A.I.F.A. - ITALIAN ASSOCIATION FOR FATIGUE IN AERONAUTICS

DEPARTMENT OF AEROSPACE ENGINEERING - UNIVERSITY OF PISA

Review of aeronautical fatigue investigations carried out in Italy during the period April 2003 - March 2005

by
A. Salvetti and L. Lazzeri
Department of Aerospace Engineering
University of Pisa - Italy

This document summarizes the main research activities carried out in Italy about aeronautical fatigue in the period April 2003 – March 2005. The main topics covered are: load monitoring, fatigue of metallic structures, fibre metal laminates, full scale testing.

29th ICAF Conference, Hamburg, Germany, 6-7 June 2005

CONTENTS

1. INTRODUCTION

This paper summarises aeronautical fatigue investigations which have been carried out in Italy during the period April 2003 to March 2005. The different contributions have been arranged according to the topics, which are loading analysis, fatigue and fracture mechanics of metallic materials, fatigue behaviour of composites, joints and full scale component testing. A list of references, related to the various items, is presented at the end of the document.

The review is based on the activities carried out within the various organisations belonging to A.I.F.A., the Italian Association for Fatigue in Aeronautics. The authors gratefully acknowledge the fundamental contribution, which has made this review possible, given by several A.I.F.A. members, who are the representatives of Universities and Industries in A.I.F.A.

2. MEASUREMENT AND ANALYSIS OF OPERATIONAL LOADS

2.1 - AM-X life monitoring (Alenia Turin)

The life monitoring program for the AM-X aircraft is an activity that has been in progress for a long time and regularly information has been given in the various National Reviews; it is based on g-meter readings, together with configuration/mass analysis and mission profiles. With respect to the situation described in the last Review, where the data base included 108,000 flight hours, corresponding to 92,000 flights, the flight activity has made progresses, reaching 130,600 flight hours corresponding to 108,800 flights. The usage severity is measured by means of the Load Severity Index (L.S.I.), that is the ratio between the damage cumulated in a flight hour and the damage of an average hour of the reference spectrum. The analysis of the data, reported in fig. 1, is an update of the similar analysis carried out two years ago, and shows that the utilisation is very close to the design spectrum with about 27% of the Italian Air Force fleet flying with LSI grater than 1, i.e. the flown spectrum is more severe than the design one.

2.2 - Life monitoring of the TORNADO fleet (Alenia Turin)

This aircraft is in service since 1980. Alenia continues the Italian fleet fatigue management using its in-house developed computer program, based on g-meter readings and configuration/mass control, that has already been described in previous versions of the Italian National Review. This activity is performed in parallel with the Maintenance Recorder System, that is managed by the Italian Air Force: this is a monitoring system based on flight parameters recordings on board and fatigue life consumption calculation on ground, now on a PC. From the beginning of the monitoring activity, 205,800 flight hours were processed, corresponding to 150,000 flights. The analysis of the data of this large statistical basis produced a good knowledge of the fatigue consumption behaviour of the fleet. The average fatigue consumption rate of the fleet is quite low in comparison with the design one, with an average LSI that is steadily around a value of about 0.2 (see fig. 2), but, looking into more details, significant changes can be observed in the years among individual aircraft, fig. 3.

The general trend shows that the life of Tornado can be extended over the original design assumption of 4000 flight hours and on the other hand the individual tracking must be maintained. On this basis, a long term work, aimed at the re-assessment of the fatigue status of the aircraft, is on going, in order to guarantee airworthiness during future operational life which is expected to be extended for further 20 years.

In co-operation with other PANAVIA Partners the reorganisation of qualification data cumulated during the past years took place, identifying for each significant item all modifications applied; the job is now continuing with the identification of all the tests and analyses performed to sustain the qualification of each item.

Moreover, a great importance has been given to the evaluation of the fatigue consumption of items that are not specifically monitored.

For the wing, that is under Alenia responsibility, an in-depth investigation on some sub-components that were tested at sub-component level, was performed to re-assess their qualification process, that took into consideration the assumptions used for the full scale test of the whole aircraft. Analysis was performed on the back-up structure of the wing sweep actuator, the pylon alignment control rods, the flaps and their back-up structure on the wing box.

2.3 - EF Typhoon (Alenia Turin)

In February 2003 the first series trainer aircraft was delivered to the Italian Air Force, and so far 5 twin seater and 1 single seater aircraft have been delivered to the IAF. In total, the production reached the number of 30 aircraft delivered to European air forces. The monitoring of the IAF fleet usage has started and the comparison of flown spectra versus test spectrum shows an intense utilisation of the aircraft, fig. 4.

Moreover, the two Alenia prototypes (DA3 and DA7) are continuing the flight activity tests. For such two airplanes, a simplified structural fatigue consumption monitoring is being applied, using flight test instrumentation and comparing design spectra with flown spectra. Such a comparison shows that the prototypes are flying with a spectrum quite close to the test one. A specific monitoring of buffet loading is performed also, recording the time spent in flight conditions potentially prone to generate the phenomenon.

In co-operation with BAe Systems, Alenia performed the verification activity of the Structural Health Monitoring system (SHM), that is the on-board life monitoring system for the Typhoon. The SHM system, uploaded in the Interface Processor Unit of the aircraft, is programmed to perform 3 major functions:

- calculation of the Fatigue Index in 10 structural significant locations;
- collection of Auxiliary Data relevant to flight data (normal acceleration, roll rate, Mach number, aircraft mass, altitude, etc);
- identification of critical events, through the Event Monitor module that points out the significant structural events, in accordance with User's defined envelopes.

The SHM system has the capability of analysing up to 8 different event types.

In particular, the "Event Monitor" is the function that was checked by Alenia by means of an "end-to-end" testing activity, to reach the validation of the SHM system. The end-to-end testing activity consisted in the analysis of the Instrumented Production Aircraft flight data, with the aim of finding the significant structural events during flight and of comparing them with the results provided by the SHM. As anticipated in the last National Review, the defined envelopes, tested in this activity, are:

- Normal acceleration versus Roll rate;
- Sideslip angle versus Angle of attack;
- Foreplane angle of attack versus Dynamic pressure;
- Sink rate versus Mass.

Two examples used for analysis are given in figs. 5 and 6.

Recently, after the qualification of the SHM system and the early aircraft deliveries, support to Italian Air Force was given in order to facilitate the reading of results and the correct interpretation of "event monitor" messages.

2.4 - M346 prototype flight activity monitoring (Aermacchi)

The M-346 had its first take-off on 15 July 2004. Up to now, the aircraft collected 55 flights for a total of 60 flight hours and 102 landings, during which a complete operating test campaign has being performed. The monitoring of load environment and life usage started at the same time.

In particular, fatigue consumption monitoring is being performed by means of n_z spectrum comparison. Life usage and damage monitoring will be obviously part of a more sophisticated software analysis and monitoring activity, but this first simple check can give an immediate sensitivity on the accuracy of the predictions and on the possible actions to be programmed. The measured n_z spectrum, in the current phase of the flight envelope expansion, results lower than the design one, as shown in fig. 7.

2.5 - C 27-J Individual Aircraft Tracking Program (Alenia Naples)

The C 27-J aircraft is a derivative of the Alenia G222/C27A aircraft, that has been certificated according to the JAR/FAR requirements. The TC (Type Certificate) was achieved on June 2001.

Alenia Aeronautica, in charge of the Structural Design, is responsible of all the activities necessary to guarantee the C 27-J In-Service Structural Integrity.

In general, the structural design and the related Maintenance Plan, which assure the Continued Airworthiness, are based on a specific set of Typical Missions. This usage scenario needs to be investigated and confirmed during the operational life; significant discrepancies between the "Design Hypothesis" and the "Real Usage" can be mitigated by a proper updating of the Maintenance Plan.

For the above reasons, for the C 27-J an I.A.T.P. (*Individual Aircraft Tracking Program*) has been defined in order to track, aircraft by aircraft, the In-Service Usage through the "On Board Monitoring" of the most significant flight parameters.

Starting from these recorded data, the IATP software determines the "Stress-Time-Histories" on 9 specific structural locations (Control Points). The nine Control Points selected are:

1 - Crew Door Surround: Skin Corner

2 - MLG Attachments: Fwd Lwr Lug

3 - HT Attachments: F/S Upper Lug

4 - C-Wing Upper Skin : Door Cutout Rib # 3

5 - C-Wing Lower Skin: Joint at Rib # 3
6 - Wing-to-Body Attachment: F/S Lug Rib # 3
7 - Nacelle Attachments: F/S Lower Lug Rib #13
8 - Cargo Ramp Hook: Hook at Sta. # 1012
9 - Vertical Tail: Skin at VT Root

The “Stress-Time-Histories” are used to determine the Fatigue Life and the Crack Growth Life of each Control Point. A comparison between the Fatigue and Crack Growth Lives evaluated according to the “Design Hypothesis” with respect to the “Real Usage” allows to determine both Residual Fatigue Life and the Residual Crack Growth Life.

The above Data Management and Comparison is produced by an I.A.T.P. Computer Code, that is based on the following Routines:

A *Loads Routine*, which manages the Input phase, the “pre-processing” of the In-Flight recorded parameters and produces the In-Flight loads evaluated according to the monitored data;

A *Stress Routine*, which evaluates the Stress-Time-History derived from the local loads coming from the previous routine on each Control Point;

A *Fatigue Routine*, which evaluate the Fatigue Life “spent” during a certain period of utilisation and compares it to the Fatigue Life expected during the usage assumed in the Design Hypothesis;

A *Crack Growth Routine*, which evaluates the Crack Propagation of an initial defect and compares it to the Crack Growth assumed in the Design Hypothesis.

The Main Outputs are:

- The Stress-Time-Histories for each control point;
- The Load Severity Index (i.e. the ratio between the Real Fatigue Life and the Design Fatigue Life);
- The Residual Fatigue Life;
- The Residual Crack Growth Life.

According to the above Outputs it is possible to determine:

- The End of Life for the “Safe-Life” Structural Components
- The Updating of the Maintenance Plan for Damage Tolerant Structural Components

3. METALS

3.1 - Fatigue behaviour of notched and un-notched materials

3.1.1 - The effect of interference fit fasteners on the fatigue life of central hole and pin loaded hole specimens (Uni. Pisa)

A basic research activity has been carried out at the Department of Aerospace Engineering of the University of Pisa to study the effect of interference fit on the fatigue life of simple coupons containing a hole. For this purpose, two types of specimen have been used: a no-load transfer specimen (the hole was filled with a pin, inserted with different levels of interference) and a load transfer specimen (the pin inserted in the hole acted as a lug). All the specimens were made of 2024-T351, thickness 1.6 mm. During the insertion of the pin, a sleeve was interposed in the pin/hole contact, to avoid hole damage, and was obviously left in the hole for the whole test duration. FTI (Fatigue Technology Inc., Seattle) split sleeves were used for this purpose. Fatigue tests were performed under a Constant Amplitude loading, with a 0.1 stress ratio. In both specimens, fatigue test results (shown in figs. 8 and 9) clearly demonstrated the beneficial effect of interference fit on the fatigue resistance, up to the maximum value examined, 2.5%.

The stress field around the hole, due to the interference and the external applied load, was analysed in detail by means of a 3D finite element model. Elasto-plastic FEM results demonstrated the well-known effect of interference fit fasteners on reducing the local stress range in the critical location. By increasing the interference level, the circumferential stress range remains practically unchanged, while the mean stress decreases, due to plasticity effects. Fig. 10 shows the stress distribution in the critical location, in terms of tangential and radial stresses. Interference fit produces a biaxial stress state, with radial compressive stresses that must be taken into consideration to predict the fatigue life. In the present case a simple criterion, based on the hoop strain, correlated quite well the fatigue results.

More details can be found in [1] and [2].

3.1.2 - Fatigue behaviour of Cold Worked holes (Uni. Pisa)

A research activity started at the Department of Aerospace Engineering of the University of Pisa on the fatigue analysis of cold-worked holes. Comparative fatigue tests on open hole specimens, material 7075-T73, thickness 2.3 mm clearly demonstrated the beneficial effect of cold working on fatigue life. Additional tests demonstrated the even better effect of "double cold working". Several studies demonstrated strong differences in the residual stress field of cold-worked holes between the mandrel entry and exit faces. FEM calculations, experimental X-ray diffraction measurements and crack propagation rate measurements demonstrated that the residual stress field is more effective on the mandrel exit face than on the entry face [3,4,5]. To limit the through-the-thickness variation of the residual stress field, some authors [6] suggested double cold-working: the operation is repeated twice, exchanging the mandrel entry face. The results obtained show a further beneficial effect compared with single cold working, fig. 11.

FEM analysis was used to better understand the residual stress field in cold-worked holes; the process was simulated both with a radial expansion of the hole and, more realistically, by an axial displacement of the mandrel (see fig. 12). In the last case, important differences between the entry and the exit faces residual stress fields were observed. Other aspects under examination are the asymmetry in the residual stress fields due to the sleeve split and the effect of the final reaming. Further details will be presented in [7].

3.1.3 - Evaluation of Hot Isostatic Pressing Technology applied to castings in A357 (Agusta)

It is known that similarly to other alloys also the fatigue performances of cast aluminium alloys can be enhanced by a Hot Isostatic Pressing (HIP) process. This process consists basically in the pressing of the component in a special autoclave at high temperature (less than 500 °C) and pressure (more than 300 bar). By this process the micro-porosity that exists internally to the casting is literally healed and its effect disappears. Internal porosity of big size and other defects may or may not remain depending on the size, while all surface defects are not affected by the process.

This is fundamentally the limit of this process, because the fatigue behaviour is strongly influenced by the external surface condition. Therefore, to improve the quality of the casting surface can have positive consequences on the fatigue life, as this may eliminate defects that potentially influence the whole performance. The tests carried out in the past at Agusta on Hot Isostatic Pressed specimens, i.e. on specimens machined from HIP sand cast rods (shown in the last National Review and repeated in fig. 13), have been now enriched by adding the evaluation of “As cast specimens” of rather complex shape. It comes out quite clearly that the advantages of pressed castings would be substantial only if the most stressed areas have a quite good finishing, such as to eliminate possible surface defects. In the case of “As cast specimens”, the “As cast” and the “Hot isostatic pressed” specimens gave very similar results, as shown in figure 14.

3.1.4 - Fatigue behaviour of Aluminium Alloy 2024-T351 in abnormal thermal conditions (Agusta)

The aluminium alloys may have different performances at elevated temperatures due to several metallurgical factors. Some specific alloys have been developed for operating in elevated temperature environment and particularly for supersonic airplanes. The behaviour in temperature of the most common 2024 alloy has not been investigated from the fatigue point of view, although creep and static strength data are available.

Experimental tests carried out at Agusta have confirmed, as expected, that the exposure of a bar of 2024-T351 brings to a meaningful drop in the static tensile properties such as UTS, YTS and %Elongation, even in room temperature tests carried out after exposure (see figure 15 referring to an exposure of 8 hours at 250°C in air). Fatigue performance at room temperature in presence of notches (Kt=3, R=0.1) is not affected in the same way. As it is possible to see from the highest of the fatigue curves shown in figure 16, the difference in room temperature fatigue before and after preliminary soaking at 250°C for 8 hours is negligible. Tests were also run in high temperature conditions, as shown in the same figure, giving lower fatigue limit results which are in any case quite less than the drop in static properties found in literature for those conditions.

3.1.5 - Evaluation of High formability SP-700 Titanium Alloy (Agusta)

The use of Titanium alloys in helicopter components is continuously increasing due to its capabilities to withstand dynamic loading and severe environmental conditions. The possibility to be applied without the need of a surface treatment is also well appreciated. A new commercially available Titanium alloy (Ti-4,5Al-3V-2Fe-2Mo) is suitable for machining of small/medium size components from plate and/or bar. This alloy is offering superior fatigue resistance properties due to its very fine grain structure. From the metallurgical point of view, it is an α/β alloy, which like the classical Ti-6Al-4V can be applied in the annealed condition.

The static properties of this alloy appear interesting, especially from the point of view of fracture toughness. A preliminary evaluation of the fatigue behaviour has been carried out at Agusta on un-notched specimens, subjected to an

R=0.1 CA loading, showing superior fatigue limit compared to the traditional Ti-6Al-4V, from plate as well. Figure 17 shows both S/N curves obtained by rotating bending. Other tests for crack propagation resistance evaluation showed that from this point of view both alloys are equivalent.

3.1.6 - Application of Titanium alloys to rotorcraft fatigue critical parts (Agusta)

Information about this activity, focused to investigate the possible improvements to fatigue crack nucleation resistance and mainly to fatigue crack propagation resistance of Ti-6Al-4V alloy solution treated in β phase, was already given in the last National Review. In particular, some preliminary results obtained from rotating bending tests on un-notched specimens were presented. The investigation has been completed in the last two years, by carrying out tests in axial fatigue (see fig. 18, relevant to load ratio R=0.1). Tests were run for other load ratios as well, giving the same type of results, whereas the results from tests on notched specimens did not show the same improvement. Extensive metallurgical and fractographic analysis was carried out, also in support of the crack propagation tests, which demonstrated an improvement in terms of propagation threshold of a factor two in comparison to the annealed condition (fig. 19).

3.1.7 - Surface treatments alternative to Cadmium Plating (Agusta)

Many mechanical components of helicopters need to be produced using low alloy steels which are inherently not resistant to corrosion. So far, the corrosion protection has been obtained by cadmium plating, which is well known as an health hazard. Anyhow, from the point of view of substrate protection, it is very effective and therefore it is difficult to replace with alternative processes: its corrosion potential, similar to aluminium, makes it ideal for interfacing steel and aluminium, which is the most common situation, while on the other hand it is anodic with respect to steel and then provides the possibility to anodically protect the substrate also in case of local damage of the layer.

With the aim of collecting information on the possible alternatives to cadmium which have been developed, in some cases outside the aerospace community, other electro-chemical deposition processes were investigated at Agusta and namely the application of Zn Co Fe and the application of Zn Ni. In addition to the issues regarding pure corrosion protection (electrochemical potential, hydrogen embrittlement, primer grip, environment resistance, self lubricating characteristics) some specific issues relevant to fatigue were addressed and namely fatigue behaviour of coated parts in air and in corrosive environment.

The latter has required a specific experimental set up with the application of a environmental cell conceived to keep a salt solution film (NaCl 3,5 %, with oxygen, T=27°C, pH 6,4÷7,2) on the specimen gauge length during rotating bending fatigue. The rotation speed was reduced to 50 r/sec in order to enhance the environmental factor.

Fig. 20 shows the results obtained with this test set up: starting from the fatigue curve of the uncoated material in air, the environmental effect can be easily seen at longer cycles/exposure times, which separate quite sharply the performance of cadmium, Zn Ni and Zn Co Fe protections.

3.1.8 - Force Mate bushing evaluation (Agusta)

An extensive test plan (more than 100 fatigue tests) was carried out for fatigue and Damage Tolerance evaluation of Forcemate ® bushings, applied in aluminium and titanium lugs, mainly for rotors applications in the AB139 helicopter. The objective of the test program was to assess the influence on the fatigue strength of the installation interference (two levels were investigated), as well as the effect of defects (0.15 and 0.25 mm defects were introduced in the hole, prior to the bushing installation). The Forcemate bushings provided an important contribution in improving the durability of mechanical parts and in demonstration of DT capabilities.

Fig. 21 shows the results relevant to the pristine holes in 7475-T7351 alloy, and the effect of the interference level can be appreciated; an increase of about 30% in the fatigue strength is observed, passing from the minimum to the maximum interference level. The improvement of the Forcemate® bushings over the standard bushing installation is anyhow quite remarkable.

The results of the Ti-6Al-4V lugs are considerably different, not only because the curve shape obtained is different from any other standard curve for this material, but also because there is almost no difference between results from minimum and maximum interference specimens. In addition, the improvement with respect to traditional bushing installation is present only in the range 10E5 – 10E7 cycles, and is of much smaller intensity.

A paper on this activity was presented at the 2004 European Rotorcraft Forum in Marseille (France), [8].

3.1.9 - Fatigue behaviour of FSW Aluminium-Lithium butt joints (Univ. Pisa)

A cooperation between the Department of Aerospace Engineering and Alenia-Space took place, with the objective to evaluate the fatigue behaviour of 2195-T8 Friction Stir Welded (FSW) joints. The investigation obviously was completed by tests on the base material. The fatigue resistance of the material was high, but anomalous crack behaviour was observed (fig. 22): after nucleation and initial propagation, fatigue cracks deviated in the longitudinal direction as a consequence of the "stratified" structure of the material. Fatigue tests in the Short Transverse (ST) direction were carried out to point out the possible consequences of the stratified structure. Very small specimens were machined, from a plate of 13 mm in thickness. The results obtained, fig. 23, show the lower fatigue resistance of the material in the ST direction in comparison with the longitudinal direction. Anyhow, this behaviour was observed also in other aluminium-lithium alloys.

Fatigue tests, carried out on FSW joints, demonstrated the relatively high resistance of this type of welded joints, in this material. Tests were carried out on butt joints welded with single and double pass. Double pass welding is necessary to complete circumferential welds on cylindrical elements, as in typical space applications, like those of interest for Alenia Space. A special retractable pin tool was used to avoid the typical hole at the end of the weld bead. Some specimens were machined in order to have the weld closure in the center. The test results show that double pass and weld closure are not critical from the fatigue point of view, fig. 24 [9, 10].

3.2 - Crack propagation and fracture mechanics

3.2.1 - Fracture Mechanics behaviour of Friction Stir Welded Al-Li flat panels (Uni.Pisa)

The investigation on the fatigue resistance of 2195-T8 FSW joints, described in a previous paragraph, was completed by fracture mechanics tests. Crack propagation tests demonstrated the good damage tolerance properties of the base material, when compared for instance with 2024-T3, fig. 25. The crack propagation rate along the weld bead was slightly higher than in the base material, fig. 26, while instead a strong increase in the crack propagation rate can be observed when a defect propagates across a weld bead, due to the welding residual stresses, fig. 27. These stresses were measured by a destructive method: strain gauges were bonded in the middle section of a plate, which was subsequently sectioned to allow the internal stresses relaxation. By using the analytical expression of the stress intensity factor produced by the residual stress in a weld bead, [11], good prediction of crack propagation was obtained by starting from the properties of base material and residual stress values.

3.2.2 - Damage tolerance assessment of the M346 wing to fuselage attachment (Aermacchi/Uni. Pisa)

A new trainer military aircraft, M346, is currently under development at Aermacchi. The aircraft will be certified as Damage Tolerant; the design life is 15000 flight hours. Some tests were performed at the Department of Aerospace Engineering of the University of Pisa on a critical element, to verify Damage Tolerance calculations.

Among others, the wing-to-fuselage connection is one of the most significant elements from the fatigue point of view. Spars, integrally machined, are connected to integrally machined frames by two lug/fork joints; both elements are made of 7050-T7451 aluminium alloy. High interference bushes, ForceMate®, produced by FTI (Fatigue Technology Inc., Seattle) are used in lug/fork connections.

The experimental activity was carried out on two different specimens. The first one, a Compact Tension specimen, was used in constant amplitude crack propagation tests to verify the data contained in NASGRO, the software used for Damage Tolerance evaluations. The results obtained demonstrated a slightly better behaviour of the material compared with the data contained in the NASGRO library. Besides, variable amplitude (VA) loading tests were carried out with a sequence simulating the loads acting in the lower wing skin near the wing root. The sequence is composed of 178 different flights; the results obtained from these tests are useful to evaluate the retardation effects of the load sequence.

The second type of specimen was a lug/fork joint, designed as the actual joints present on the aircraft (figs. 28 and 29). Both constant and variable amplitude loading fatigue tests were carried out in this case too, for a total of 18 tests. Fig. 30 shows the first flights of the time history used in VA loading fatigue/crack propagation tests. The results obtained clearly indicated the beneficial effect of ForceMate® bushes in comparison with standard shrink fit bushes, fig. 31. Under the application of actual loads, no crack propagation, or very slow crack propagation, was observed, even when a 1.27 mm spark eroded start notch was introduced. For this reason, larger defects, such as corner cracks up to 6 mm in depth, were introduced. Nevertheless, the crack propagation life was about four times longer than the design life, fig. 31.

Anomalous crack shapes were observed; particularly, cracks grow faster in "c" direction (surface) instead of the "a" direction (depth), fig. 32. This event was observed also in specimens containing very low interference shrink fit bushes and subjected to CA loading, so it can not be put in correlation with ForceMate bushes or variable amplitude loading. Different factors were considered to explain this behaviour, such as pin elasticity, friction coefficient between pin and hole and clearance between pin and hole. Recent analysis have show that the material used has a stratified structure in the thickness direction, fig. 32, which is probably responsible of the low crack propagation rate observed in this direction. Additional tests will be performed to quantify this effect.

More details are reported in [12] and [13].

3.2.3 - Development of a Flaw Tolerance helicopter fatigue design methodology (Agusta)

Fatigue certification according to the JAR 29 Rules require compliance with the Flaw Tolerance requirements. Agusta preferred method for compliance with Flaw Tolerance requirements for dynamic components is the adoption of the "no damage growth" concept. The typical flaw size assumed is a corner or a semi-circular crack of radius r = 0.38 mm, for parts exposed to accidental damage in flight, and a smaller flaw of radius r = 0.25 mm for parts protected in flight, after maintenance inspections. In a paper presented at the 2003 ICAF Symposium, [14], an efficient method to determine the threshold ΔK was illustrated; in the last two years, the material data base for flaw tolerance was fully developed and now provides Kitagawa diagrams covering at present all the materials applied in fatigue critical parts. They are:

Al alloys:	7475-T7351, 7075-T7351, 7050-T7452, 6061-T4 and T6, 2009, A357-T6
Steel:	4340 1250 UTS, 17-4PH H1025, 15-5 PH H1025
Titanium:	Ti-6Al-4V annealed

An example of Kitagawa diagram for 7475 is shown in fig. 33.

