

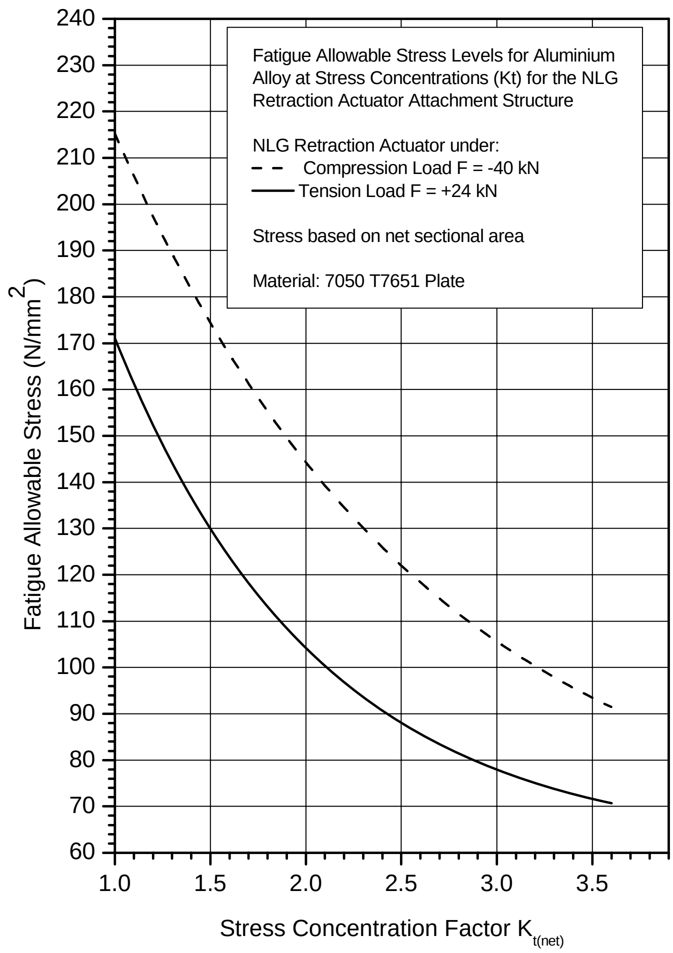

Figure 3: Fatigue Allowable Stress Levels

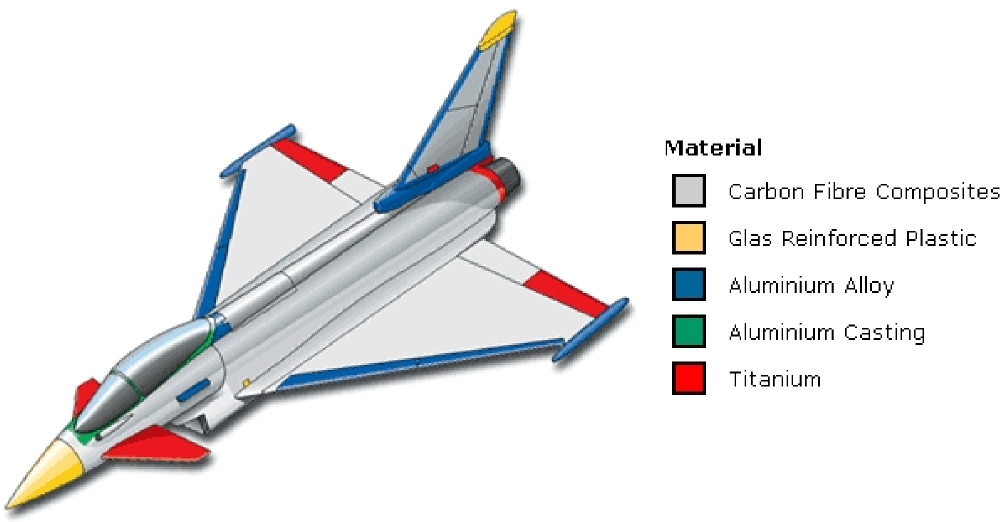

Figure 4: Eurofighter – Material Selection