Most of the Fatigue and Flaw Tolerant methodologies developed in the latest years were successfully applied in the programs for the Civil Type Certificate of AB139 and the Military Qualification of NH90. The approach is fully consistent with the proposed new rule FAR 29.571, that should be published by FAA within summer 2005.

A summary of the approach will be addressed in the paper for the ICAF 2005 Symposium 'Flaw Tolerance Assessment of Rotorcraft for Civil Certification', by U. Mariani and M. Vicario (Agusta).

3.2.4 - Development of a probabilistic fatigue design methodology (Uni. Pisa)

The Department of Aerospace Engineering of the University of Pisa (UP) was involved in ADMIRE (Advanced Design concept and Maintenance by Integrated, Risk Evaluation for aerostructures), an European research program aimed at the research, development and validation of tools for probabilistic analysis in fatigue aircraft design. In this context, UP developed and validated a computer code, named PISA, that can simulate the fatigue behavior of typical aeronautical components, such as riveted joints and stiffened panels, from the beginning of the life up to the failure. This code was already presented in previous ICAF Symposia and National Reviews, but in these last two years the statistical distribution of the random parameters used as inputs for the code, in particular the distribution of the Equivalent Initial Flaw Size and the parameters for the description of the crack growth law, were investigated.

The EIFS distribution was obtained starting from experimental fatigue cracks in simple strip lap joints with a simplified draw-back procedure; a very refined crack growth analysis method requires to consider many parameters, such as load transfer, secondary bending, rivet squeeze force, joint flexibility, friction, etc, which for practical reasons cannot be implemented in a Monte Carlo method. Therefore, a simplified method has been applied for the draw-back procedure and, obviously, for the propagation analysis. In the period of the present Review, a great effort was dedicated to the assessment of pro's and con's of the possible simplifications that can be introduced to describe the stress distribution inside the joint.

As the tests for the crack growth law characterization were carried out in the central ΔK range, the Paris law has been selected; different statistical models have been considered for the evaluation of the C and m parameters.

The code uses the EIFS approach to transform the nucleation and propagation phases into a single propagation phase starting from an 'equivalent' initial crack dimension that is characterized by a statistical distribution, derived from a set of experimental test results on simple coupons by means of a draw-back procedure. Starting from it, for complex components such as lap joints or panels the code can simulate the growth of the cracks and the final failure. Typical outputs for the code are the crack size distributions at a given number of cycles (fig. 34) and – last but not least – the distribution of the fatigue life. This approach was validated by means of the comparison with experimental test results, fig. 35.

In addition, the code can be used to plan the maintenance actions for a typical aerospace component, such as a lap-joint, and to compare the benefits of a risk assessment approach rather than the 'classic' damage tolerance or safe life approach for fatigue life design.

4. COMPOSITES AND FIBER METAL LAMINATES

4.1 - Metal Matrix Composites: SiC particles reinforced Aluminium alloy (Agusta)

The continuous effort in the research of weight saving solutions is highlighting a new class of materials: Metal Matrix Composites. Those materials have been studied in various forms for long time. The material reinforcement obtained by particles in a metallic matrix lends itself to the same applications where traditionally mechanical parts obtained from bulk material and totally or partially machined are traditionally applied. The presence of particles increases the material stiffness with reduced or nil effect on the total density, at the same time it is usually possible to find some improvement in the fatigue performance as well, although not so large as for the stiffness.

A specific MMC (alloy 2009 with SiC particles) has been investigated at Agusta. It is obtained by powder metallurgy technique, where the correct mixture of matrix and reinforcement is present. The obtained billet can be extruded and then forged to the near net shape. The investigation has covered many aspects, such as quality control, homogeneity, workability, fracture toughness, corrosion and, of course, fatigue.

Fatigue tests where aimed at assessing whether for two similar components it was possible to obtain a reliable increase in terms of fatigue limits and whether the threshold of crack initiation from defects was comparable with the existing alloys. Figure 36 reports one of the obtained characteristics. The S/N curve which is reported is relevant to the 15% reinforcement particles concentration and shows on the same diagram all the results relevant to longitudinal and transverse specimens, anodised and not anodised. As it can be seen from the reported experimental points, none of those factors influences the fatigue behaviour of the material. Fatigue tests carried out on a traditional alloy (7475-T73) and starting from a similar component give a lower limit in the order of 20%.

4.2 - Fatigue crack propagation in Glare panels under constant amplitude loading (Uni. Pisa)

Fatigue crack propagation tests were carried out on six different configurations of Fibre Metal Laminates, using 2024-T3, thickness 0.3 and 0.4 mm, 7475-T761 thickness 0.3 mm, and the common S-2 glass fibre system. Different lay-up and number of glass fibre layers were investigated. Constant amplitude loading was applied as a first evaluation. The results obtained show once again the much lower crack propagation rate in FML panels in comparison with monolithic aluminium, fig. 37.

Additional details are given in [15].

4.3 - Residual strength of Glare flat panels of various dimensions (Uni. Pisa)

Within the framework of the DIALFAST 6FP project, funded by the EU, the Department of Aerospace Engineering of Pisa is engaged in a collaboration with Alenia Aeronautica to study the damage tolerance behaviour of advanced Fibre metal laminates. For this purpose, an experimental program has been defined to study the residual strength of flat panels in FML. The major technical problem is linked to the selection of the test standard to be used: it is quite common to use the standard test practice developed for the metals, even if the presence of internal glass fibre layers strongly modifies the constitutive behaviour and the fracture mechanisms.

In this particular experimental activity, the R-curve methodology has been adopted, which requires to measure, during the performance of the test, carried out under displacement control, the COD in the crack centreline and the position of the crack tip. There are two possible methods to define the R-curve, which are based on two different methods to keep plasticity effects into account, so defining an equivalent “effective” elastic crack length. The first one is based on the use of the COD measurements, and relies on a relationship (derived for ideally elastic and isotropic material) that links the COD to the crack length; the tuning parameter is the elastic modulus, which can be fitted in order to obtain the initially measured crack length. The second one is based on the use of the Irwin plastic zone size correction for obtaining the “effective” crack length, which keeps into account of the larger panel compliance, as a consequence of the presence of a plastic zone. In this second case, the tuning parameter becomes the yield stress, which is quite questionable, since the stress-strain curve of a FML is typically a bi-linear plot.

The purpose of the test program was to assess the invariance of the R-curve obtained from panels of different width and therefore two panel geometric configurations were defined (W= 800 mm and 1200 mm). Six FML materials were used to manufacture two samples for each geometry, that were tested starting from $2a_0/W$ of 0.25 and 0.33. The tests were carried out under displacement control conditions and the digital controller of the actuator (capacity: 1500 KN) interacts with a PC, that at each displacement step acquires a picture from a videocamera and stores information about load cell, the actuator LVDT, the clip gauge used to measure the COD. All the test data are analysed after the end of the test. The results obtained allow to assess the influence of the specimen width on the R-curve derived: fig. 38 shows results, elaborated using the Irwin correction, coming from a single FML material, but three different panel widths (400 mm panel results were available from a previous test program).

The two procedures for the analysis of the data collected in the test (COD compliance method and Irwin plasticity correction) quite often produce R-curves that are almost identical. An example of this result is shown in Fig. 39, relevant to the same material already shown in Fig. 38.

4.4 - Influence of temperature on the fatigue behaviour of FML (Milan Pol.)

A research activity has been carried out at the Department of Aerospace Engineering of the Milan Polytechnic on the manufacturing processes of Fibre Metal Laminates, with particular attention being paid to the joining techniques, the behaviour after ageing and the impact resistance.

The most common lay-up has been considered, i.e. the so called Glare 3, 3/2, that is composed by three metal layers, embracing two couples of glass fibres layers (0/90). For the metal layers, thin 2024-T3 sheets, 0.3 mm thick, have been used, while the glass fibres / epoxy resin single layer was about 0.2 mm thick. The total Glare 3 - 3/2 – 0.3 thickness was therefore about 1.7 mm. All the fatigue tests have been carried out using a CA load with R=0.1.

A preliminary investigation on the fatigue performance was carried out; the influence of the temperature was assessed, by carrying out tests at RT, at 75 °C and -50 °C. Fig. 40 shows the results, that point out that the best performance is at -50 °C, while the high temperature performance is the lowest.

Also joints have received attention, and in particular bonded joints; the double strap butt joint, the configuration that generally has the best performance, has been fatigue tested. The failure mode has always been in the adhesive and the results do not show a particular temperature influence, particularly at low number of cycles, while a slightly better behaviour at low temperature can be observed at high number of cycles. Fig. 41 summarizes the results, in the form of the best-fit lines.

One of the most interesting characteristic of the FMLs is linked to the possibility of obtaining very long panels, limited in length only by the autoclave dimensions, by means of internal splices, made possible by the Self Forming Technique. Among the various configurations, an internal splice with overlaps of 12.7 mm of the couples of sheets has been selected for a detailed examination. In this case, the failure mode is progressive. The results obtained do not show clear trends, because the fatigue strength is influenced in two separate ways by the temperature: at high stress, longer fatigue lives are associated with low temperature tests, while at low stress levels, the best fatigue performance is shown by the RT tests. Fig. 42 shows the trend in the results.

Riveted joints are commonly used for the FMLs, and therefore the study has included also a simple lap joint, with a single column of two rivets. Protruding head rivets in 2117-T3 Al alloy have been used. Only RT tests have been carried out in this case, and the results are shown in fig. 43. The fatigue endurance limit is about 20% of the static strength. The failure is the result of many damage processes, with evidence of fatigue crack in the outer layers, in the hole net section, but the presence of intact fibres is capable of retarding the failure of the joint, that anyhow takes place for rivet head cut, as in the static tests.

5. JOINTS

5.1 - Fatigue study of a frame-to-stringer bonded connection (Uni. Pisa)

This activity was carried out within the DIALFAST 6FP project, funded by the EU and aimed at the development of innovative Fibre Metal Laminate systems. This particular activity was dedicated to the assessment of different frame-to-stringer bonded connection, [16]. For this purpose, 52 static and fatigue tests have been carried out on bonded "L-Pull" specimens. This specimen (fig. 44) is representative of the connection between a stringer and the external skin of an aircraft fuselage, in correspondence with a frame intersection. Both the skin and the stringer were made of Fibre Metal Laminates: the skin is a FML3, 3/2, 0.3, 2024-T3, while the stringer is a FML2, 3/2, 0.3, 2024-T3. Two different adhesive systems have been examined: 3M Scotch-Weld™ Structural Adhesive Film AF-163 and Loctite Aerospace Hysol® EA 9696. Besides, two bonding procedures have been considered: co-bonding of the stringer during the skin curing cycle and secondary bonding between pre-cured skin and stringer. In any case, the stringer is cured first.

The tests demonstrated the higher resistance of the adhesive EA-9696 with respect to AF-163 both from the static and fatigue point of view, fig. 45. Whichever the adhesive system, secondary bonding produces thicker adhesive layers, characterized by lower stiffness and higher resistance to static loads when compared with co-bonded joints. This is a consequence of the lower pressure applied during secondary bonding, in comparison with the co-bonding process (2.5 bars vs. 6 bars).

Fatigue results were comparable for EA-9696 secondary bonded and co-bonded joints, while in the case of AF 163, co-bonded joints behave better than secondary bonded joints.

Additional fatigue tests were carried out under low frequency cycling, f=0.0222 Hz. The load cycle was trapezoidal, of the duration of 45 seconds, while the hold time at maximum load was 30 secs. Five specimens broke during these tests. Referring to the number of cycles that for each group would cause failure under the same load in fatigue tests carried out at 10 Hz, the shorter life, (11.8% of the high-frequency life) was relevant to a secondary bonded AF-163 specimen, fig. 46. No failure was observed for the EA-9696 secondary bonded specimens.

6. INTERNATIONAL RESEARCH PROGRAMS

6.1 - IDA Brite Euram Research (Alenia Naples)

The main goal of IDA (**I**nvestigation on **D**amage Tolerance Behavior of **A**luminum Alloys) is to improve the knowledge of the Crack Growth mechanism of small cracks in advanced aluminium alloys. The investigation is focused on the microstructure analysis with the objective of defining a material modelisation useful to perform mathematical simulation of the crack propagation phenomena. This advanced analysis tool will enable the design offices to compute, on the basis of a stochastic approach, the in-service damage growth with a significant reduction of test activity.

The main partners of Alenia in this project are: EADS France, EADS Deutschland, Airbus UK, Pechiney (F), ONERA (F), GKSS (D), DLR (D) and University of Limerick (IRL).

6.2 - DIALFAST Research (Alenia Naples)

The technical focus of the DIALFAST (**D**evelopment of **I**nnovative and **A**dvanced **L**aminate for **F**uture **A**ircraft **St**ructures) project is the development of a new generation of Fibre Metal Laminates-FML and Metal Laminates-ML, that provide significantly improved strength and stiffness properties for tailored fuselage applications. The fatigue properties of these innovative laminates are required to match those of the rather expensive GLARE material.

Alenia main partners are: Airbus Deutschland (AI-D), Fokker, EADS CRC – G, NLR, TU Delft, University of Pisa and University of Linkoping (S).

The research activity is organised in the following five work packages:

WP1 – Fibre metal laminates: Development of advanced fibre metal laminates, with higher static properties than state-of-the-art material but match the fatigue and damage tolerance behaviour.

WP2 – Metal laminates: Within the framework of the WP2 the possibility for the application of un-reinforced adhesive bonded sheet materials (Metal-Laminates) with additionally bonded crack stopper bands (strap) in the fuselage constructions should be examined.

WP3 – Structure optimisation: The improvements from innovative FML have to be combined with advanced design and structural weight and cost optimisation.

WP4 – Analysis methods: The aim of this WP is a series of finite element based models specifically developed for Fibre Metal Laminates (FML) taking into account the complex behaviour of the materials involved and providing a detailed simulation of the damage behaviour until failure through the post-buckling regime, including joints and defects.

Alenia activity in this project is described in the following:

- Leadership of WP3
- Sub-WPs 3.1, 3.2 and 3.4. The work is the optimisation of the preliminary design of structural elements and sub-components of FML.
- Sub-WPs 4.1, 4.3, 4.5 and 4.6. The work is the development of microscopic and macroscopic models of FML/ML and FML/ML joints. The objective of the work is the prediction of damage behaviour and static failure.

6.3 – WELAIR Brite Euram Research (Alenia Naples)

The main objectives of the WELAIR (Development of short distance **WEL**ding concepts for **AIR**frames) are:

- To build up the generated knowledge on the laser beam and friction stir welding technologies and basic weld joint characteristics/properties with the provision of data on the damage tolerant behaviour of the welds.
- To optimise, apply and validate the most suitable LBW process parameters for various Al-alloy combinations for the joining of stiffener-skin connections of airframes of tomorrow`s aircraft.

Alenia main partners are: EADS F, EADS G, EADS CRC, Piaggio Aero, Pechiney (F), ONERA (F), GKSS (D), DLR (D) and Institute de Soudure (F).

The research activity is organised in the following five work packages:
WP1 – Welding and property improvement
WP2 – New alloys and joint configurations
WP3 – Damage Tolerance analysis and Durability
WP4 – Components welding feasibility
WP5 – Components behaviour analysis and concepts validation

Alenia activity is the following:

- To optimise the Laser Welding process parameters in particular for structural details based on “Run-in” and “Run-out” solutions (initial and final part of welding). – **WP1**
- Development of repair schemes. – **WP1**
- Evaluation of new alloys for welded joints also in case of different materials – **WP2**
- Mathematical models for Crack initiation and Growth of welded structures. – **WP3**
- Definition, development and manufacture of medium size stiffened components related to the use of the laser beam welded concepts – **WP4**

7. COMPONENT AND FULL-SCALE TESTING

7.1 - Development fatigue test of the M346 wing (Aermacchi)

The set up of the fatigue test of a LH prototype wing structure has been completed in the last months and a configuration very similar to the final one can be seen in fig. 47.

The aim of the test is to validate the analytical calculations about fatigue strength and crack propagation behaviour of the structure, but above all to verify the predictions about the location of the critical areas and to highlight any other not foreseen criticality (hot spots).

The wing structure will also constitute the attachment rig for the certification fatigue test of the flap and the aileron surfaces. The wing and the surfaces are loaded by means of 16 jacks that will reproduce the load distribution for the 200 load conditions of the reduced Flight-by-Flight spectrum.

The original Flight-by-Flight spectrum had to be reduced in order to contain the time necessary for the test. The severity indexes of the reduced spectrum have been evaluated for the critical areas (so that the equivalent life can be calculated) and the number of cycles have been calculated based on the item with the lowest severity index.

A random time history covering 200 FHRS has been defined in order to simulate a reasonable load sequence, particularly in the perspective of the damage tolerance evaluation. The spectrum will be repeated until the target of 2 operative lives will be reached; subsequently some artificial crack should be introduced in the damage tolerance critical sections and added to those initiated spontaneously. Another test life will then be applied to monitor the crack growth.

7.2 - EF Typhoon (Alenia Turin)

After the successful conclusion of the Major Airframe Fatigue Test (MAFT) performed on the prototype structure, a production aircraft structure fatigue test (PMAFT) started in October 2004.

The Production Major Airframe Fatigue Test is loaded with 102 jacks plus an electromagnetic shaker to apply buffet loads to the fin; moreover a pressurisation system with 8 channels gives pressurisation to cockpit, centre fuselage tanks, 4 wing fuel tanks and 2 air intakes.

Alenia had the direct responsibility of the definition of spectra to be applied to simulate buffet on the wing. After the in-depth analysis of buffet phenomenon, the comparison between buffet and manoeuvres spectra led to identify four sections in the outer part of the wing where buffet is significant. A picture in the last National Review showed such sections.

In the period of the present Review, in addition to supporting the Production Major Aircraft Fatigue Test, some full scale tests of structural components were arranged and performed.

The fatigue test of the outboard flaperon structure was already presented in the last National Review; two years ago the test had just started, while now it has been concluded, reaching 18,000 Simulated Flight Hours. The spectrum was calculated using loads from manoeuvres (symmetric and asymmetric), gusts, landings and buffet. In addition to loads, deformations imposed by the wing were calculated to be simulated by means of a jack applying a displacement to the central support hinge of the flaperon. The test setup includes 7 jacks acting by means of pads on the flaperon surface plus the actuator applying the imposed displacement.

A test on a box representing the outer region of the wing, after the fatigue test for 18000 simulated flight hours and after temperature and moisture conditioning, sustained successfully the Residual Strength Test. The test set-up was a 4 points bending specimen with 6 jacks acting on the 2 central loaded sections plus a pump for pressure cycles simulating the outboard wing region, where aerodynamic and inertial loads interact with fuel pressure in the wing. The fatigue test, and consequentially the Residual Strength one, were performed after impact damage having been inflicted on carbon fibre panels. The test confirmed the anticipated good fatigue performances of CFC.

In order to verify the fatigue performance of the wing structure surrounding the central pylon housing, the Central Pylon Housing Box, after having been successfully fatigued for 18000 simulated flight hours, was conditioned under temperature and moisture and then subjected to Residual Strength Test up to 170% Limit Load. The test was arranged with 2 jacks producing bending on the box to simulate the wing passing stresses of the wing and with 3 jacks loading the pylon dummy spigot.

During the period of the present Review, a fatigue test on the wing inboard pylon started and reached now 3000 simulated test hours. The spectrum was calculated to verify pylon fatigue capabilities in excess to original fatigue requirement of the aircraft and so loads coming from heavy stores were included; moreover a spectrum for store release was also added. Fig. 48 shows the test article in the rig.

8. AIRCRAFT FATIGUE SUBSTANTIATION

8.1 - C 27-J JAR 25 civil certification (Alenia Naples)

The C 27-J aircraft is a derivative of the Alenia G222/C27A aircraft which has been modified to meet expanded or more stringent system-level requirements, as determined primarily by market assessments and Certification Requirements. The main modifications are related to the new engine installation (new engine nacelles design) and to the new landing gear design.

The major aircraft structural data, design objectives, mission profiles were presented in the last version of the Italian National Review, together with the certification path, according to the JAR/FAR requirements, for the new components (engine nacelles, landing gears) and for the unmodified parts (wing, fuselage, empennage,..). The TC (Type Certificate) was achieved on June 2001.
Anyhow, a number of tests is in progress on specific structural elements, such as engine nacelles and landing gears; the major comments are reported below.

<u>Engine Nacelles Full Scale Fatigue and Damage Tolerance Tests</u>

The Engine Nacelles Full Scale Fatigue and Damage Tolerance Tests is in progress. The test programme has the objective to demonstrate:

- Two Lifetimes (50.000 SFH) for the Durability assessment of Nacelle Metallic Structure, based on C27 J flight-by-flight spectra applied twice in order to guarantee one Service Life (SF =2.0 according to D.T. Design Concept)
- One additional Lifetime (25.000 SFH) for the Damage Tolerance capability assessment of the Nacelle Metallic Structure;
- One additional Lifetime (25.000 SFH) for the Durability and Damage Tolerance assessment of the Nacelle Composite Structure (C/Epoxy Lower Cowl); based on C27 J flight-by-flight spectra applied, at R.T. wet conditions, with a Load Enhancement Factor of 1.17.

At the Certification date, the Test Article has completed, as required by JAR Requirements, one year of utilisation (scatter factor included) i.e. 1,500 Simulated Flight Hours. To date, the Durability Test is completed and no cracks were found after NDI inspections, while the Damage Tolerance test (Single and Multi Load Path approach) is still in progress.

<u>Nose and Main Landing Gear Full Scale Fatigue Tests</u>

The Nose and Main Landing Gear Full Scale Fatigue Tests are in progress. The test programme objective is to demonstrate:

- Five Lifetimes (73530 FSLs) for the Fatigue assessment of both NLG and MLG Structure, based on C27 J flight-by-flight spectra applied five times in order to guarantee one Service Life (SF =5.0 according to Safe Life Design Concept)

The NLG Full Scale Fatigue Test started on 28th February 2003, while the MLG Full Scale Fatigue Test started on October 2002; at present, both tests have reached the 65% of the scheduled test life.

8.2 - ATR 42- ATR 72 Ageing program (Alenia Naples)

The aim of these activities is to insure the airworthiness of the older aircraft structures and, also, to increase the Design Service Goal of the ATR Models by a factor of 1.5.

The ATR aircraft have been certified on the base of the Damage Tolerance concept (post JAR 25.571 ch. 7 and post FAR 25.571 amdt. 45).

The design of the aircraft (material selection, surface protection, static fatigue and Damage Tolerance evaluations) was developed in a way to allow, to all the ATR models, a Design Service Goal (DSG) of 25 years and 70,000 Flights/Landings. So the objective of the ATR Ageing Structures Program is to certify the ATR Fleet for an Extended Service Goal (ESG) of 105,000 Flights/Landings.

The maintenance program was defined on the base of the MSG-3 analysis method, at the issue dated October 1980 and the results were then reported in the Maintenance Review Board (MRB) report for each model. The MRB reports, however, do not state the DSG of the ATR aircraft: the notion of DSG, as well as of Extended Service Goal (ESG), will be clearly stated and included in the maintenance documents.

To develop an Ageing Structures Program, for the ATR aircraft, the following activities have been planned:

- Supplementary Structural Inspection Program (SSIP)
  Since the ATR Family was conceived after JAR 25.571 ch. 7 and FAR 25.571 amdt. 45 (requiring Damage Tolerance design), no SSIP is strictly required. Nevertheless, the SSIP program will be in any case issued to account for some “Late Damages” discovered during the ATR Full Scale fatigue test.

- Corrosion Prevention & Control Program (CPCP)
  A CPCP program will be issued according to the in-service experience (corrosion findings).

- Repair Assessment Program
  This program will check each aircraft configuration, to assess the fatigue life of the existing repairs.

- Service Bulletin Review
  This activity will check each aircraft configuration, to verify the embodiment of Mandatory Service Bulletins.

- Widespread Fatigue Damage Evaluation
  This program will confirm that Widespread Fatigue Damage (WFD) or Multi Element Damage (MED) will not affect the Fatigue or Damage Tolerance capability for the remaining aircraft life (Life Extension Time). This activity will be based on the Full Scale fatigue test results, with particular reference to the final tear-down inspection and on service experience.

8.3 - A380 - Upper Centre Fuselage Durability and Damage Tolerance design (Alenia Naples)

In the past two years, Alenia was in charge of the Design, Analysis and Manufacturing of the Airbus A 380 Centre Fuselage Upper Part.

For the passengers version, today in the Flight Test activity, Alenia developed the full design of Fuselage Section 15 crown segment, including all the Analyses for Static, Durability and Damage Tolerance Justification. The MSG-3 Analysis, devoted to the development of the Structural Maintenance Plan, is in progress.

At the beginning of this year, Alenia started the activities related to the Design and Analysis of the Airbus A 380 Cargo Version.

8.4 - Boeing B 787 – Fuselage Section 44-46 and Horizontal Tail Damage Tolerance design (Alenia Naples)

At the beginning of 2004, the activity related to the design, analysis and manufacturing of the Boeing B 787 fuselage sections 44-46 and the Horizontal Tail started in Alenia. The fuselage sections 44 and 46 are conceived completely in composite materials, as well as the Horizontal Tail, which will be produced adopting the “One Shot” cocuring process.

Together with the design, Alenia is in charge of the Damage Tolerance analysis and of the test definition for the Structure Configuration development, manufacturing processes tuning and certification.

8.5 - Agusta A109 helicopter family (Agusta)

In the period of the present Review, some improvements have been introduced in the A109 helicopter and in its variants. A list of the modifications and of their fatigue substantiation activity is given in the following.

A new full composite Tail Rotor blade was designed and certified for all the A109 variants, including the single engine A119. This new blade improves airworthiness and has a retirement life of 15,000 hours, compared to 3,000 hours of the current metallic design. A picture taken during the full scale test is shown in fig. 49.

The certification of A109E Power was re-examined, as a consequence of the increase in Take Off Weight to 3000 Kg and up to 3100 Kg for the US Coast Guard variant. Both activities required extensive load survey plans and re-analysis of the fatigue life, including prototype monitoring for the new TR blade. In addition, several fatigue tests were carried out for the new blade, the TR Grip and the elastomeric bushing which are part of the improved composite blade.

A109 LUH is the military variant developed for South Africa, Sweden and Malaysia. The South African contract involves also a new manufacturing site for A109 parts, including blades and rotors, according to a production licence. A validation plan is being carried out covering also fatigue performances. Tests are carried out both in Cascina Costa and South Africa (Denel Company). These tests were strongly supported by the Agusta Test Laboratory, which designed, manufactured and supervised the assembly of all the test rigs. Moreover, Agusta provided assistance for rig set up, approval of testing procedures and analysis of the test results.

The A109 'Grand' is the latest variant with extended AUW (3175 Kg), improved composite rotors, MR blades with anti-nodal masses for better dynamic response, winglet tailplane and extended fuselage for better cabin arrangements. Certification is expected for April 2005.

8.6 - AB 139 Helicopter (Agusta)

This is a new helicopter of 6000 kg gross weight, twin-turbine, multirole capability. Some basic information about the Certification process was already given in the last National Review. This is the first helicopter that Agusta fully designed and certified according to the “Flaw Tolerance” requirements, including all dynamic parts, fuselage and transmission. The only exceptions are gears and MR and TR shafts. This is the second helicopter, after S-92, fully designed and validated for compliance to the FAR / JAR 29.571 amendment 29-28. A paper will be presented in the Symposium giving a survey of the design, development, qualification and certification processes.

The helicopter received the Type Certificate in June 2003 from ENAC and in December 2004 from FAA.

Extensive testing and flight activities are in progress, for the certification of role kits (rescue hoist, cargo hook,..) and higher AUW at 6400 kg.

Some experimental activities have been carried out, with the objective of development of improved solutions. Among others, it is worth quoting the extensive testing of metal sandwich panels, under tension and under shear loading, for fatigue and DT properties evaluation. These tests support the structural analysis of the AB139 Fuselage. The shear test data will be presented in a paper at the Symposium.

8.7 - EH101 and derivatives (Agusta)

Extensive analysis was carried out to define the usage spectra for the customers Portugal and Japan Navy, including a comprehensive re-assessment of the maintenance manual and the retirement lives. Moreover, evaluation of extended take off weight to 15.600 Kg was completed.

18 panels for safe life plus 8 panels for damage propagation were tested to characterize fatigue and DT of Rear Fuselage of EH101 made by Al 8090. These data will improve the present evaluation based on analysis and coupon data. Tests on a second set of panels are in progress for validation of material change to Al 2024, required by some customer instead of AL-Lithium.

Relevant efforts were devoted to support the bid for the new US President helicopter, the VXX. These included fatigue substantiation criteria and detailed presentation of the Damage Tolerance properties of the Agusta parts, already demonstrated in the 90ies for the civil type certificate.

As an example, the following table contains a list of components and the relevant damage tolerance concept applied.

Component	D.T. concept applied
Main Rotor Hub	No growth / Slow growth / Fail safe
Support Cone	Fail safe
Elastomeric Bearings	Slow growth
Civil Tension Link	FTSL / Fail Safe
Inboard Tension Link	No growth / FTSL / MLP / Fail Safe
Outboard Tension Link	Fail safe
M.R. Damper attachment	No growth / FTSL

Main Rotor Damper	Fail safe (demonstrated by a failure occurred on prototype)
Tail Rotor Blade	Slow growth / FTSL
Tail Rotor Hub	FTSL
Tail Unit	No growth / Fail Safe
Rear Fuselage (Utility and Naval)	No growth / Slow growth

8.8 - M346 trainer (Aermacchi)

The M346 is the Aermacchi fourth-generation training system, designed to meet the requirements of pilots who will fly the multirole air superiority aircraft of the 21st century. M-346 took-off for its first flight on 15 July 2004 and up to now has collected 55 flights for a total of 60 flight hours and 102 landings (fig. 7). The M346 has been designed according to damage tolerance principles, keeping also durability requirements into consideration during the fatigue design process.

In the last two years, durability and damage tolerance activities have covered the following issues:

1. Wing structure development fatigue test
2. Structural characterisation of a new design solution for the fin
3. Certification analysis activity: critical parts criteria identification, fatigue and DT substantiation, parts management
4. PSD approach for fatigue/DT analyses under dynamic spectra
5. FCS actuators qualification
6. Flight activity monitoring

In addition, basic activities have just started to develop some of the processes that will be applied in the manufacturing of the M346 series aircraft; those with grater impact on the fatigue behaviour are shot-peening and surface treatments, alternative to chromium and cadmium plating, since their application is being progressively reduced, due to environmental and health safety issues. In the following some information will be given about the points 2-5, while the others (1 and 6) are treated in the appropriate chapters of the National Review.

8.8.1 - Structural characterisation of a new design solution for the fin

Aermacchi is developing a new structural design for the fin of the M-346 series aircraft, different from the one used in the prototype. Since the structure (which consists of metal to metal primary bonded joints and honeycomb full-depth) is unconventional, an extensive experimental program, as well as analytical activities, is planned in order to certificate the vertical tail of the aircraft.

To define the structural properties of the bonded joints designed for the fin structure, Aermacchi has planned a series of tests inspired to the building block approach. Laboratory development tests (static and fatigue/damage tolerance) on specimens of increasing complexity will be performed in order to evaluate, among others, the drop off in the bonded joints mechanical properties, with the introduction of artificial defects, and the ageing effects due to exposure to an adverse environment (mainly hot/wet, salt fog).

Fatigue tests will be carried out, starting with constant amplitude load spectra applied to simple specimens and concluding with flight-by-flight spectra (including dynamic loads) applied during the fin full scale fatigue test.

The test program has just started and, so far, the first tests on single lap bonded joint specimens, under constant amplitude loading (R=0.1), have been carried out. The two adherends are different 7xxx series alloys (7050 and 7475). Materials and production technique adopted are coherent with those prescribed for the bonded joint between skin and root rib of the fin.

The static tensile test confirmed the adhesive (AF163-2K) failure shear load used for the static design.

The activity will prosecute with scarf bonded joint tests, where also the sensibility to defects in the bonding area will be evaluated. Subsequently, also the effect of an adverse environment on the fatigue performance of a scarf joint and of the honeycomb full depth structure will be evaluated. The last (and more complex) tests of this activity will be a fin box rear fitting test (under a block spectrum, simulating also the aggressive environment effect) and the full scale fatigue and damage tolerance test of the complete fin. In this case the load spectrum will be a flight-by-flight spectrum, where also the dynamic loads will be included.

8.8.2 - Certification analyses activity: critical parts identification criteria, fatigue and DT analyses, critical parts management

a) Critical parts identification criteria

Control processes shall be implemented to prevent premature failure of safety-of-flight structure and to minimise service maintenance problems due to fatigue phenomena. Therefore, all activities related to the structural integrity of aircraft components with service life requirements are listed in an appropriate control program.

The critical parts of the aircraft have been divided in two categories: damage tolerance critical and durability critical, depending on the consequences caused by the failure of the part itself. For the M346 aircraft, those parts, which are identified as critical, are placed in a “critical parts list” and are subjected to special controls throughout the manufacturing process and are monitored during service life. In particular, fracture (or damage tolerance) critical parts require traceability (the item is serialised or identified by means of the batch number depending on its degree of criticality, material qualification testing including fracture toughness, special handling procedures and non destructive inspection). Durability critical parts require special handling procedures and non destructive inspection.

b) Fatigue and Damage Tolerance Substantiation

One of the main activities focused on M-346 is obviously constituted by the verification of the airframe. Fatigue and Damage Tolerance criteria are applied following the military international regulations.

The substantiation activity is developed in collaboration with the Department of Aerospace Engineering of Pisa and with IDS – Ingegneria Dei Sistemi, a consulting company.

8.8.3 - PSD approach for fatigue/DT analyses under dynamic spectra

In order to evaluate the fatigue life of the structures that undergo dynamic loads spectra, such as buffet phenomena, an analysis campaign using the frequency domain approach (Power Spectral Density, PSD) has been developed. The main software used in Aermacchi for fatigue analyses of structures under dynamic loads is MSC FATIGUE, mainly the Vibration Fatigue utility. With this tool, it is possible to evaluate the fatigue life of components e.g. under buffet loads (random, gaussian phenomena – wide band approach).

As far as finite element modeling is concerned, the mesh refinement is of greatest importance since MSC FATIGUE receives as input the stress value directly on the element; moreover, the absolute maximum principal element stress value is used.

8.8.4 - FCS actuators qualification

Within the M346 program, an important activity has been developed to support the qualification of the Flight Control System (FCS) actuators (Leading Edge Flap, Trailing Edge Flap, Aileron, Horizontal Tail and Rudder). The actuation system is completely designed by external suppliers, based on Aermacchi requirements. Operational spectra had thus to be defined, both for structural fatigue verification and for system functionality substantiation.

The two phenomena (fatigue and functionality) are driven by different parameters: both spectra are derived from the aircraft design manoeuvre spectrum, but while for fatigue the meaningful variable is load, for system functionality, although load is still very important, the fundamental parameter is the deflection of the surfaces, i.e. the displacement (km covered) of the actuators. Consequently, the activities for defining the spectra have to follow different guidelines.

The rainflow algorithm (extensively used for load spectra processing) has been applied to the displacement time histories of each manoeuvre with the aim to compute the total actuator stroke in terms of displacement cycles. The maximum load cycle in the manoeuvre has then conservatively been associated to each displacement cycle. During the fatigue test the actuator will be fixed in the mean position related to the manoeuvre.

An example of the exceedances spectrum defined for the fatigue substantiation is presented in fig. 50.

8.9 - P.180 Avanti (Piaggio Aero Industries)

In the period of the present Review, activities on fatigue analysis have been carried out at Piaggio Aero Industries mainly in the framework of the P. 180 Avanti program, as a consequence of the introduction of some improvement or modification and following some in-service problem.

The fatigue analyses are mainly based on the safe-life approach, since the P180 Avanti aircraft is certified as safe life. Some components of the aircraft, such as the horizontal tail and the engine nacelle, are made in composite materials, and for such parts the damage-tolerance approach is applied.

The procedure for the fatigue life analytical evaluation follows the outline described in the FAA report AFS-120-73-2. It is based on well-known steps (mission analysis, spectra definition, statistical data base, ...) and on the use of a cumulative damage assumption (Miner rule) and a safety factor equal to 5. The aircraft design safe-life is equal to 15,000 FHs. The analyses have been validated by means of a number of tests. The stress levels in the critical “hot” points were taken from the Finite Element model of the aircraft (validated with strain gauge readings in the full scale component tests).

Fig. 51 shows a typical example of parts in the P. 180 Avanti fuselage that have been modified, as a cost reduction action. In general, numerical controlled machining has been extensively applied, in lieu of the “traditional”, but labour intensive, riveted solutions.

Similar modifications are under evaluation also for more flight-safety critical areas, such as the wing box in the wing-to-fuselage attachment, where riveted doublers will be substituted by integrally machined reinforcements.

9. OTHER FATIGUE INVESTIGATION OF GENERAL INTEREST, ALSO ON NON-AERONAUTICAL SUBJECTS

9.1 - Thermal Stress Analysis (TSA) applied to fatigue tests (Agusta)

The design of many aeronautical components takes into account fatigue tests intended to study the component behaviour under load and eventually to verify their safety before they are put into production. Components under cyclic loads undergo a periodic temperature fluctuation proportional to the local principal stress sum (thermo-elastic effect). In case of adiabatic conditions, which are achieved for frequencies above a certain level, that depends on the thermal diffusivity of the material, the measured amplitude of the oscillating temperature can be used to determine the local stress in the sample. Starting from this physical principle, Infra Red (IR) thermography is now a suitable means to perform a quantitative stress analysis on parts subject to oscillating loads when the IR thermal image can be acquired in phase with the mechanical load oscillation by using a lock-in acquisition system.

Several cases component tests, which are normally carried out for fatigue substantiation, are now integrated with this kind of stress analysis which is able to experimentally highlight the areas of stress concentration. One of the major problems is however that TSA is not reliable, if adiabatic conditions are not achieved. For a given material the achievement of adiabatic conditions depends on the load applied, on the component shape and on the cyclic frequency of the applied load. If the component has a constant section and it is put under a simple modulated mono-axial tension, adiabatic conditions are always present regardless of the modulation frequency. On the contrary, if the sample shape and the load applied produce a non uniform stress distribution in the volume, heat diffusion can take place causing a reduction of the temperature picks and an underestimation of the stress value especially where stress reaches its highest and more dangerous concentration. Practically, in limited cases this drawback can be reduced by increasing the test frequency. A study was started by the Energetics Department of the Milan Polytechnic, in cooperation with AgustaWestland, with the aim of obtaining within determined limits the possibility of a data correction suitable to reduce the diffusion effect. A specific software was developed which is able to correct, on the basis of the phase lag of the IR signal, the thermal map results and gives better stress estimate from the quantitative point of view. Figure 52 shows finite elements modelling of a fatigue tested component, figure 53 shows the result of TSA without correction and figure 54 shows the same with correction. After the correction the stress was found to stay within 10% in the high concentration and gradient areas. Considering that this was one of the most ambitious applications, due to the low test frequency and the high conductivity of the material (Al alloy), the suitability of the technique encouraged to an even more widespread use. More details can be found in [17].

10. REFERENCES

[1] A. Lanciotti, C. Polese: “The effect of interference fit fasteners on the fatigue life of central hole specimens”, paper accepted for publication on Fatigue and Fracture of Engineering Materials and Structures.

[2] A. Lanciotti, C. Polese: “Effect of pin/hole interference on the fatigue resistance of specimens with and without load transfer”, paper to be presented at the XVIII Conference of the Italian Association for Aeronautics and Astronautics, Volterra, 19-22 September 2005 (In Italian).

[3] Pavier, M.J., Poussard, C.G.C., Smith, D.J.: Finite element simulation of the cold working process for fastener holes: *Journal of Strain Analysis for Engineering Design*, vol. 32, n. 4, July 1997, pp. 287-300.

[4] Ozdemir A.T., R. Cook, L. Edwards. Residual stress distribution around cold worked holes. ICAF 93, Stockholm, pp. 207.

[5] R. A. Pell, P.W. Beaver, J.Y. Mann and J. G. Sparrow: Fatigue of thick-section cold-expanded holes with and without cracks. *Fatigue Fracture Eng. Materials Struct., vol.12, no.6, pp.553-567,1989*

[6] Stefanescu, D.: Experimental study of double cold expansion of holes. *J. Strain Analysis*, 2003, 38(4), pp. 39-347.

[7] L. Boni, A. Lanciotti: “Residual stress in cold-worked fastener holes and their effects on fatigue resistance”. Paper to be presented at the XVIII National Conference of the Italian Association for Aeronautics and Astronautics, Volterra, 19-22 September 2005 (in Italian).

[8] G. Ratti and U. Mariani (Agusta), L. Reid (FTI): “Attaining Flaw-Tolerant Design Life Objectives in Helicopter Rotor System Lugs”, 30th European Rotorcraft Forum, Marseille, 14-16 September 2004.

[9] A. Lanciotti, C. Polese: “Alcune proprietà di giunzioni 'Friction Stir Welding' in due leghe di alluminio di impiego aerospaziale”, paper presented at the Meeting "Friction Stir Welding per Applicazioni Aerospaziali", Pisa, 1 Aprile 2003 (in Italian).

[10] A. Lanciotti, C. Polese: “Resistenza a fatica e caratteristiche di Damage Tolerance di giunzioni Friction Stir Welding nella lega alluminio-litio 2195-T8”, Giornata di Studio: “Friction Stir Welding Day", Torino, 15 Giugno 2004.

[11] H. Tada, P.C. Paris: “The stress intensity factor for a crack perpendicular to the welding bead”. International Journal of Fracture, n. 21, pp.279-284, 1983.

[12] A. Lanciotti, F. Nigro, C. Polese: “Caratterizzazione Damage Tolerance dell'attacco ala-fusoliera del velivolo M346”, presented at XVII National Conference of the Italian Association for Aeronautics and Astronautics, Rome, 15-19 September 2003 (in Italian).

[13] A. Lanciotti, C. Polese, L. Cabiddu: “Attività sperimentale di caratterizzazione Damage Tolerance dell'attacco ala-fusoliera del velivolo M346”. University of Pisa, Documenti del Dipartimento di Ingegneria Aerospaziale DDIA 2004/9, June 2004 (in Italian).

[14] S. Beretta, M. Giglio, U. Mariani, M. Vicario: “Flaw Tolerance evaluation of helicopter rotor parts”, Proceedings of the 22nd ICAF Symposium, Vol. II, pp. 689-702, EMAS Publ., 2003.

[15] A. Lanciotti, C. Polese: “Crack propagation and fracture toughness tests of fibre metal laminates". University of Pisa, Documenti del Dipartimento di Ingegneria Aerospaziale DDIA 2003/7, May 2003.

[16] A. Lanciotti, L. Lazzeri: contribution to "Deliverable 3.3 - Testing of small specimens" of the DIALFAST 6FP project.

[17] S. Desiderati, A. Salerno: “Quantitative thermoelastic stress analysis in non-adiabatic conditions”, Proceedings SPIE, Vol. 5405, Thermosense XXVI, Bellingham (WA), USA, 2004, pages 466-475.

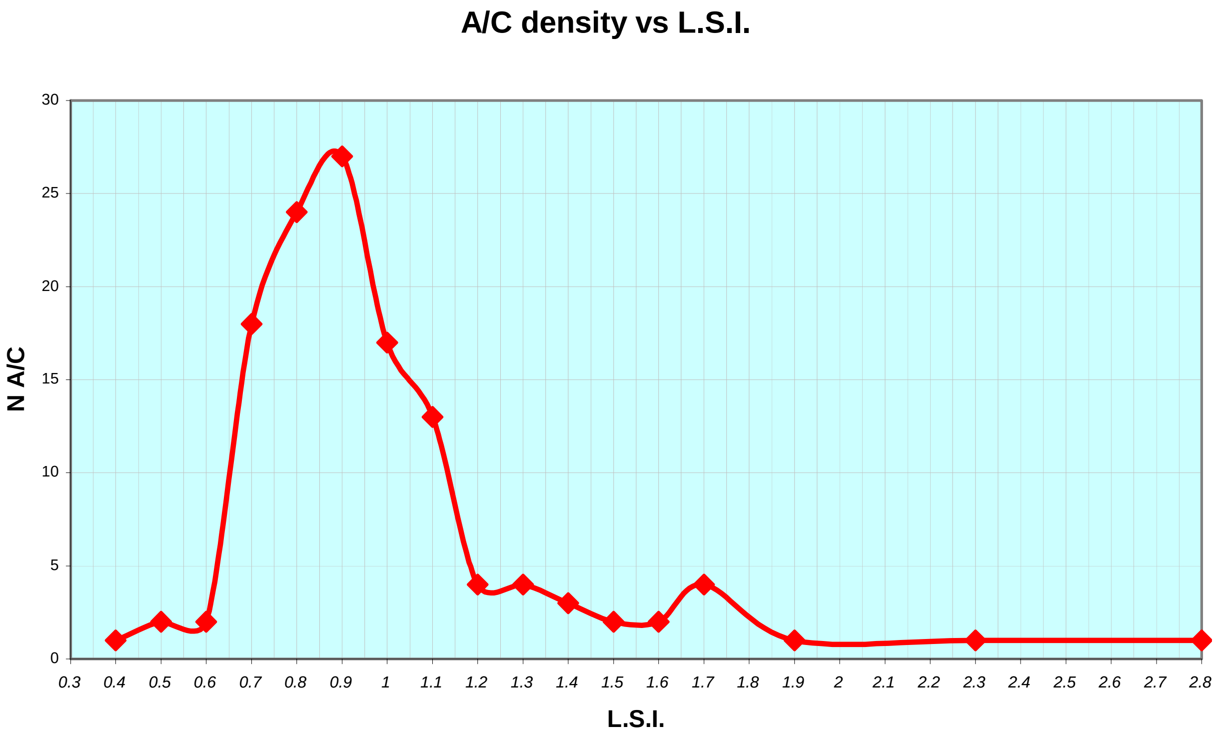


Fig. 1 – Load Severity Index distribution for the AM-X fleet.

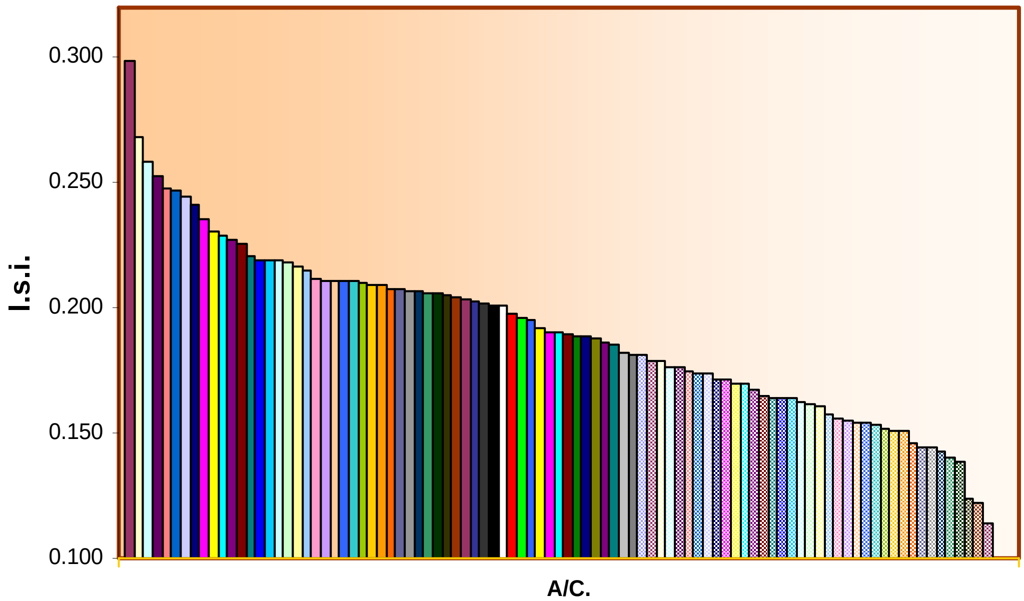


Fig. 2 - Load Severity Index distribution for the I.A.F. Tornado fleet.

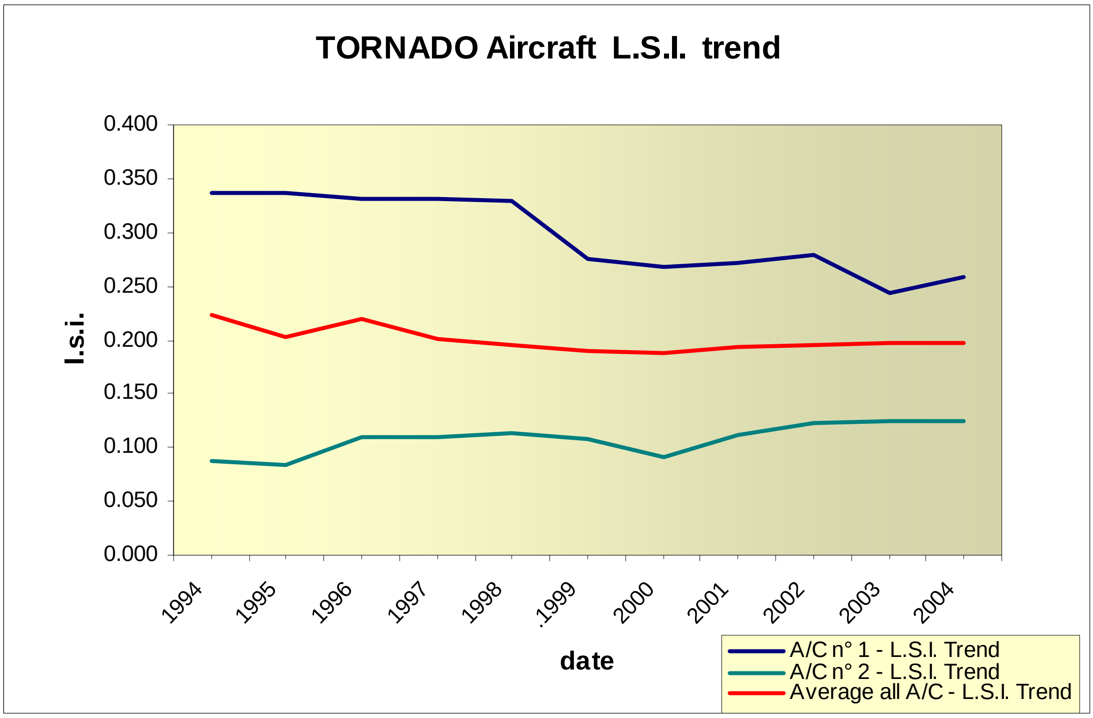


Fig. 3 - Examples of different fatigue consumption rates for individual Tornado aircraft.