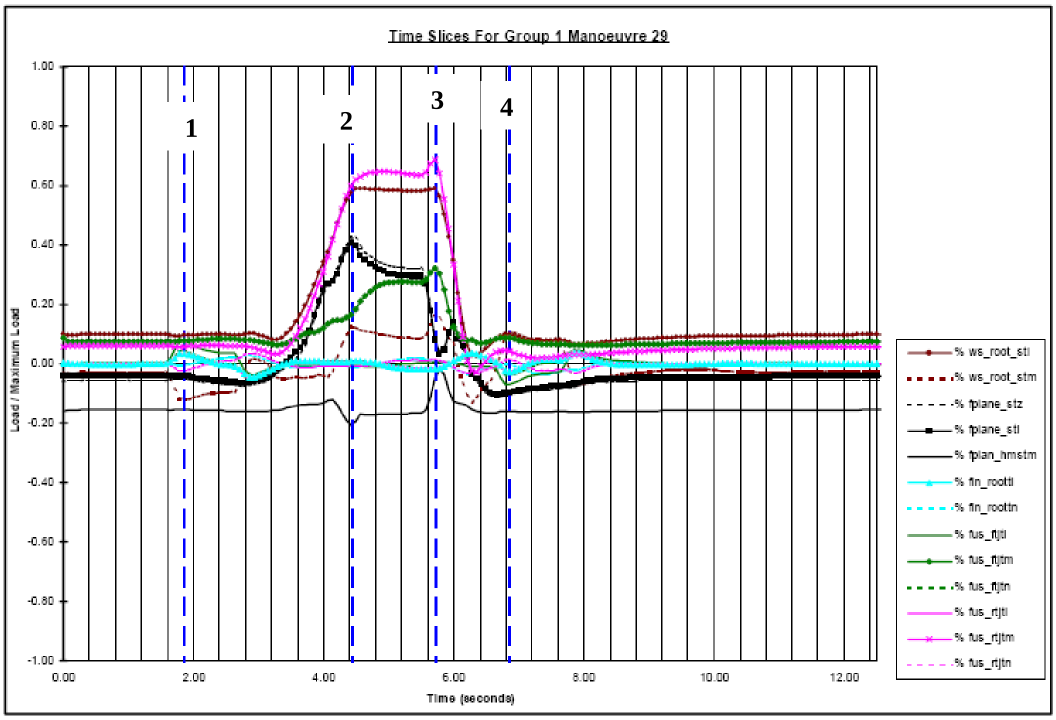

Figure 5: Asymmetric Manoeuvre – Time Slice Selection

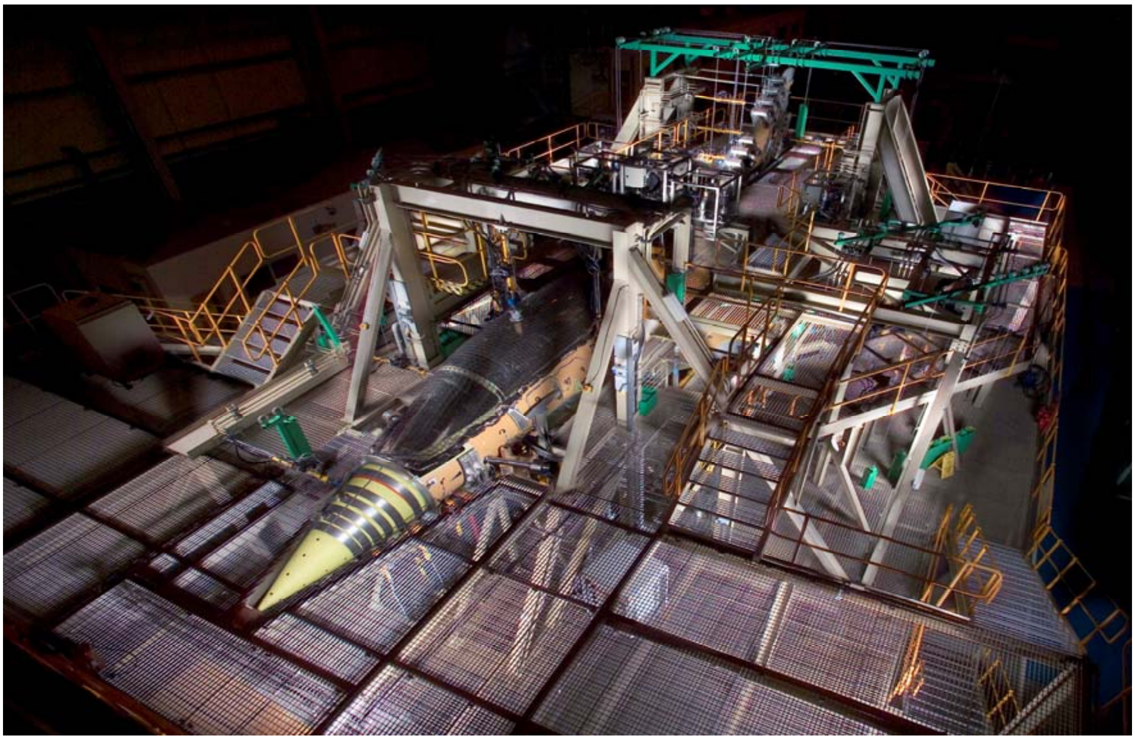

Figure 6: Eurofighter – Production Major Airframe Fatigue Test (PMAFT)