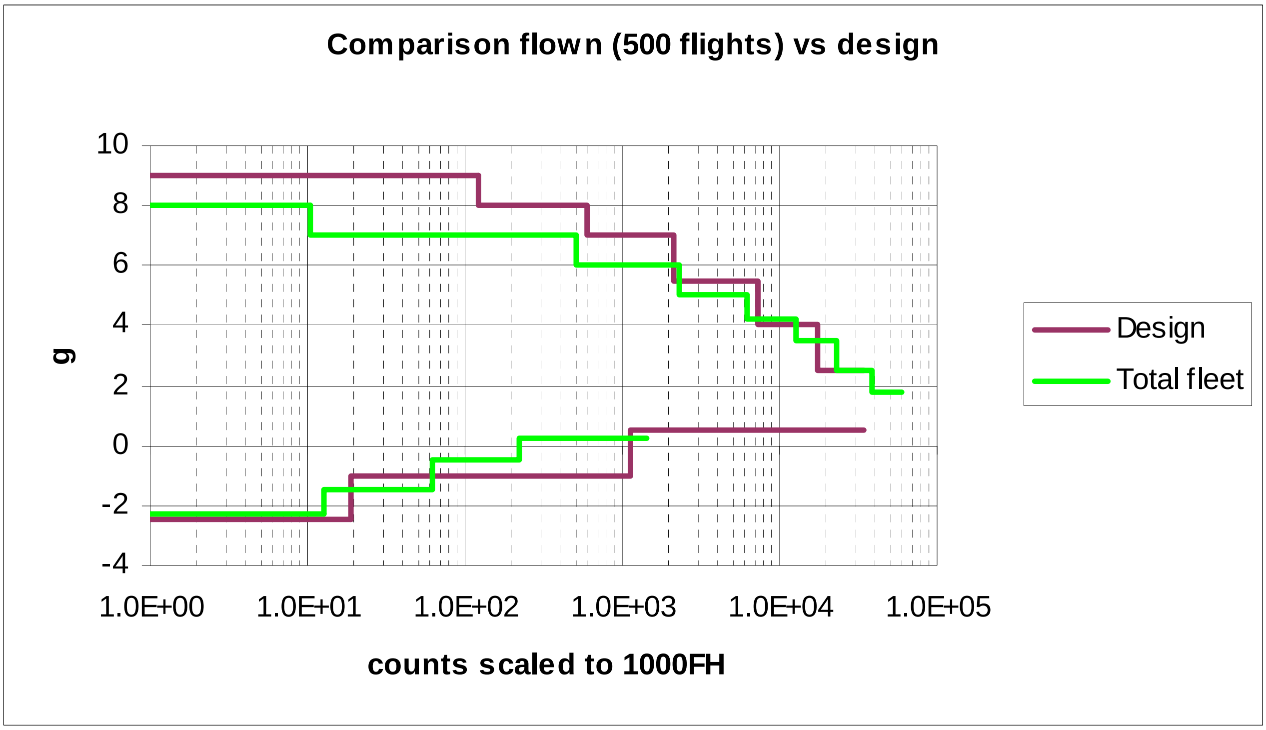


Fig. 4 - IAF EF Typhoon fleet flown spectrum, compared with the design one.

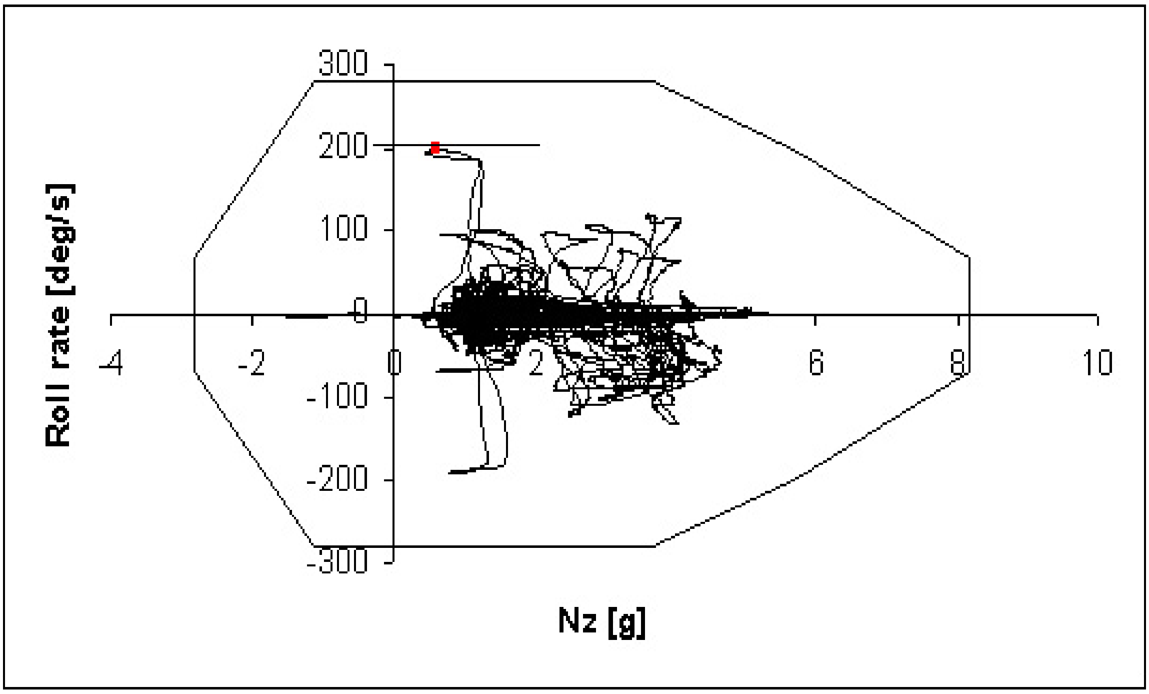


Fig. 5 – EF Typhoon roll rate vs. normal acceleration envelope.

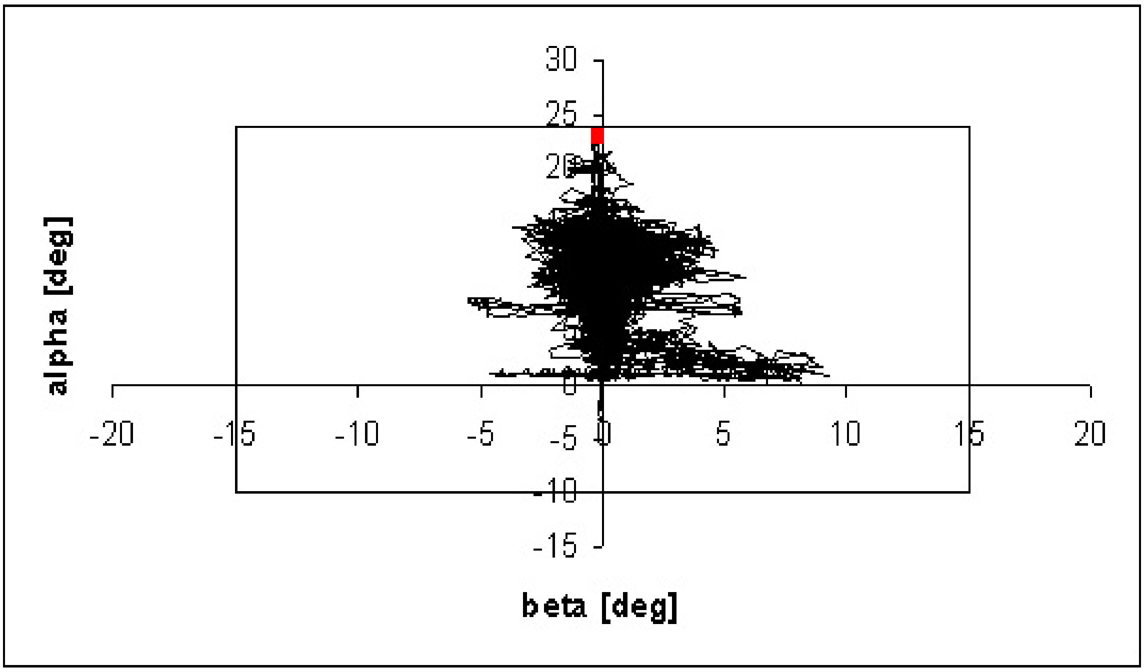


Fig. 6 - EF Typhoon sideslip angle vs. angle of attack envelope.

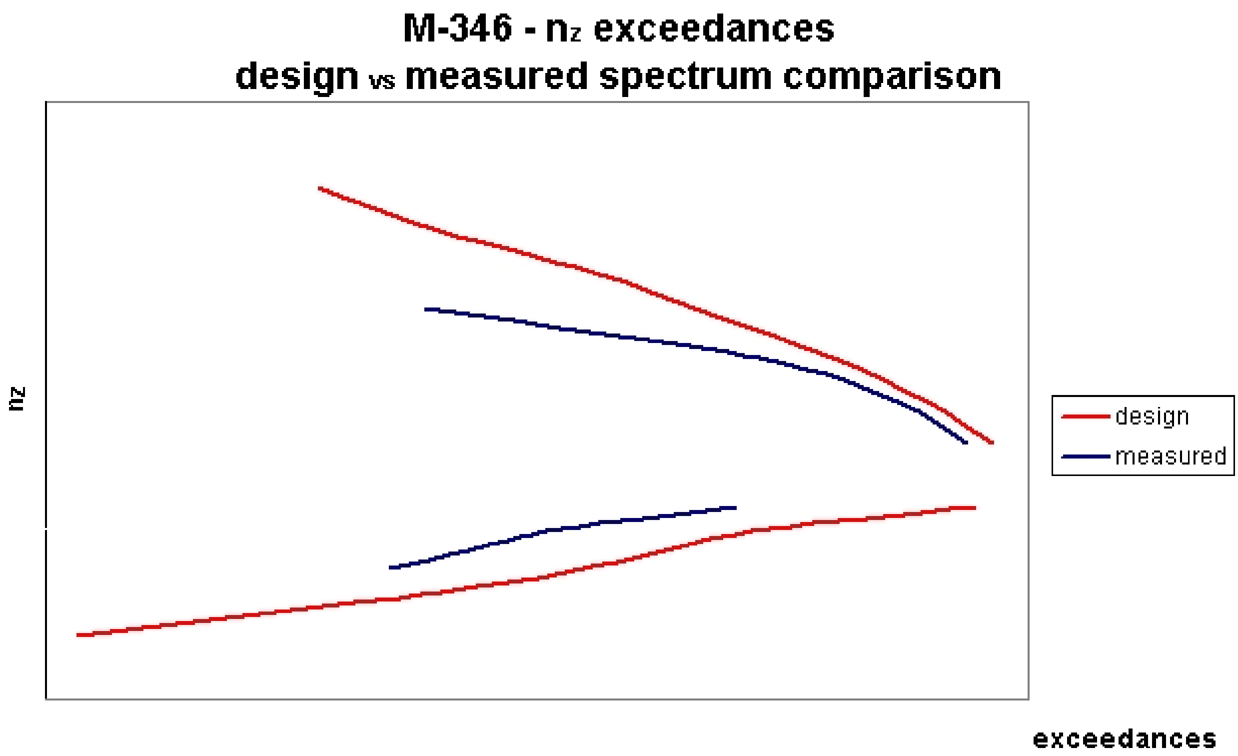


Fig. 7 - M346 prototype flown vs. design spectrum.

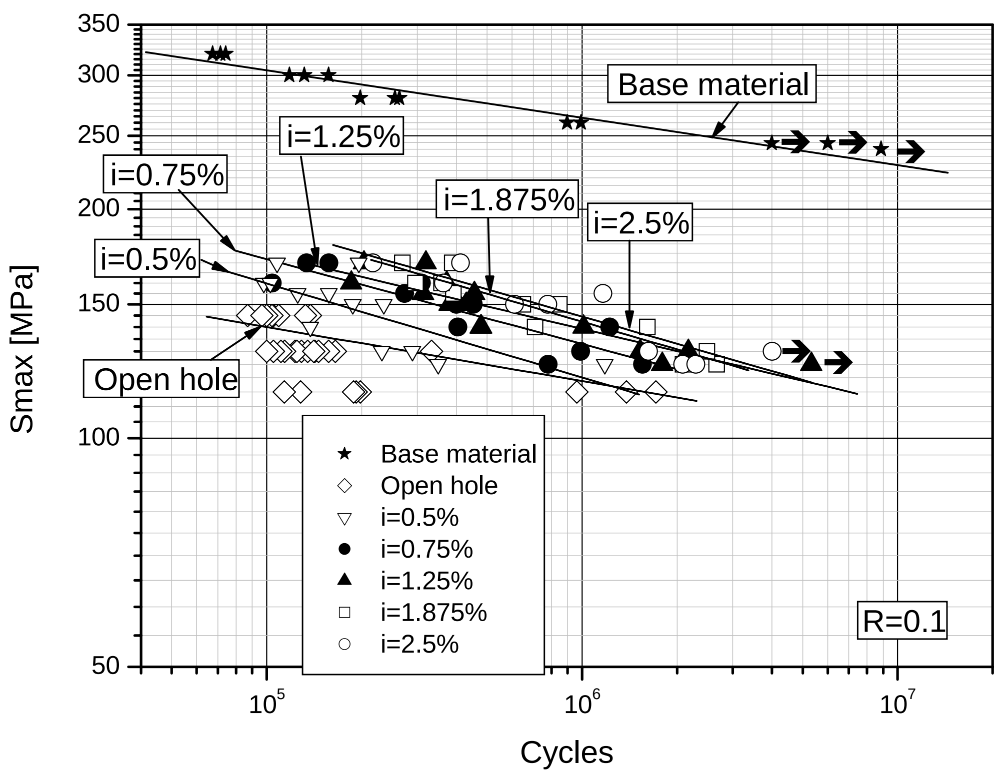


Fig. 8 - S-N curves of specimens having a central hole filled with an interference fit pin.

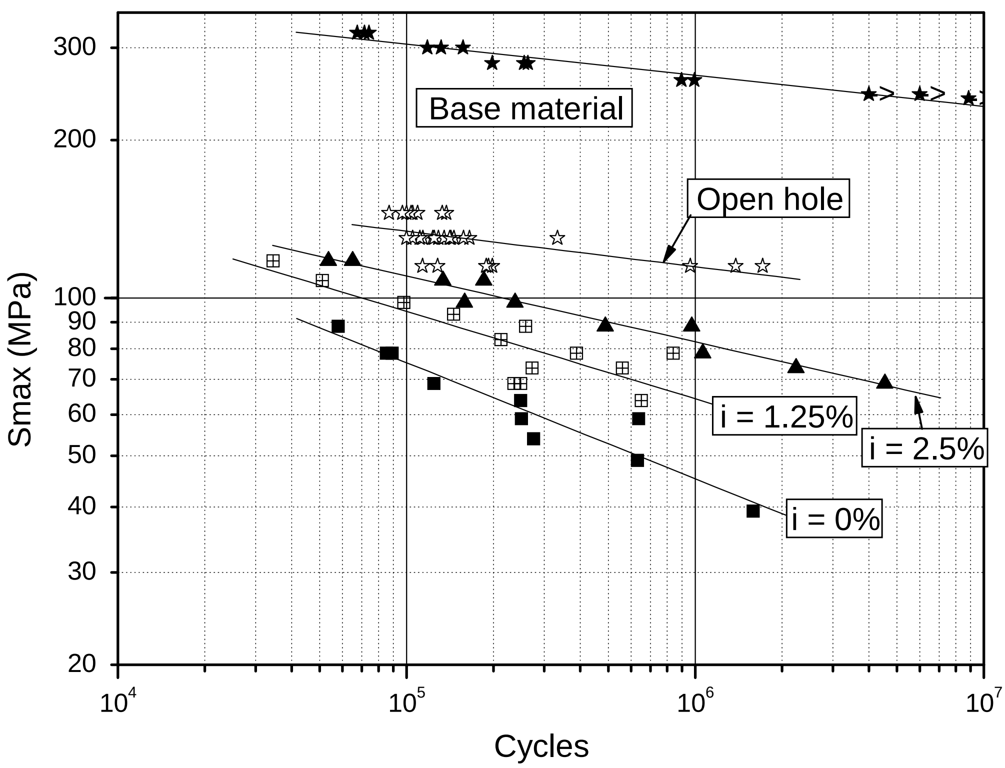


Fig. 9 - Effect of interference on the fatigue behaviour of pin loaded specimens (R=0.1).

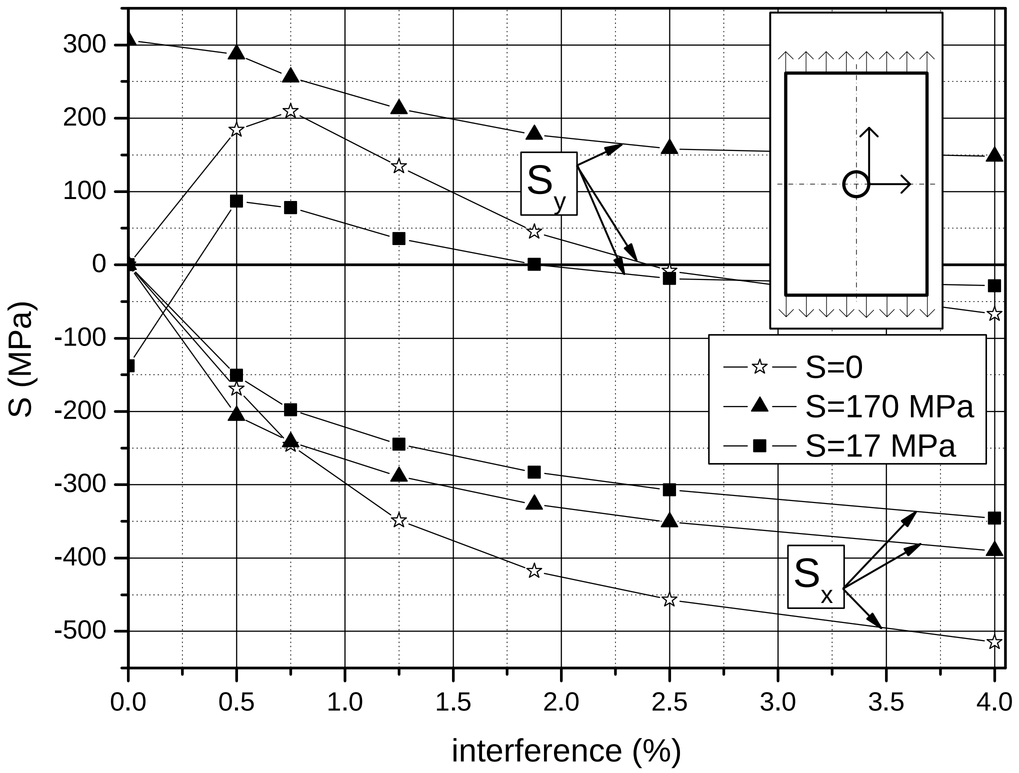


Fig. 10 - Circumferential (y) and radial (x) stress distribution in the critical location of a hole with a pin fitted with various interference levels.

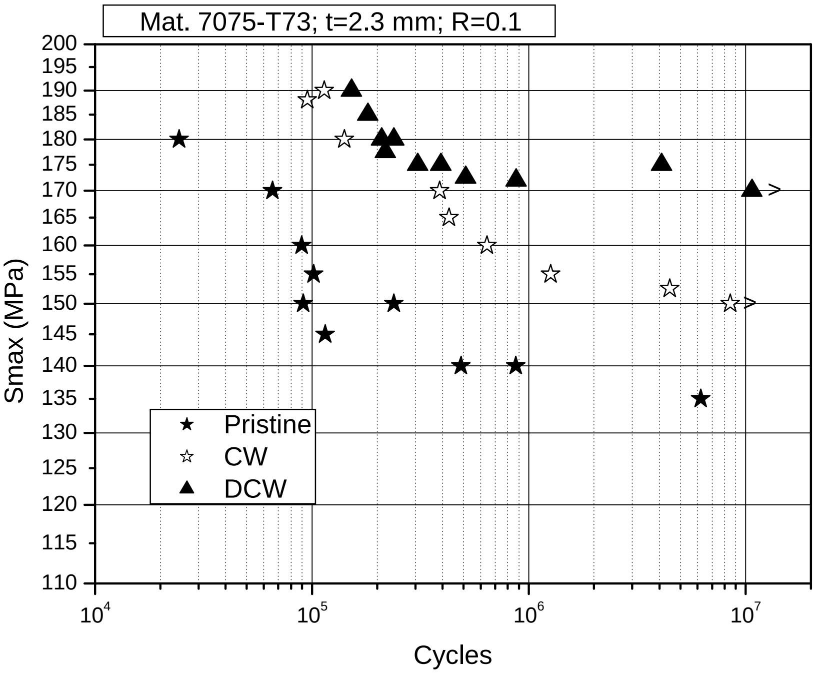


Fig. 11 - S-N curve of pristine, cold-worked and double cold-worked open hole specimens.

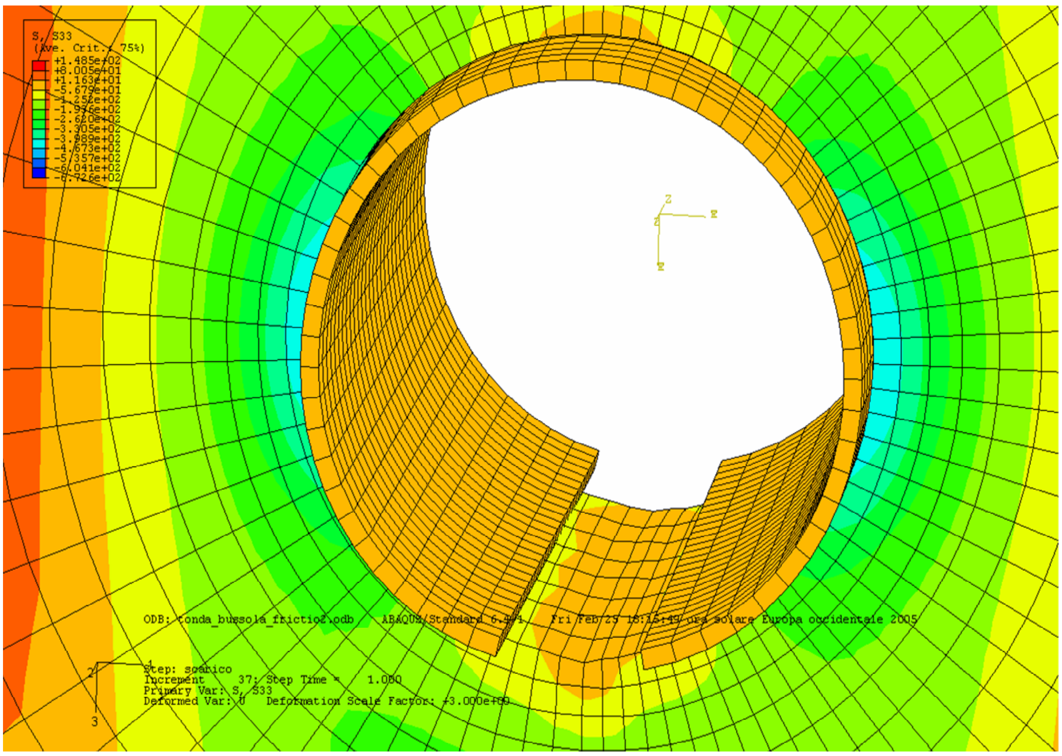


Fig. 12 – Finite Element simulation of the Cold Working process.

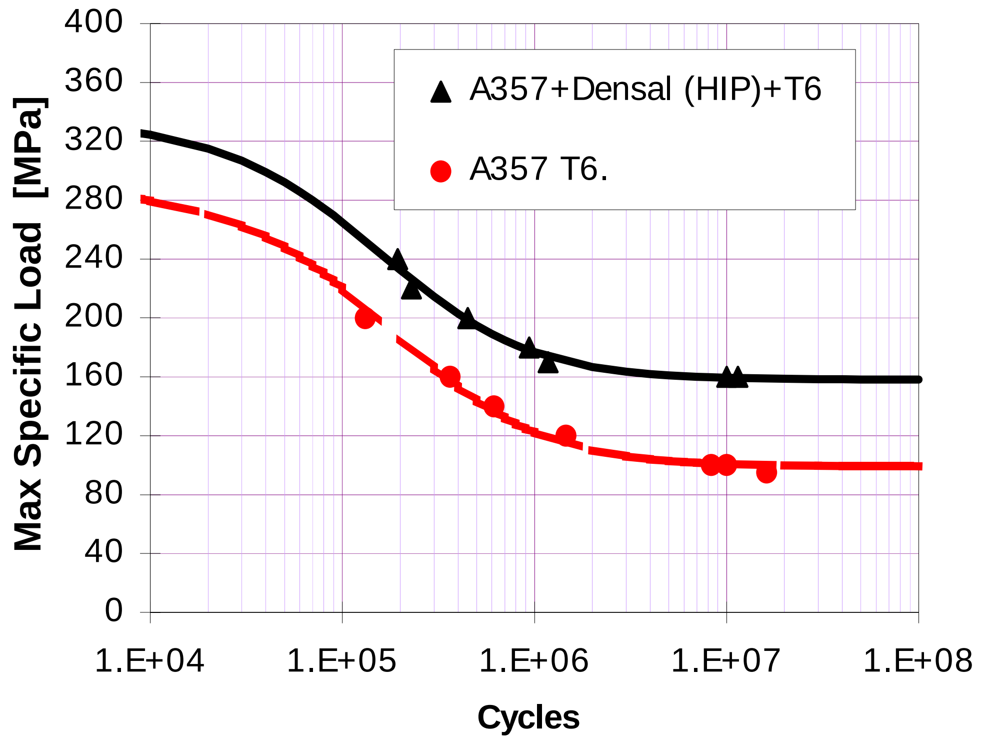


Fig. 13 - Effect of HIP treatment on the fatigue behaviour of A357 specimens, cut from cast rods.

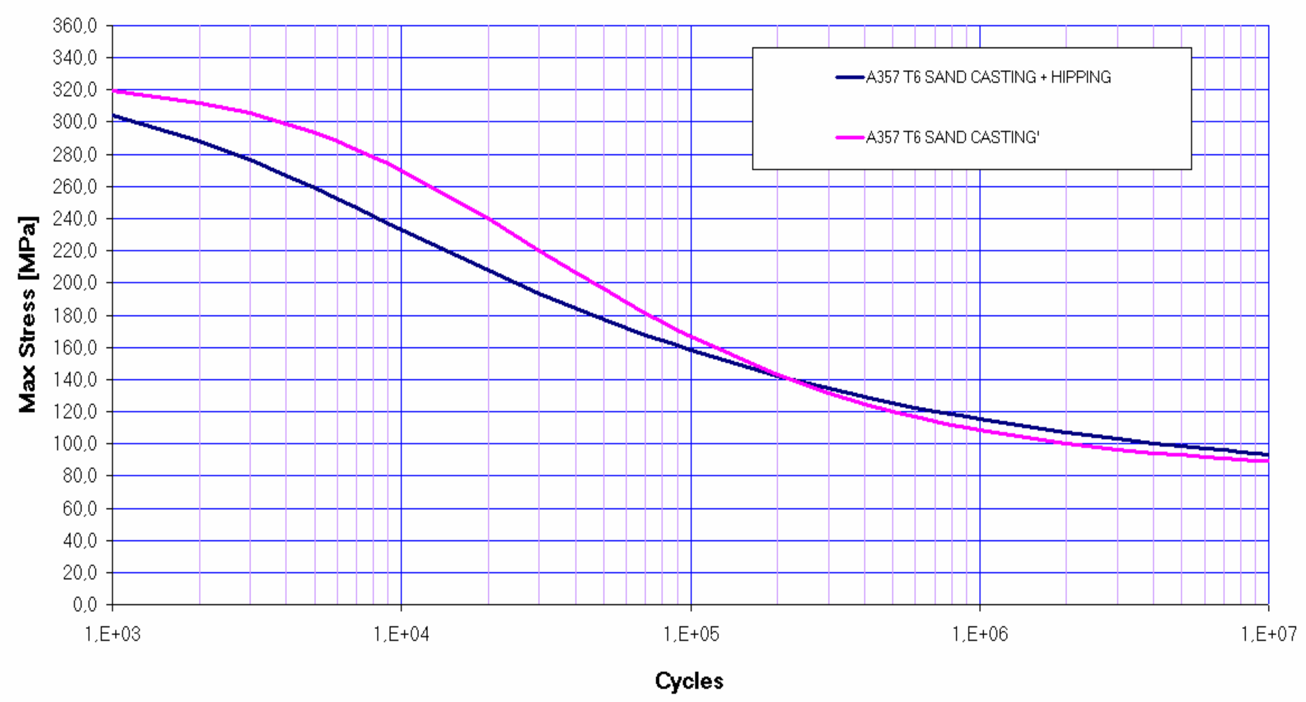


Fig. 14 - Fatigue test results of complex shape specimens in cast A357 alloy (R=0.1).

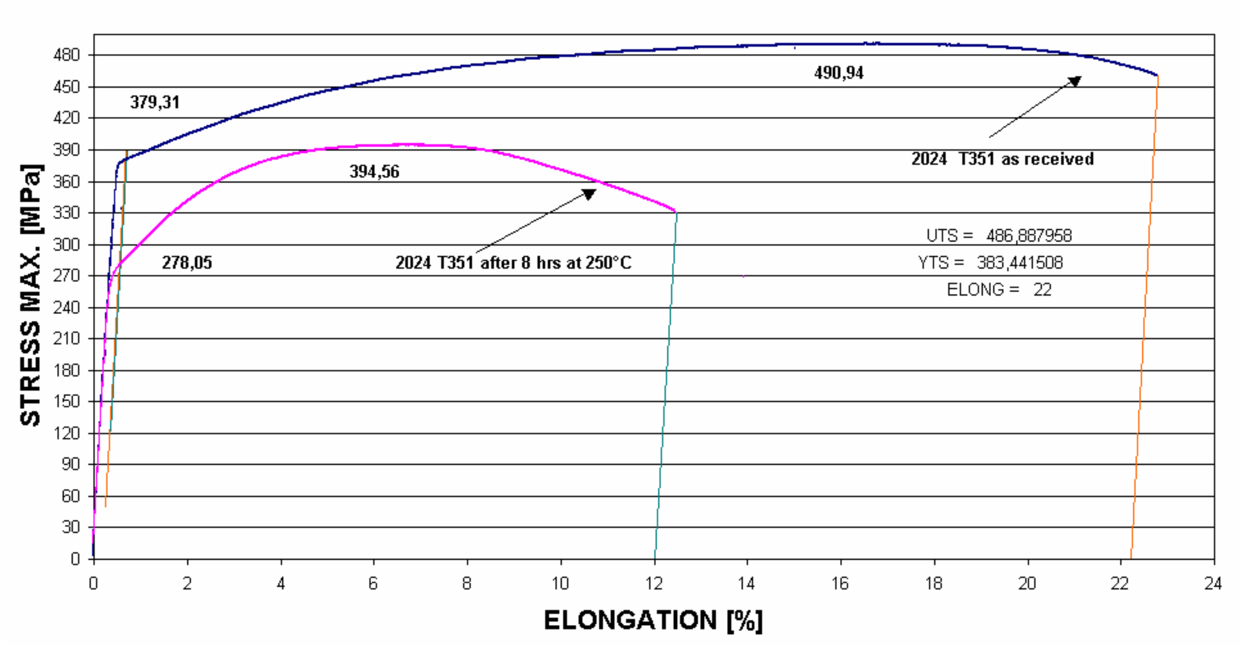


Fig. 15 - Static properties of 2024-T351, before and after soaking 8 hrs at 250 °C; tests at RT.

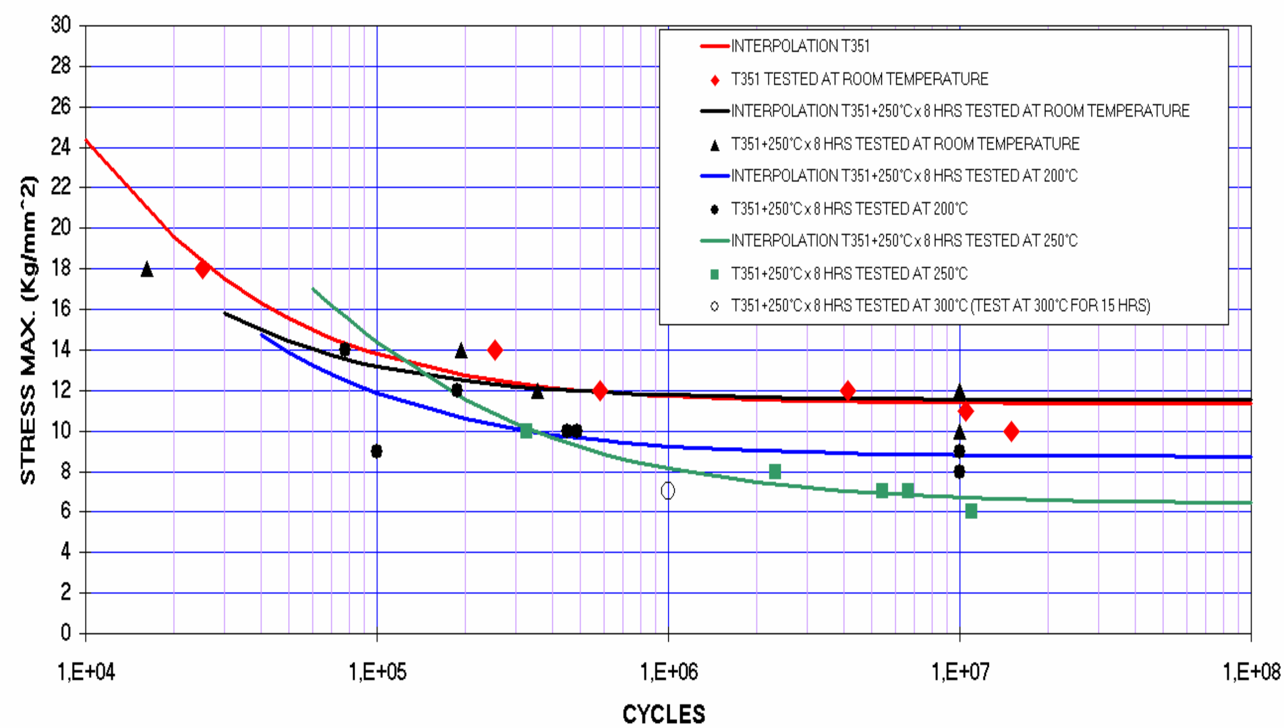


Fig. 16 – S-N curves for 2024-T351 tested at RT and at Elevated Temperature, after different thermal exposure.

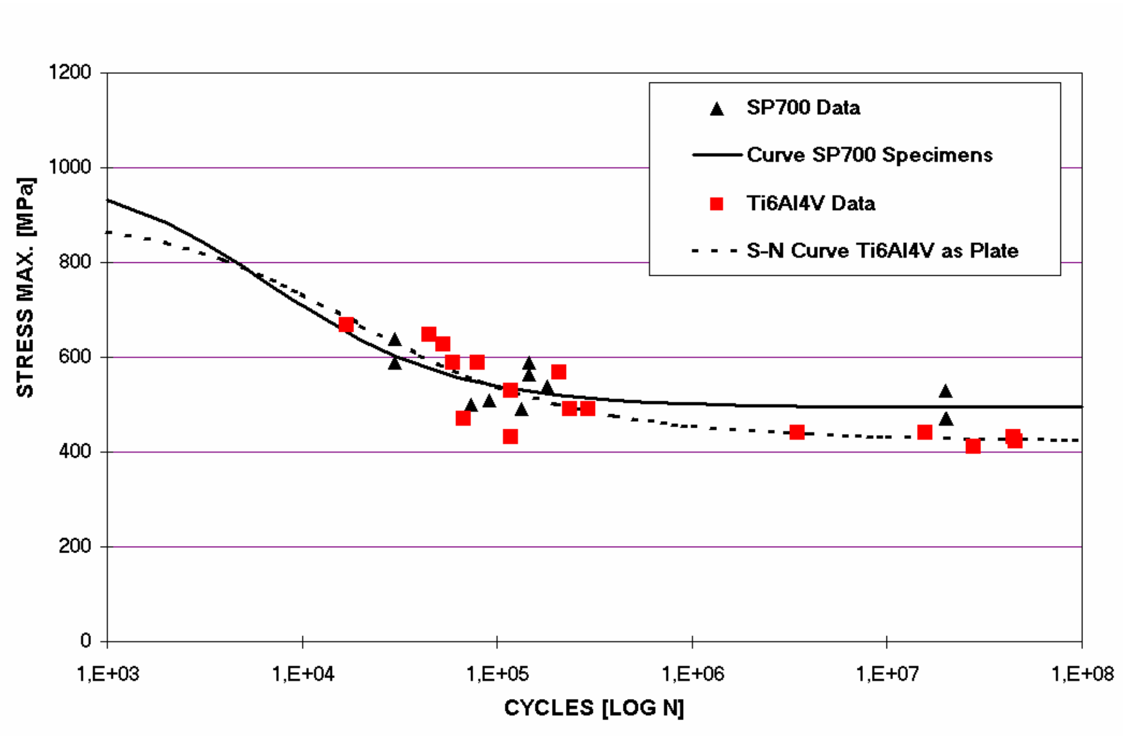


Fig. 17 - Comparison between fatigue (rotating bending, Kt=1) results from Ti-4.5Al-3V-2Fe-2Mo and traditional Ti-6Al-4V titanium alloys

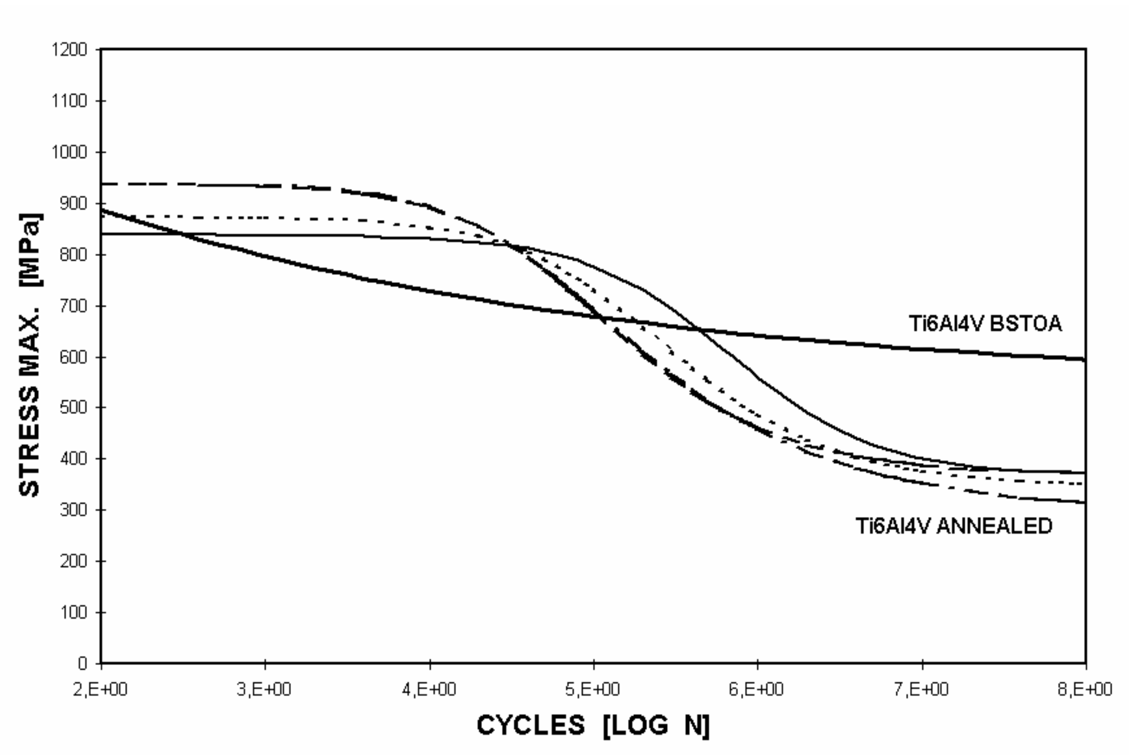


Fig. 18 - Titanium forgings in Ti 6Al 4V Alloy: S-N curves (Kt=1, R=0.1) comparing annealed condition to the β-solution treated/overaged (BSTOA) condition.

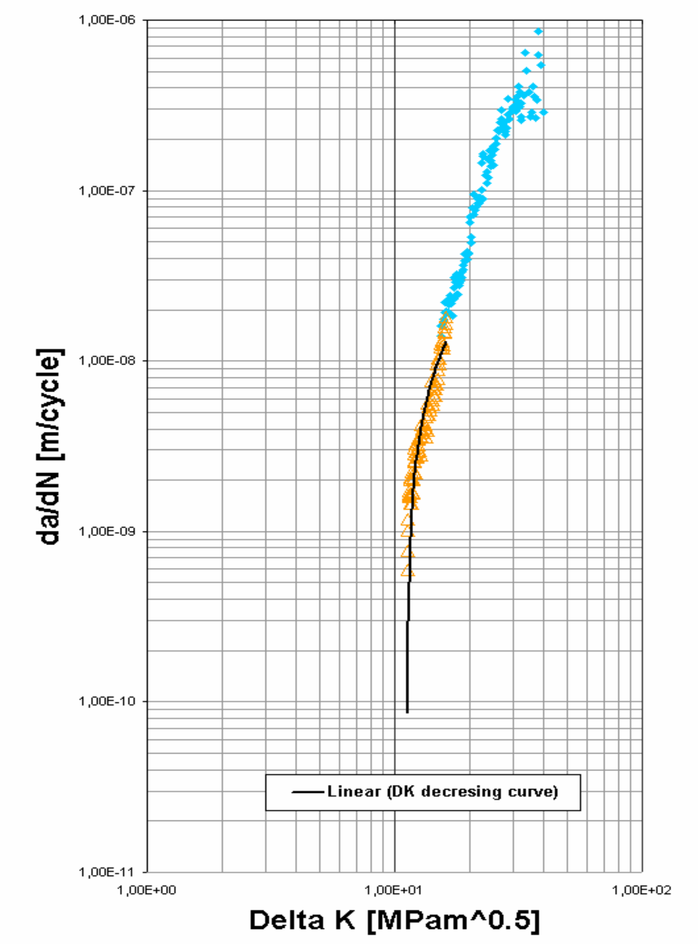


Fig. 19 - Fatigue crack propagation in Beta Solution Treated / OverAged Ti-6Al-4V alloy, R=0.1.

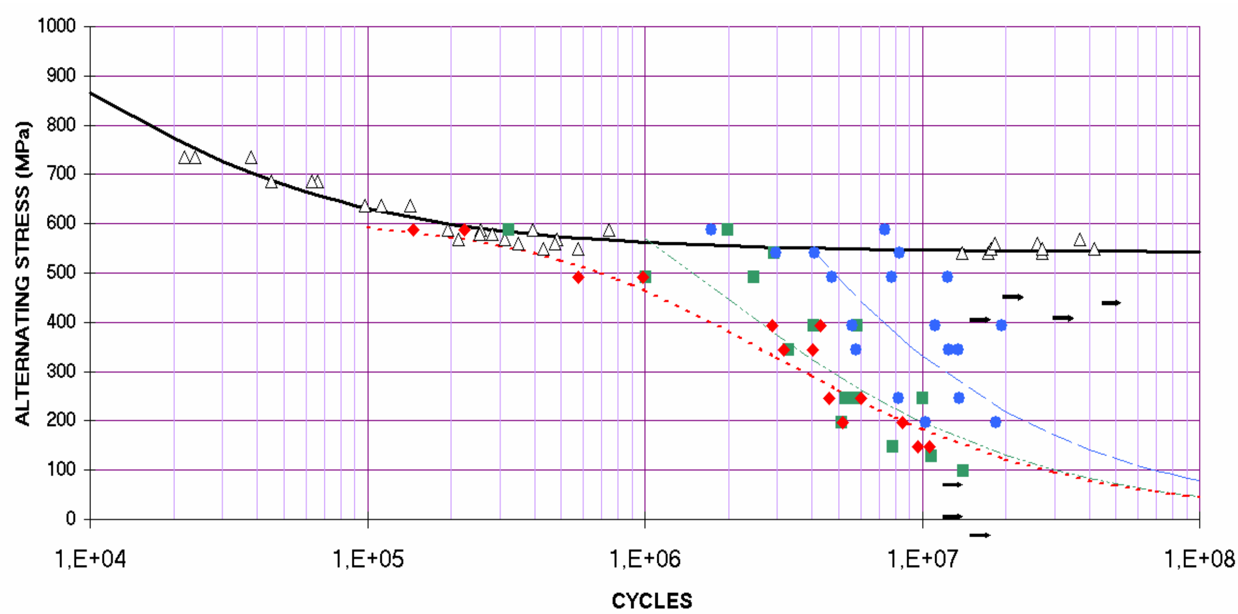


Fig. 20 - Fatigue tests results. Substrate is 4340 steel AMS6415, L direction, 1150-1250 MPa condition. Open triangles are the substrate data points in air, green squares refer to Cd plating in salt environment, blue circles refer to ZnNi, red diamonds to ZnCoFe all in salt environment. The various interpolation lines are also shown.

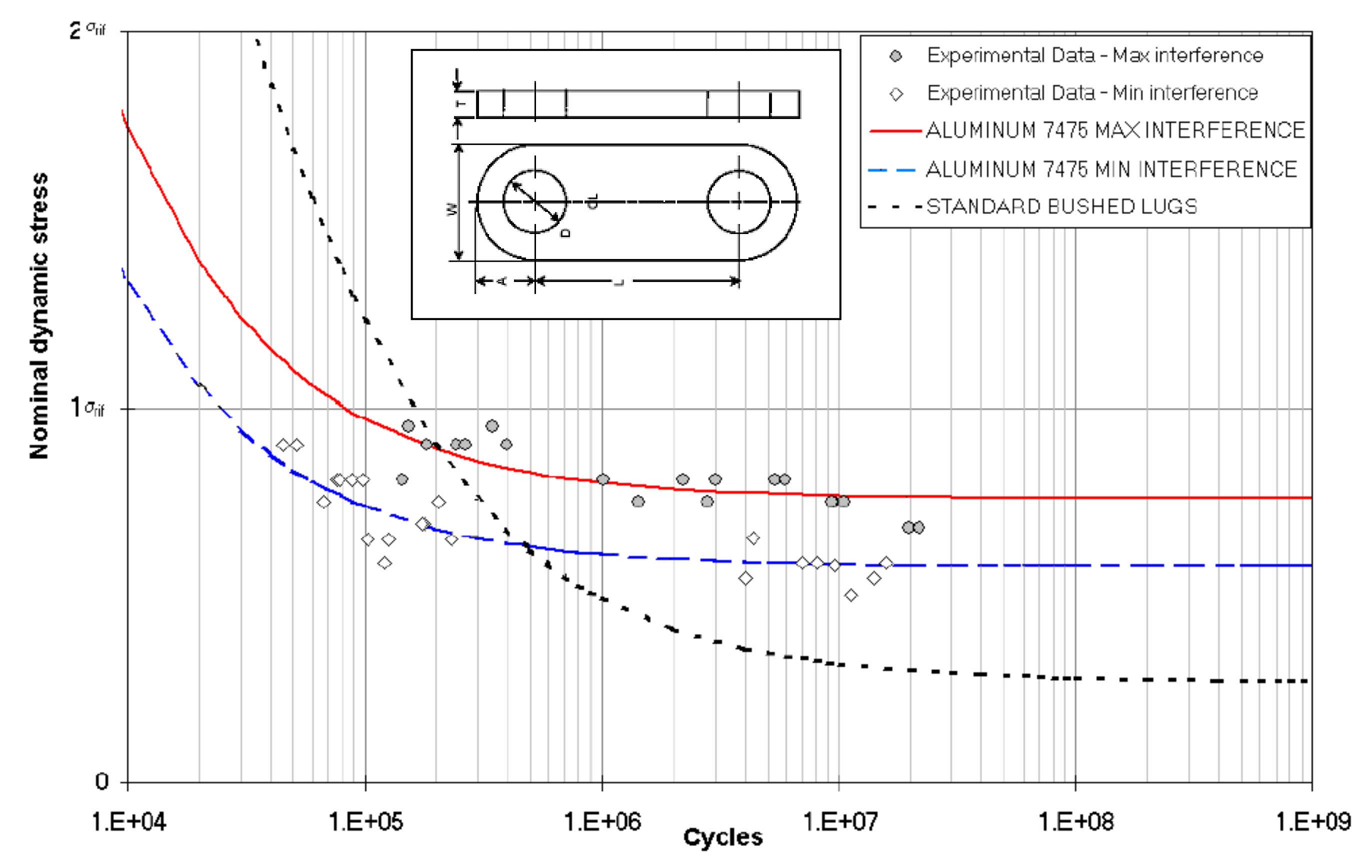


Fig. 21 - Fatigue test data from pristine lugs in 7475-T7351: effect of the Forcemate ® bushing installation interference.

Fig. 22 – Anomalous fatigue cracks pattern in 2195-T8 specimens.

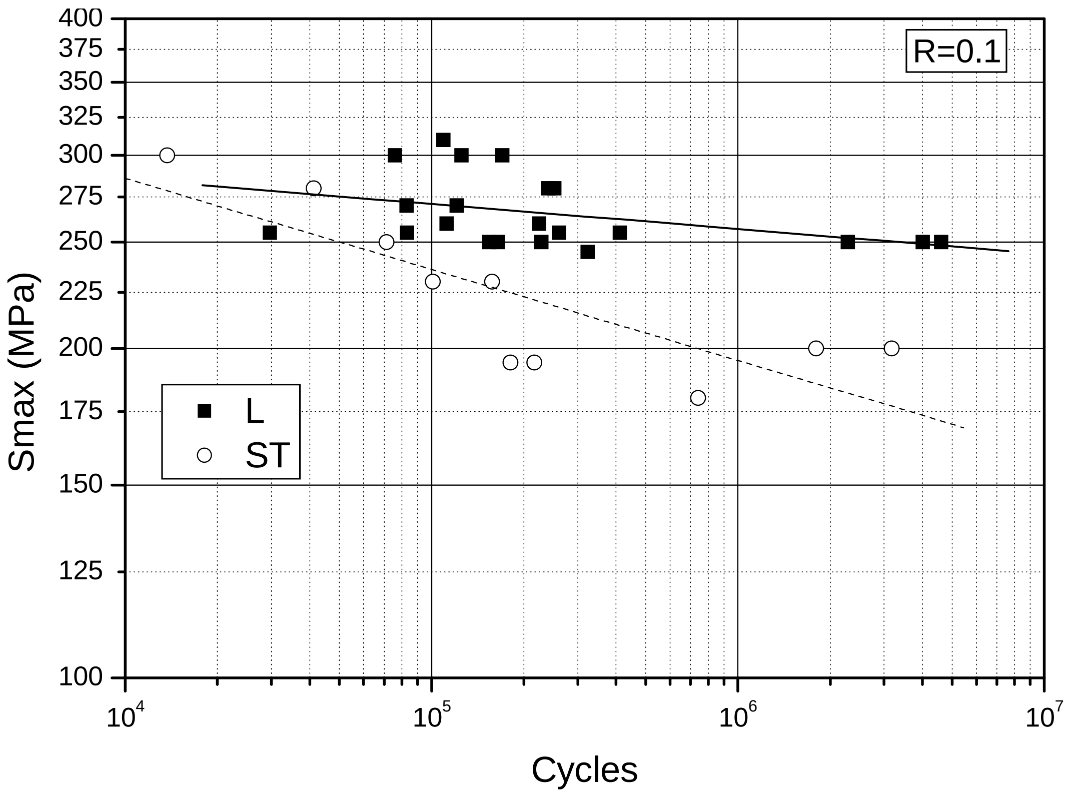


Fig. 23 - Fatigue resistance of 2195-T8 un-notched specimens, machined in different orientations.

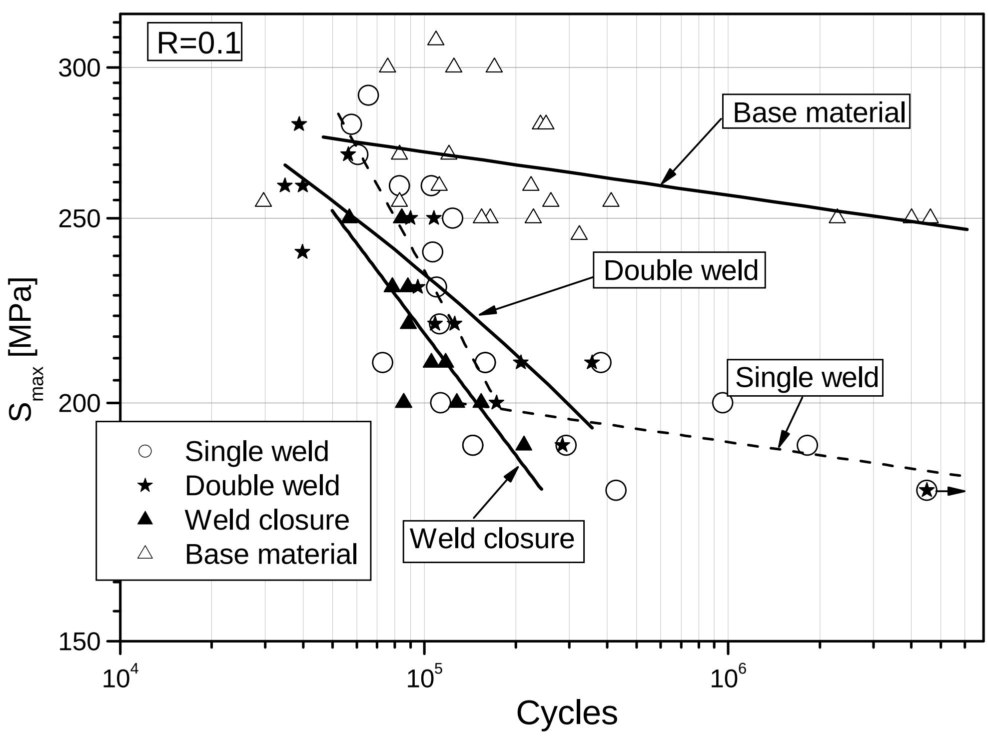


Fig. 24 - Fatigue resistance of FSW joints in 2195-T8.

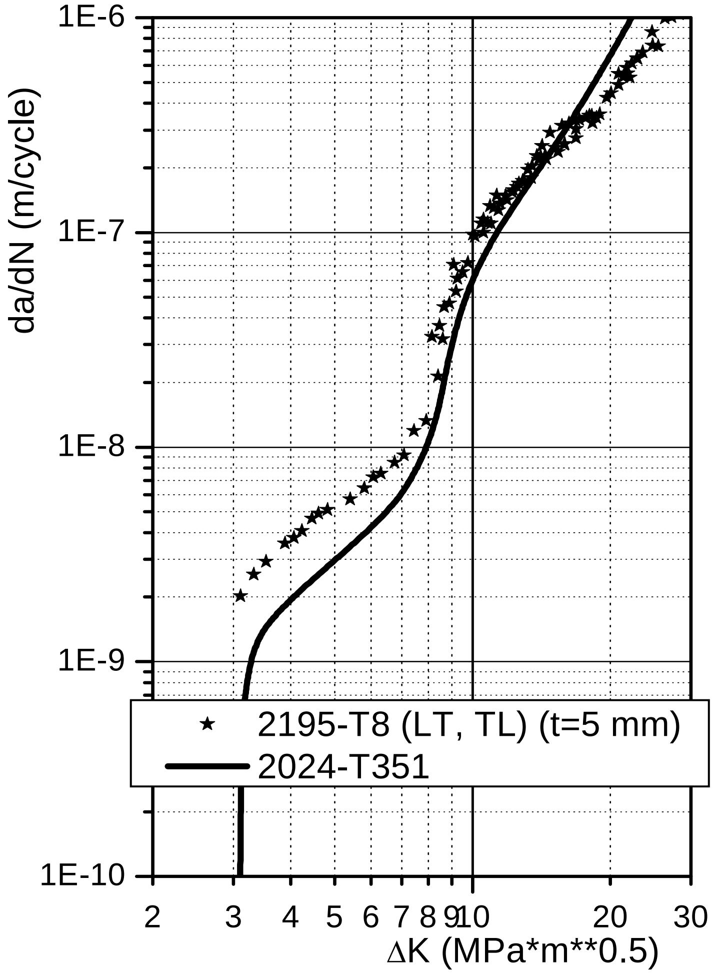


Fig. 25 – Fatigue crack propagation in 2195-T8, R=0.1

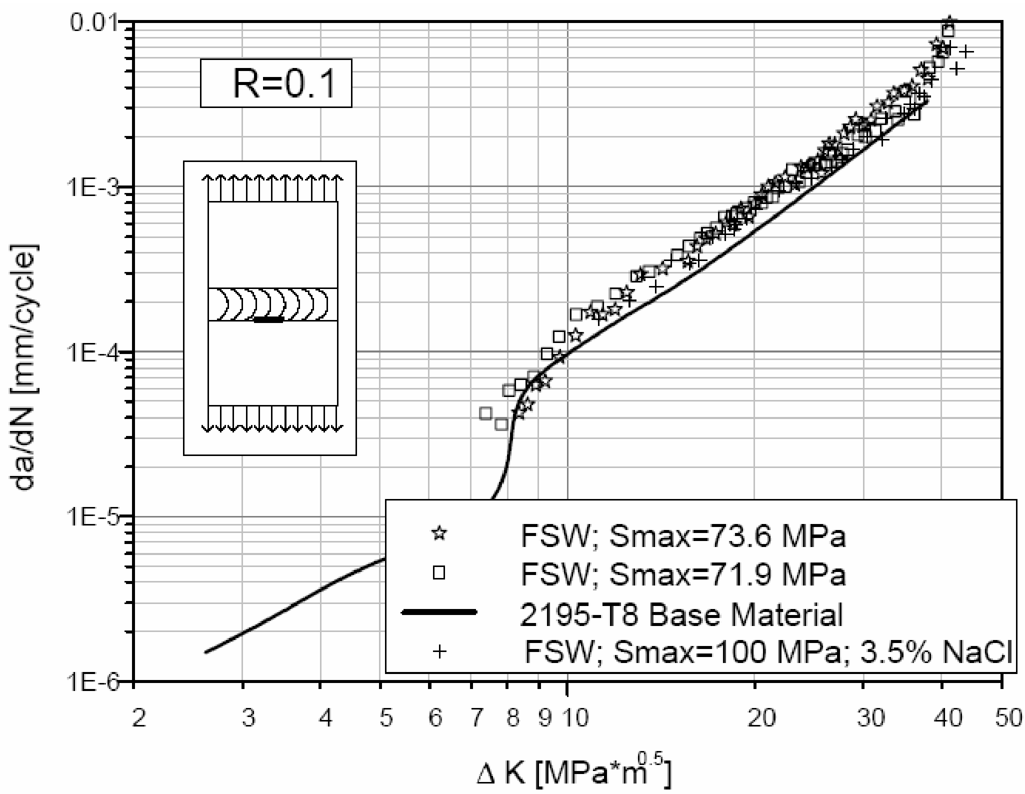


Fig. 26 - Fatigue crack propagation in 2195-T8, R=0.1, along the friction stir weld bead.

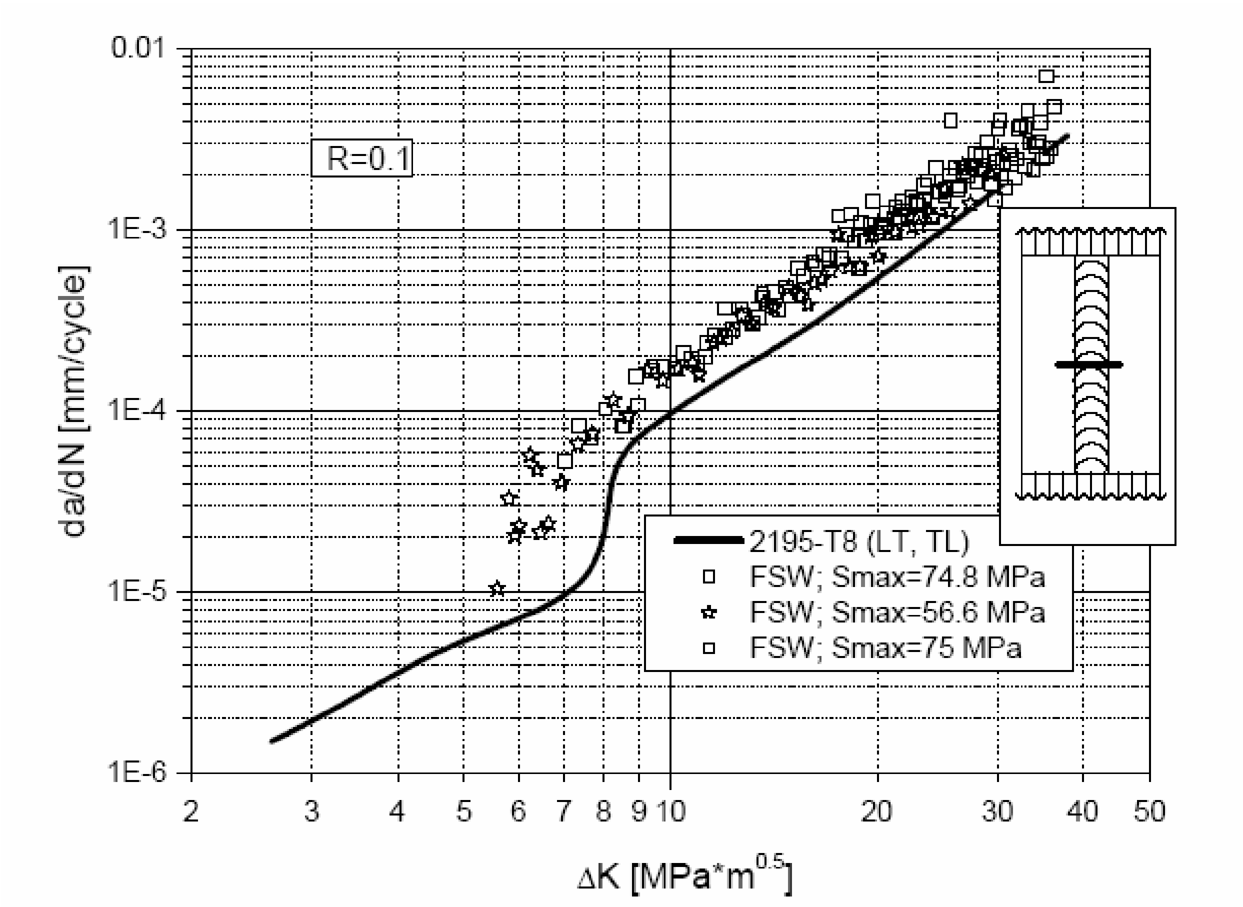


Fig. 27 - Fatigue crack propagation in 2195-T8, R=0.1, across the friction stir weld bead.

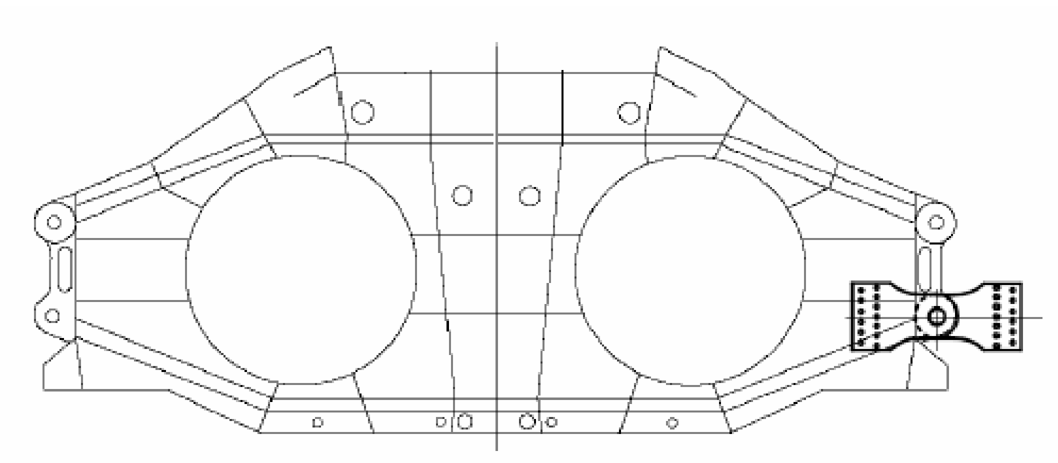


Fig. 28 – Sketch of the M346 fuselage frame with location of the attachment specimen.

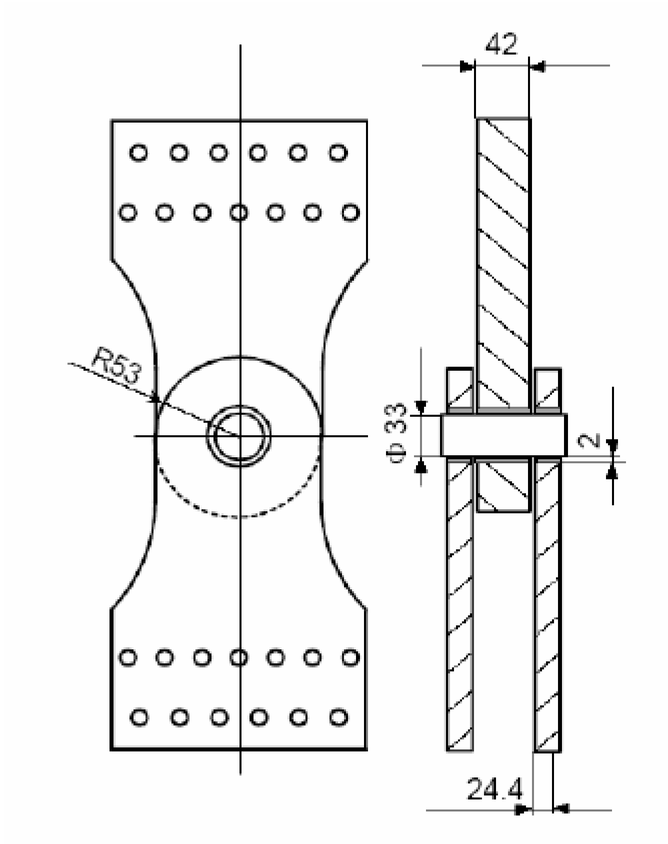


Fig. 29 – Geometry of the specimen simulating the M346 wing-to-fuselage attachment.

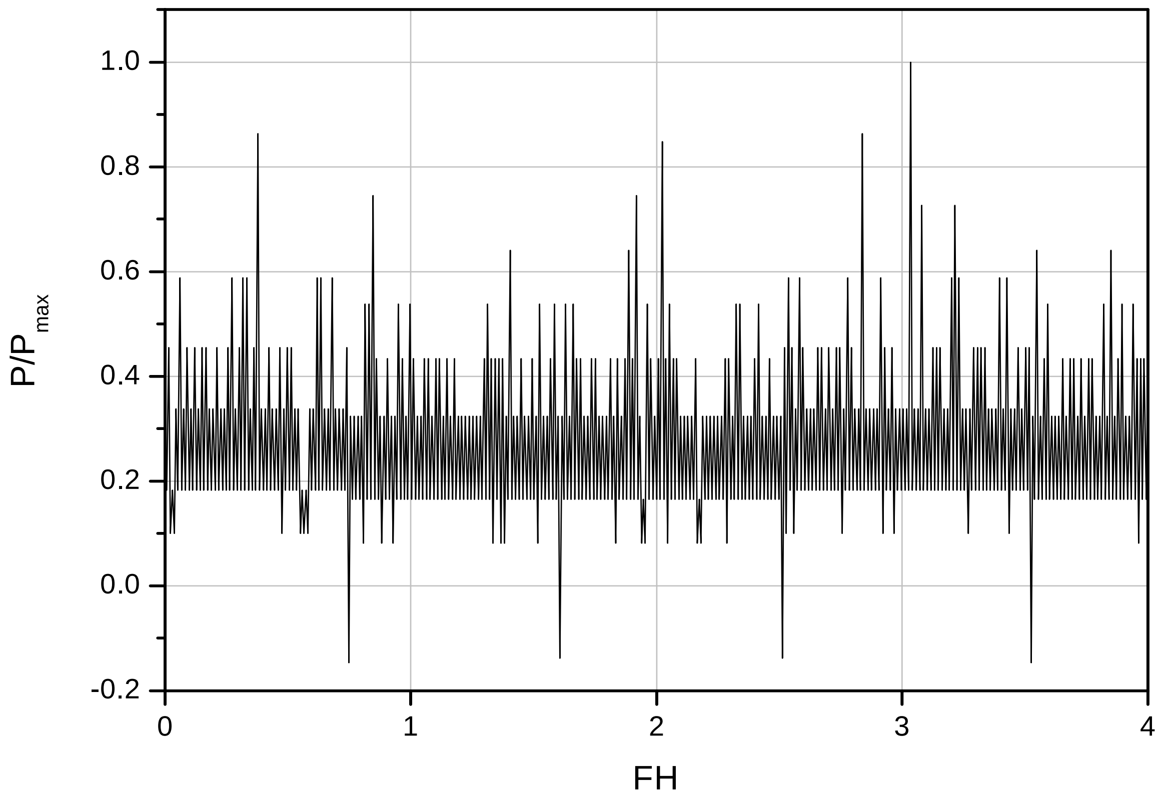


Fig. 30 – First flights of the flight-by-flight sequence of the M346 wing-to-fuselage attachment.

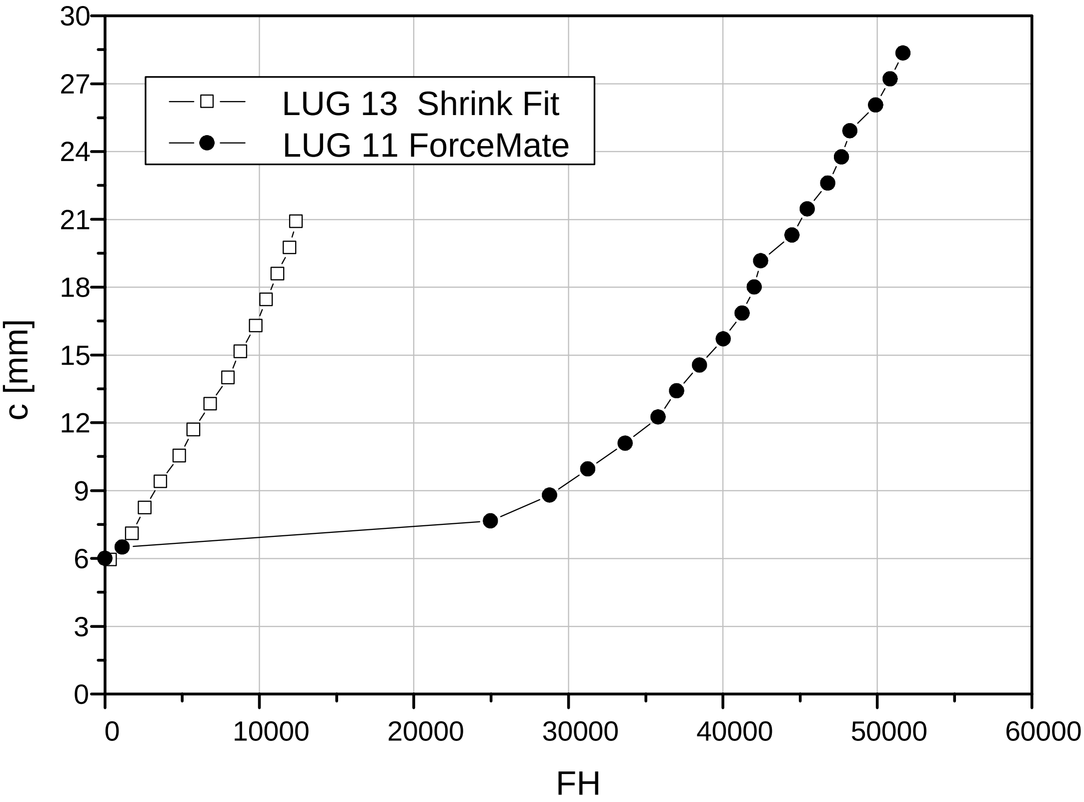
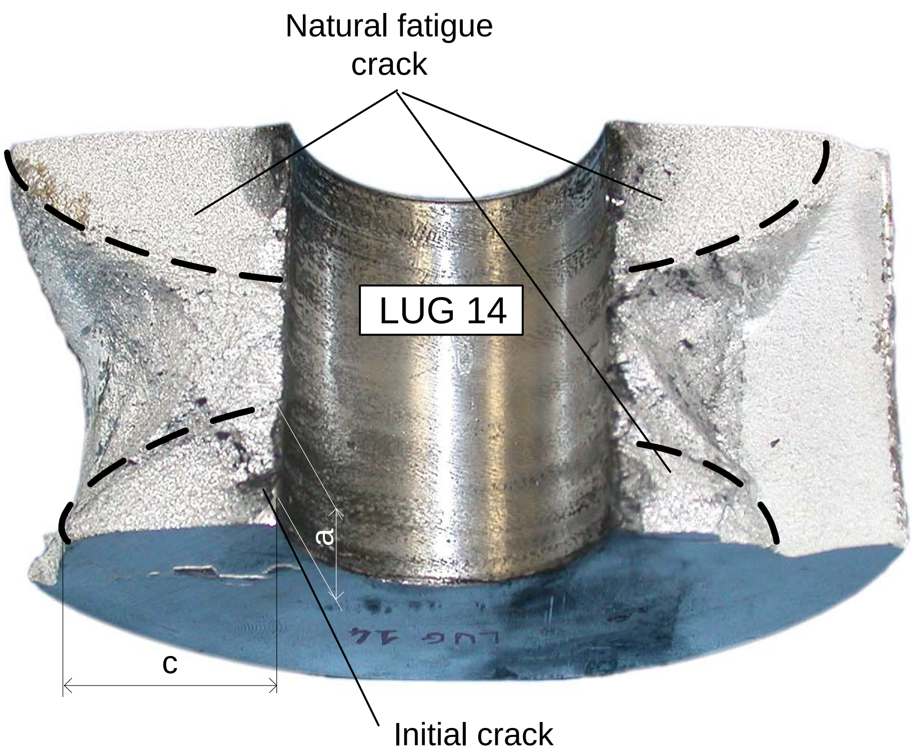


Fig. 31 - Fatigue crack propagation in specimens having a shrink fit or a ForceMate bush installed.



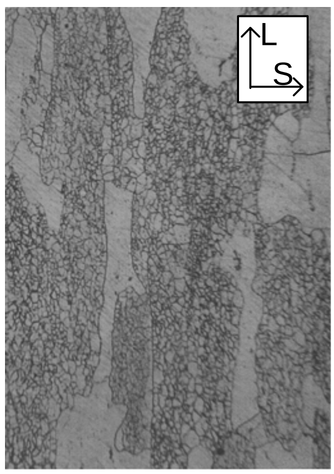


Fig. 32 - Typical fracture surface in a lug/fork specimen and micrograph of the internal structure of the material.

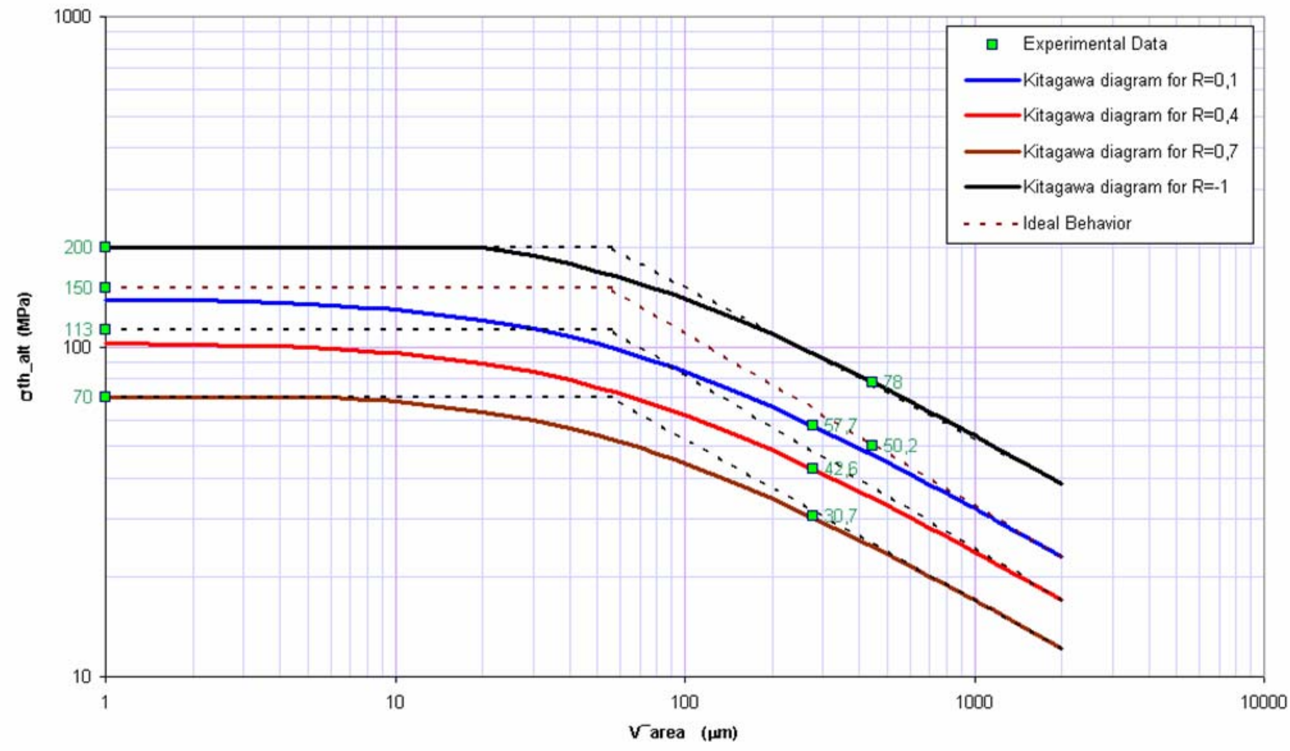


Fig. 33 - Kitagawa diagram for 7475-T7351, for various stress ratios.

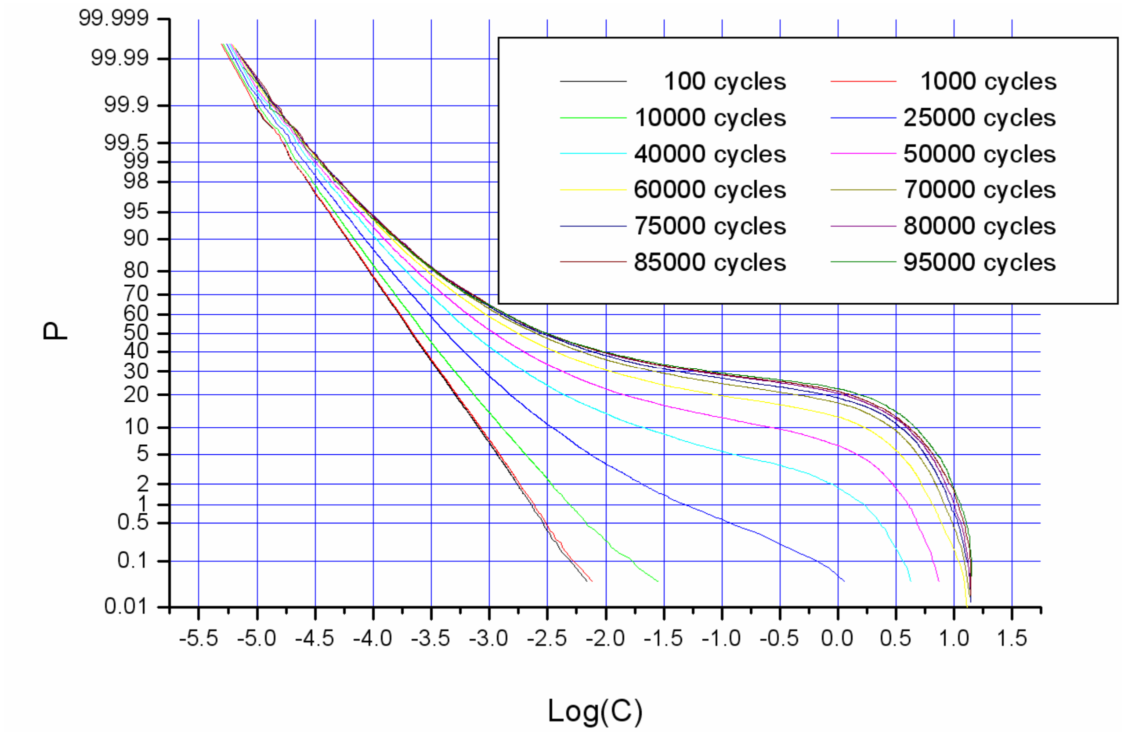


Fig. 34 - Crack distribution in a lap joint at given number of cycles (c = crack length, mm).

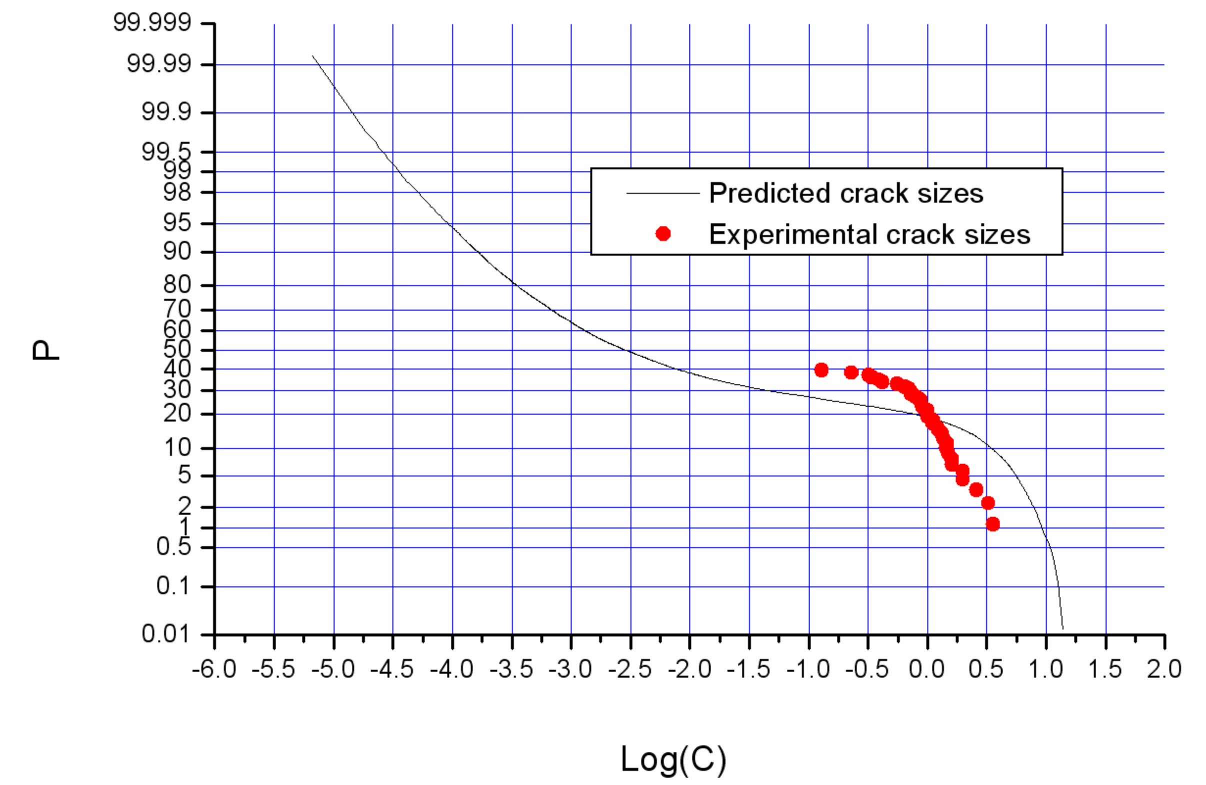


Fig. 35 - Comparison between experimental and predicted crack sizes at 75000 cycles (same example as previous figure).

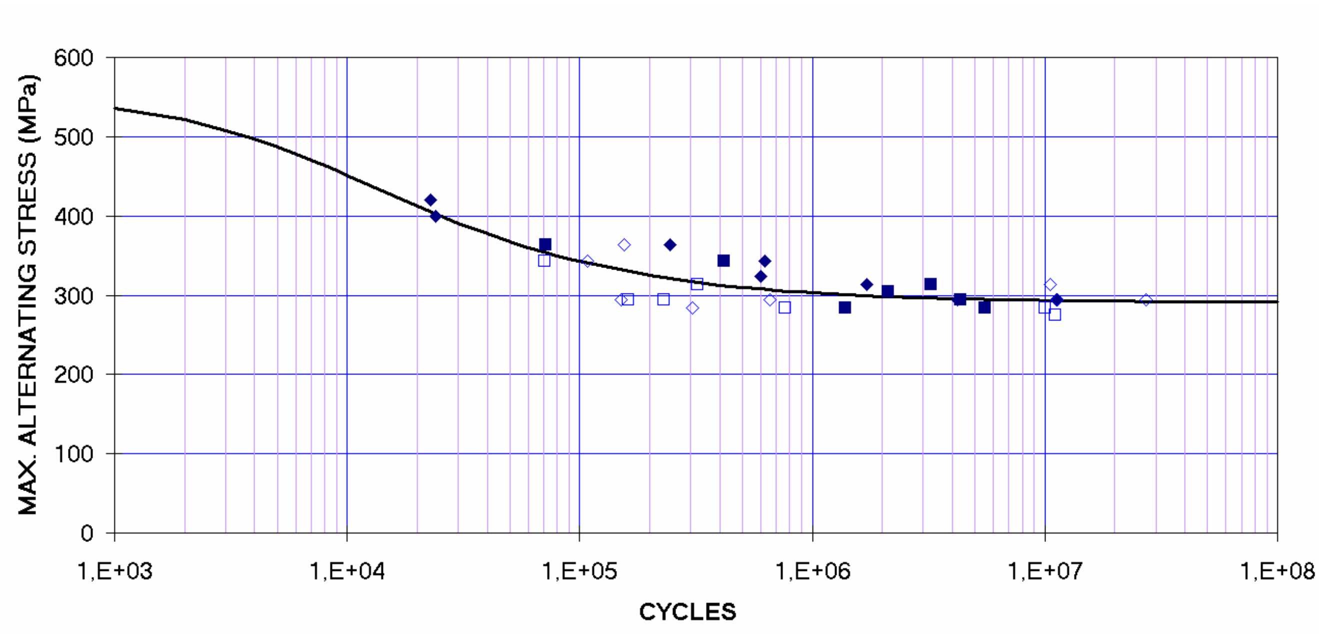


Fig. 36 - Fatigue test results (R=0.1 and Kt=1) from specimens taken from forging of 2009-T4 alloy reinforced with 15% SiC particles. Open data points are relevant to anodised specimens, solid to not anodised, diamonds are referred to longitudinal and squares to transverse specimens.

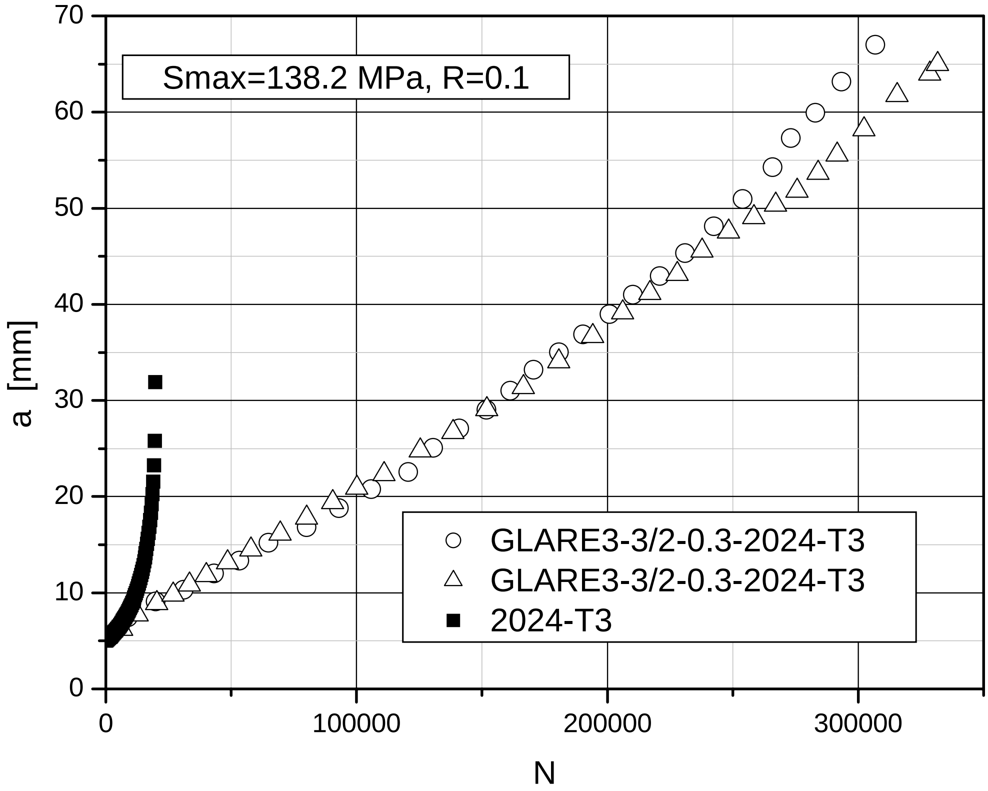


Fig. 37 - Fatigue crack propagation in monolithic and FML panels.

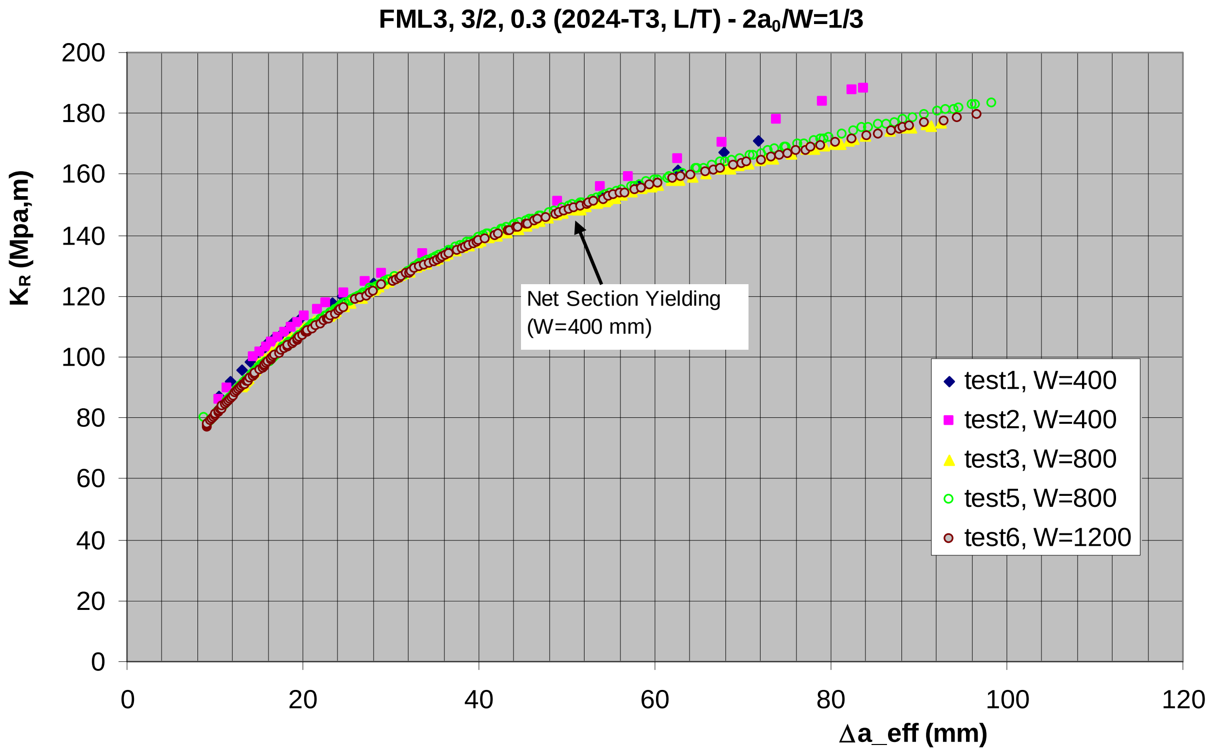


Fig.38 – Comparison of R-curves of FML panels of different width (Irwin correction, 340 MPa).

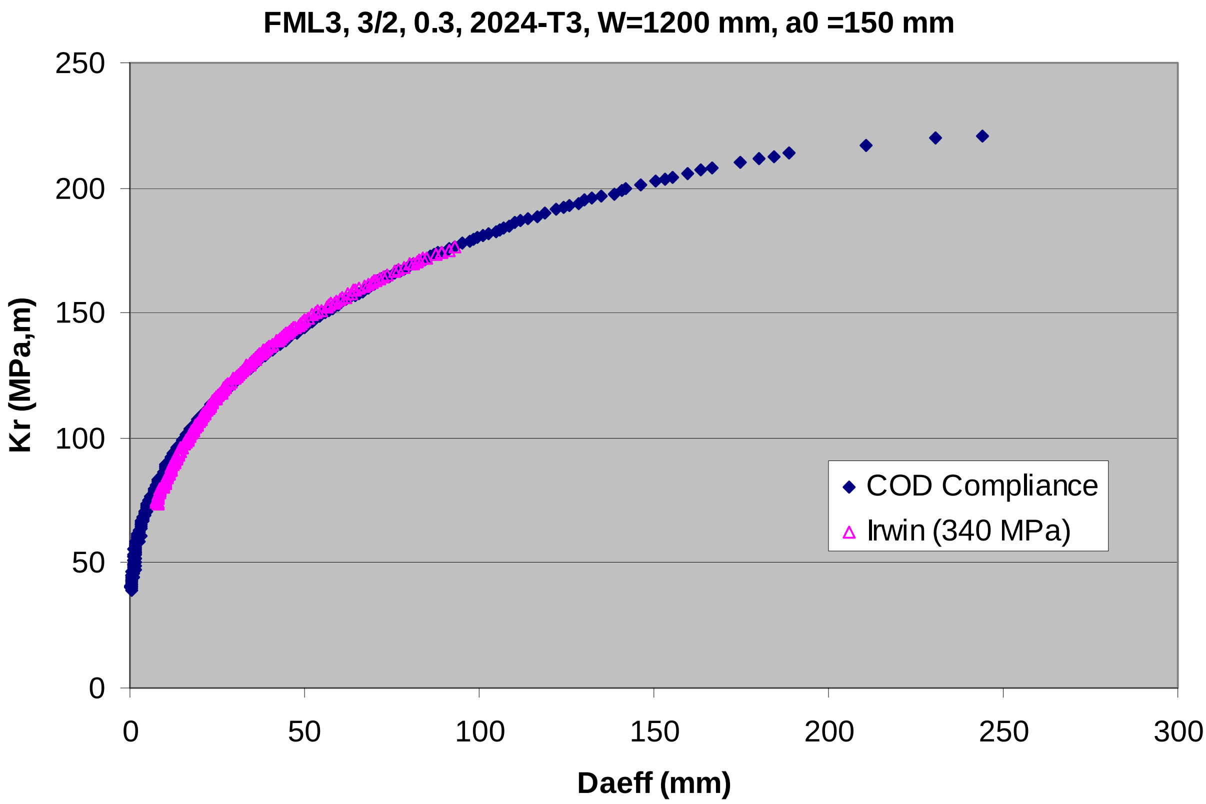


Fig. 39 - Comparison of R-curves obtained from the same test, using different data analysis procedures.

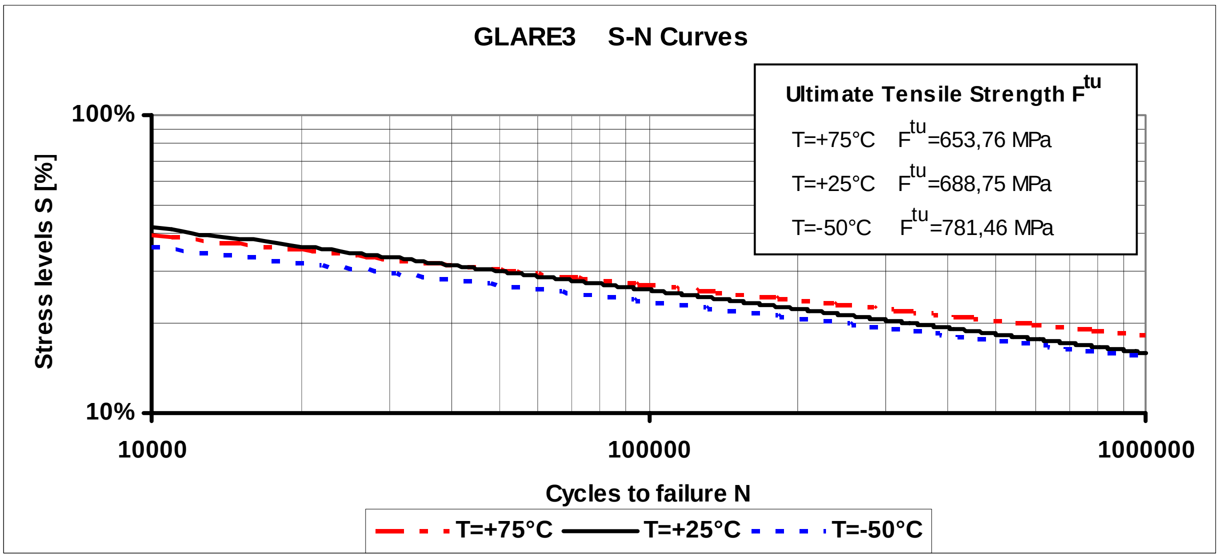


Fig. 40 - Basic fatigue property of FML3-3/2-0.3, at various temperatures.

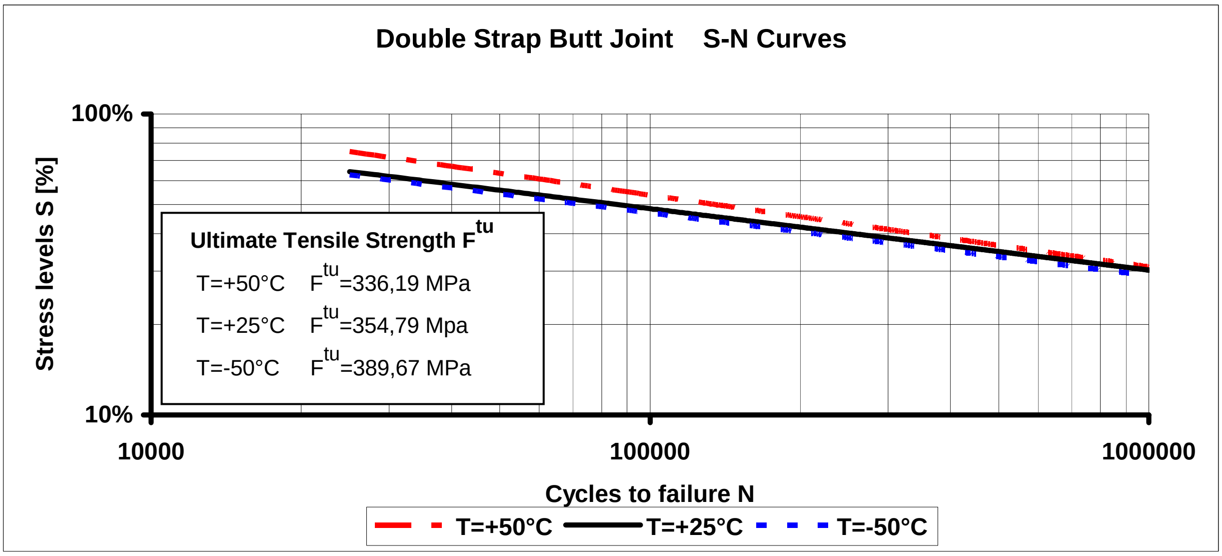


Fig. 41 - Fatigue strength of double strap butt bonded joint in FML3, at different temperatures.

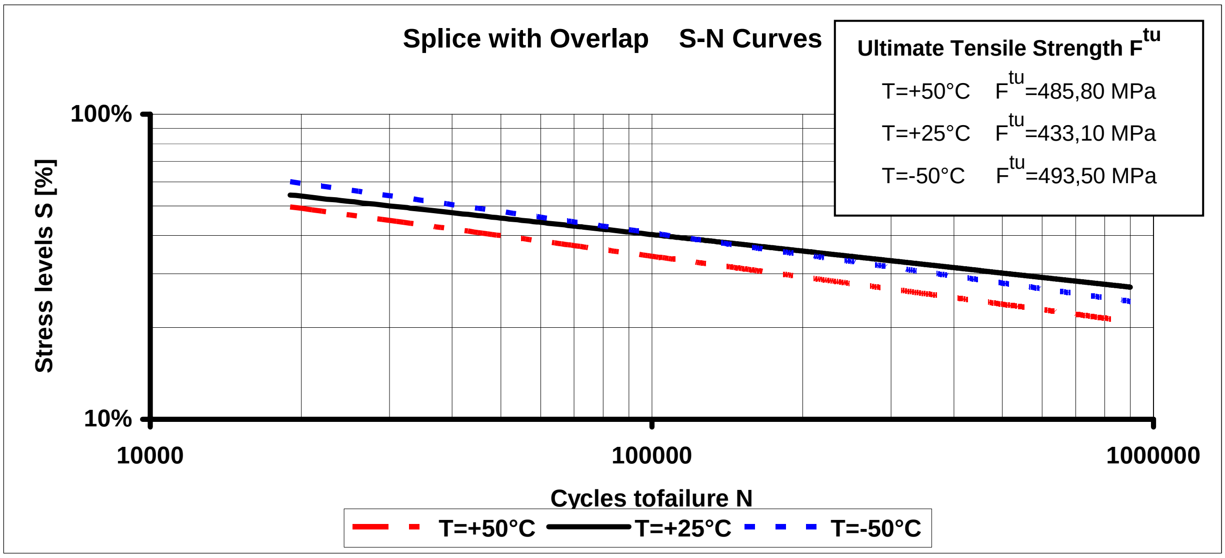


Fig. 42 - Fatigue strength of FML with internal splices (overlap, 12.7 mm), at different temperatures.

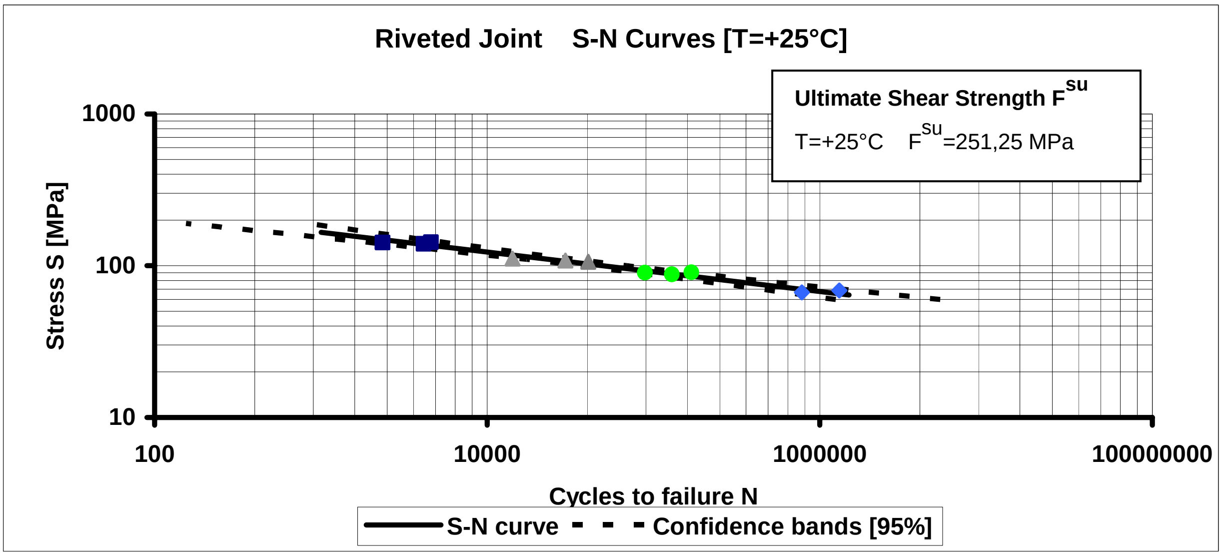


Fig. 43 – Fatigue strength of a riveted joint in FML3.

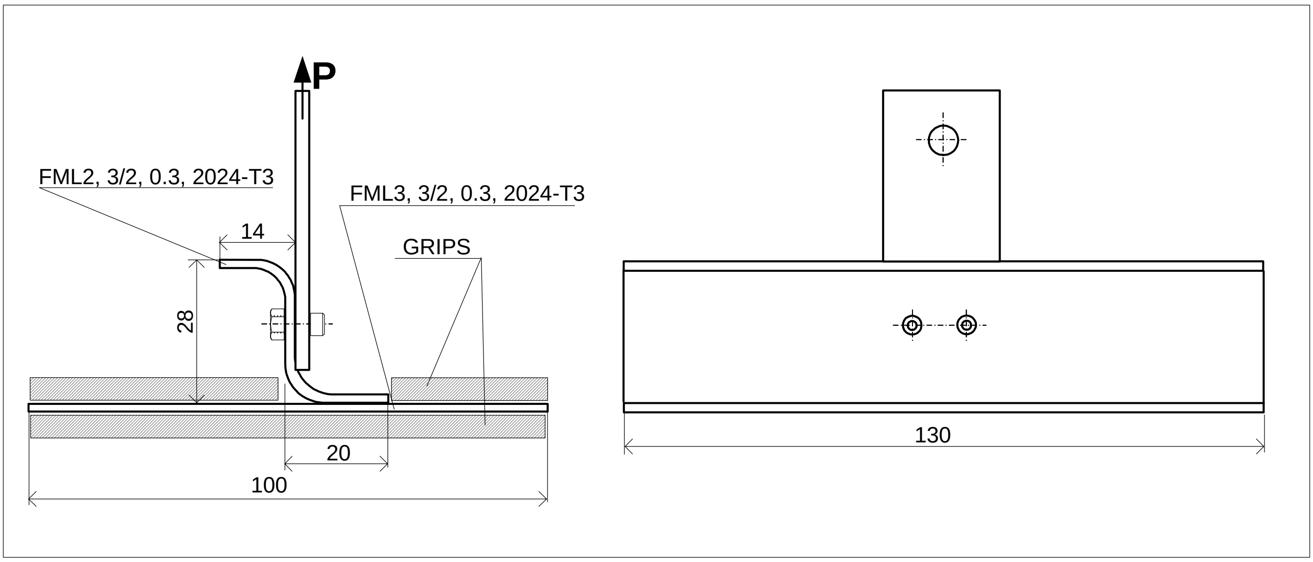


Fig. 44 - "L-Pull" specimen.

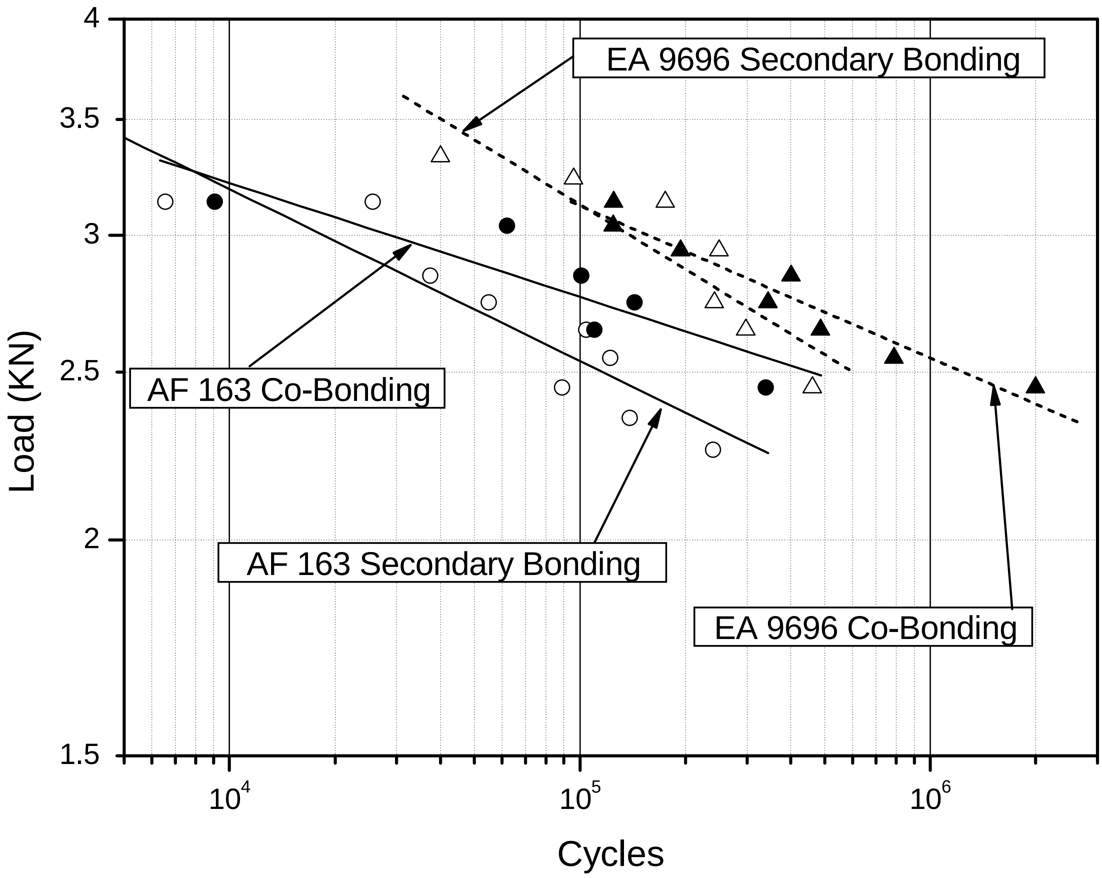


Fig. 45 - "L-Pull" specimen fatigue test results (R=0.1, f=10 Hz).

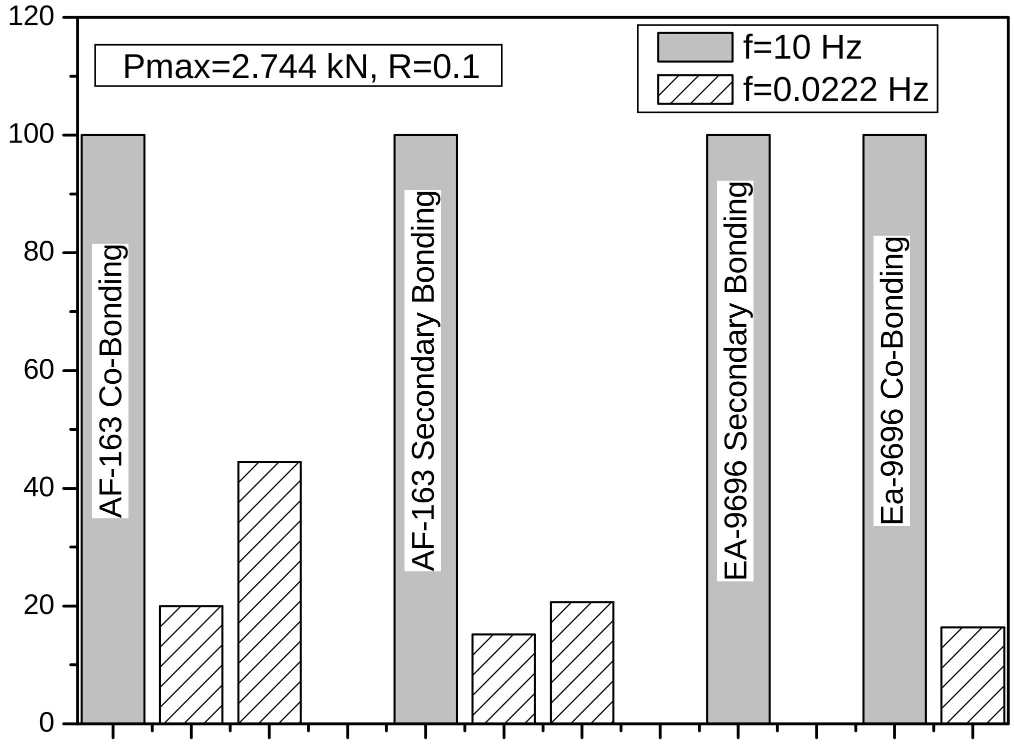


Fig. 46 - Results of the low frequency fatigue tests on "L-Pull" specimens, as a percentage of the respective standard frequency fatigue test results.

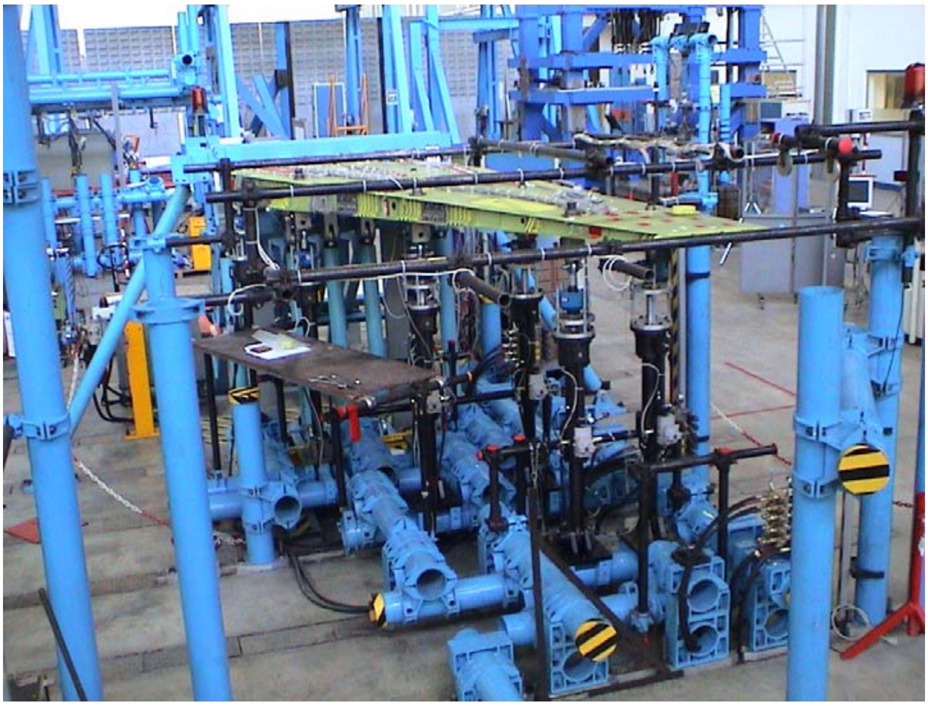


Fig. 47 – Development fatigue test of the LH wing of the M346 trainer.

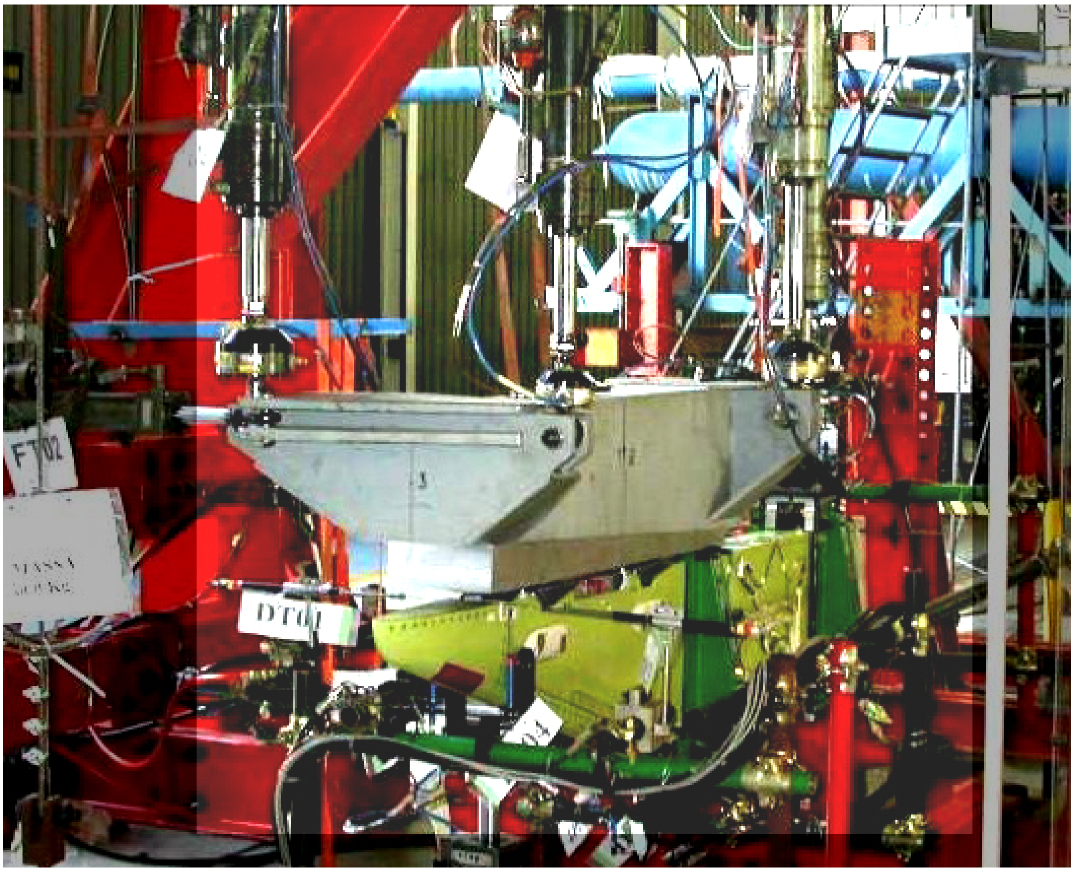


Fig. 48 - Fatigue test of the EF Typhoon wing inboard pylon.

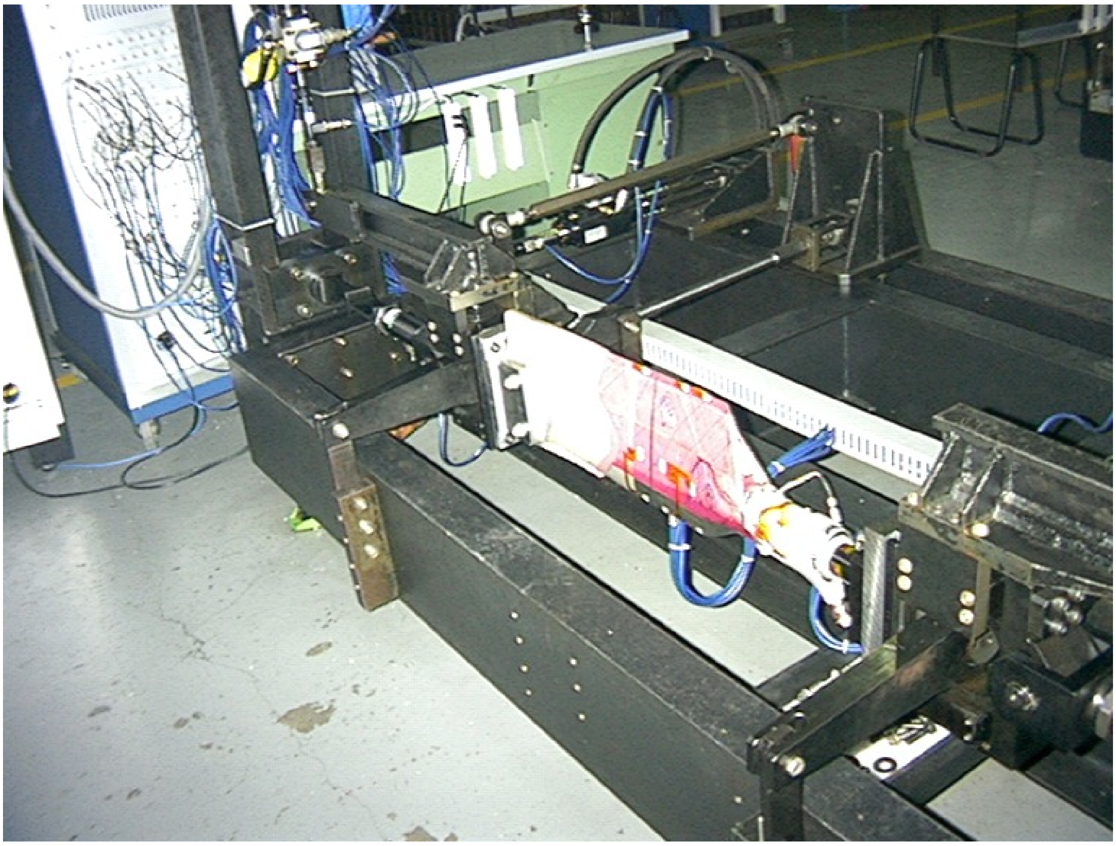


Fig. 49 - Test rig for the fatigue test of the Tail Rotor blade of the A109 helicopter.

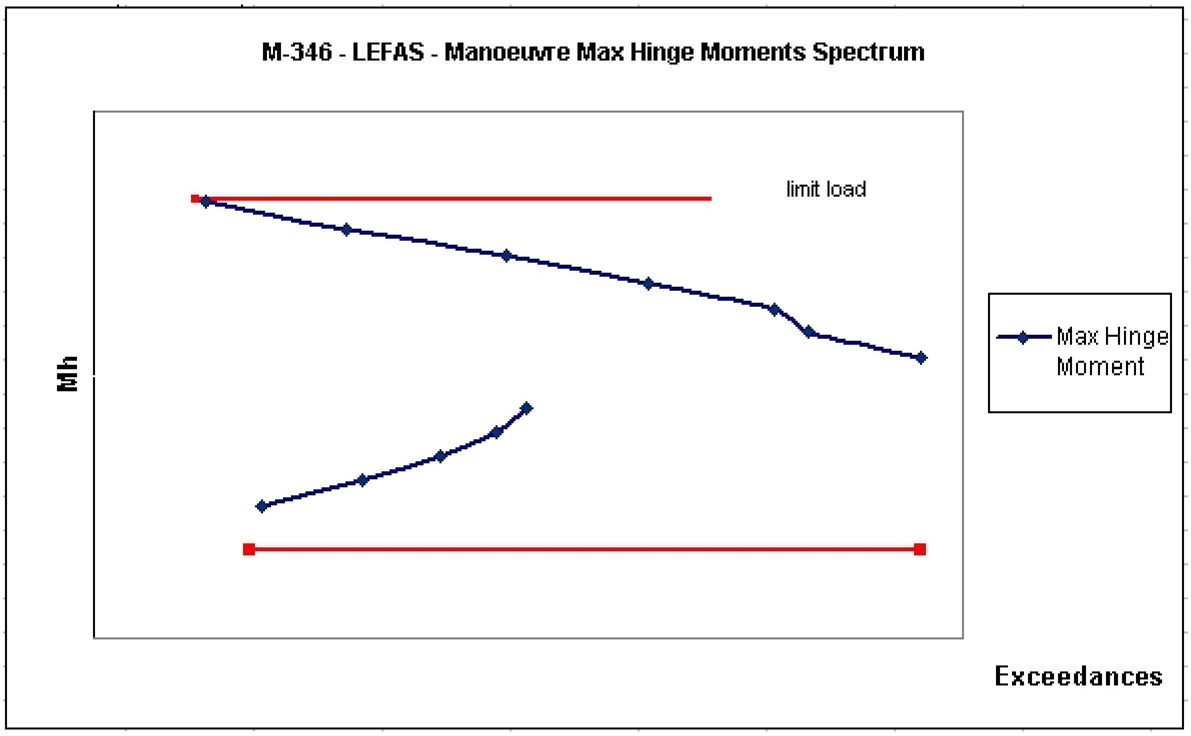


Fig. 50 - Leading Edge Flap Actuation System spectrum for fatigue substantiation.

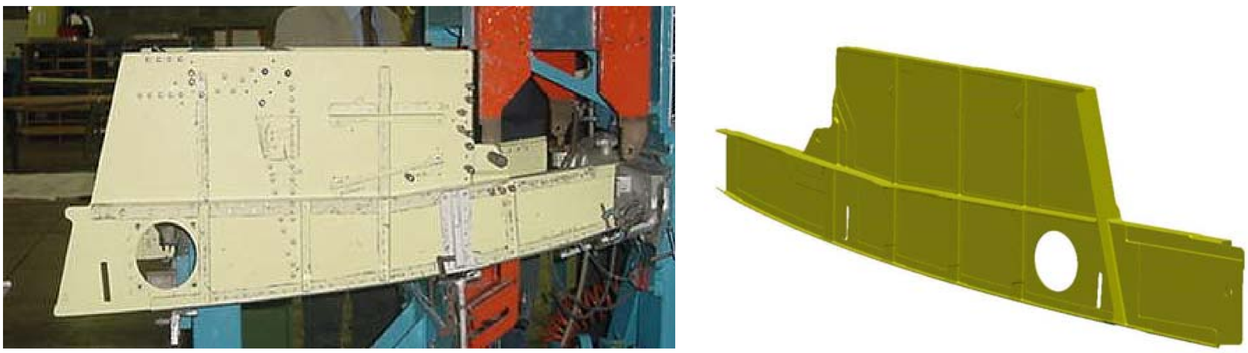


Fig. 51 – P.180 nose landing gear sidewall: change to an integral solution.

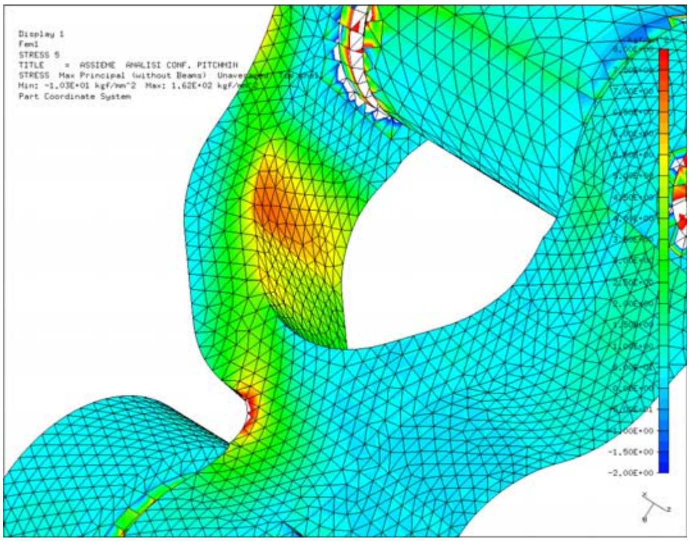


Fig. 52 - Component stress concentrations evaluated by FEM technique

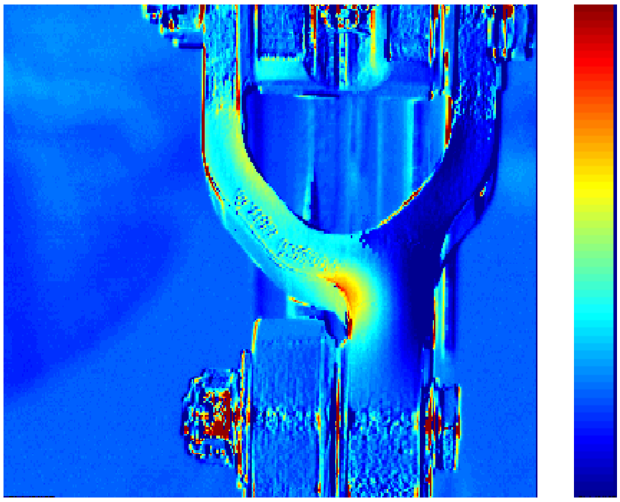


Fig. 53 - Raw TSA image at 1,8 Hz of the component in the previous figure

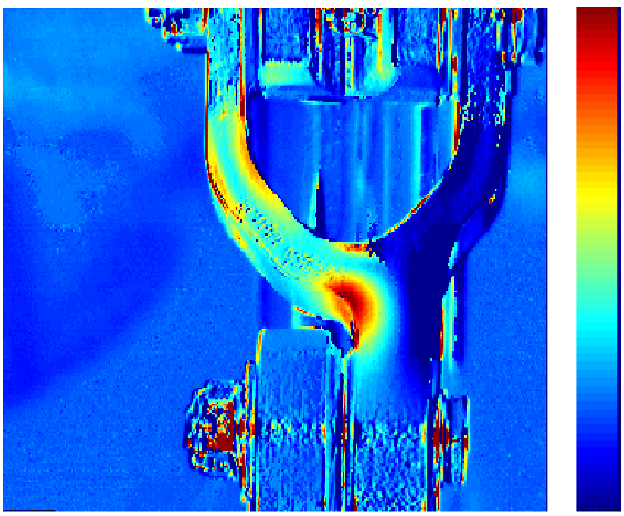


Fig. 54 - TSA image after a linear correction applied to the previous image.