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 2001 - March 2003

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 2001 – March 2003. The main topics covered are: load measurement actions, fatigue and fracture mechanics of metals, probabilistic design methodology, full scale testing.

28th ICAF Conference, Lucerne, Switzerland, 5-6 May 2003

CONTENTS

1. INTRODUCTION

This paper summarises aeronautical fatigue investigations which have been carried out in Italy during the period April 1999 to April 2001. The different contributions have been arranged according to the topics, which are loading actions, 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, made 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 going on, based on g-meter readings, together with configuration/mass analysis and mission profiles. So far, 108,000. flight hours have been monitored, corresponding to 92 thousands 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 hour of the reference spectrum. The LSI has an average value, for all the fleet, that is very close to 1, as shown in fig. 1, which means that the utilisation is very close to the design spectrum. About 25% of the fleet experiences an LSI greater than 1, i.e. the flown spectrum is more severe than the design one. Significant variations in fatigue consumption rate were observed during the time for various aircraft, according to their utilisation, fig, 2.

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. A new version of the Maintenance Recorder System was produced and has been delivered to the I.A.F. From the beginning of the monitoring activity, 190 thousand flight hours were processed, corresponding to 134,000. flights. The analysis of the data of this large statistics 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. 3), but, looking into more details, significant changes can be observed in the years among individual aircraft, fig. 4.

The general trend shows that the service life of the aircraft can be extended beyond the original design assumption of 4000 flight hours, but also that individual tracking must be maintained. Since the fleet is expected to be kept operative for further 20 years, the fatigue status of the aircraft is under re-evaluation in a long term work, that started analysing the qualification status and the required maintenance actions on the main structural items of the aircraft. At the same time, an upgrade of the fatigue monitoring algorithms is in progress, with the purpose of improving the accuracy of fatigue life calculations and so to optimise maintenance costs and to extend operative life.

In co-operation with other PANAVIA partners, a reorganization of qualification data cumulated during the past years took place, identifying for each significant item all the modifications introduced; in the next future the work will continue detailing the steps that produced the item qualification. The PANAVIA consortium is also considering the service life consumption of items that are not specifically monitored.

2.3 – EF Typhoon (Alenia Turin)

The Instrumented Production Aircraft No. 2 first took off at Turin Caselle airport on April the 5th, 2002, while about one year later (on the 14th of February 2003) the first series trainer aircraft was delivered to the Italian Air Force. Moreover, the Alenia prototypes (DA3 and DA7) are continuing the flight test activity.

A simplified structural fatigue monitoring is on going for the prototypes, using flight test instrumentation and comparing design spectra with flown spectra of some significant flight parameters. A specific monitoring of buffet is performed, recording the time spent in flight conditions potentially prone to generate this phenomenon.

In collaboration with BAe Systems, Alenia started the verification activity of the Structural Health Monitoring (SHM) system, that is the on board life monitoring system for Typhoon. This is installed in the Interface Processor Unit of the aircraft and is composed by 3 parts: a) the fatigue index calculation in 10 structural significant locations; b) the auxiliary data relevant to the flight data (normal acceleration, roll rate, Mach number, altitude, weight, etc.); c) the event monitor, that points out the structural significant events compared with user-defined flight envelopes. The SHM system has the capability of analysing up to 8 different event types.

Alenia is now performing an activity of end-to-end testing of the event monitor for the validation of the SHM system. The evaluation process consists of a separate analysis of the flight data of the Instrumented Production Aircraft, aimed at the identification of the structural significant events, and in a comparison of such results with those obtained by the SHM system. The defined envelopes, tested so far, are: normal acceleration vs. roll rate, side-slip angle vs. angle of attack, fore-plane shear flow angle vs. dynamic pressure, sink rate vs. mass.

2.4 - Assessment of buffet load spectra on the empennages of M346 (Aermacchi)

The flight envelope and the service missions profiles of the M346 have been accurately investigated in order to determine the flight environment (particularly high angle of attack manoeuvres) that generate significant buffet phenomena and to identify the related energy levels.

The number of occurrences of buffet cycles have then been defined considering the natural frequencies of the structure, while load levels have been obtained from a fin dynamic model, calibrated on DEMO flight activity and wind tunnel data.

Figure 5 shows the actual assessment of the spectrum. The buffet spectra will be compared with in-flight measured data on the first prototype. Strain gages and accelerometers will be placed on the fin and stabilator structures in order to measure the buffet loads due to high angle of attack and control surfaces displacement.

3. METALS

3.1 - Fatigue behaviour of notched and un-notched materials

3.1.1 - Flaw tolerance assessment of typical helicopter components (Uni. Pisa)

A research activity has been carried out at the Department of Aerospace Engineering of Pisa, within a collaboration with Agusta, for the assessment of the flaw tolerance capability of some helicopter components. According to the FAR/JAR 29.571, the structure must be shown to be damage tolerant (preferably), or flaw tolerant or, if the application of both these concepts is impractical for the component under examination, the “safe life” approach can still be used. The objective of the research was to evaluate the Flaw tolerance approach, that is also called “enhanced safe-life”, that is a safe life design based on the use of experimental data (S-N curves) obtained from flawed coupons.

For this purpose, some details of a new helicopter under development, considered to be critical from the fatigue point of view, have been analysed by means of Finite Element analysis, so obtaining the peak stress and the stress gradient at a number of “hot spots”. The results of the FEM analyses have been utilised for designing, for each critical area, a specimen in such a way to reproduce the same peak stress and gradients of the critical area. Three details have been examined and for each of them a specimen has been defined, accordingly.

For each specimen, 16 to 18 samples have been manufactured, with the same material, orientation and similarity in the technology of the structural element. On these samples, three types of fatigue tests have been carried out: one first group of specimens has been tested under CA load, in order to derive a standard S-N curve; a second group has also been tested under CA loading, but after that a corner crack of about 0.38 mm had been introduced by EDM in the critical section; the third group, also with an artificial flaw, was tested under VA load conditions.

During the tests, information was collected not only on the time required for the nucleation of a crack of about 1 mm in length, but also on the propagation of such a crack. This information is significant for calibrating the analysis tools utilised in the design. As an example, fig. 6 shows the S-N curves obtained for a detail representative of a reinforced hole in a 7475-T7351 plate, with evidence of the influence of the presence of initial flaw.

3.1.2 - Fatigue characterization of A357 aluminium alloy (Uni. Pisa)

Within the framework of a collaboration between the Department of Aerospace Engineering of the University of Pisa and MBDA Italia, a company working in the defence area, an investigation has been carried out about static and fatigue behaviour of a typical aluminium alloy for casting, A357. Basic fatigue tests have been carried out under Constant Amplitude loading, R=0.1, on unnotched specimens, cut from the thin shell of a missile, obtained by micro casting. The results are shown in fig. 7 and appear affected by a low scatter. In some cases, the examination of the fracture surface revealed the presence of defects, due to the micro casting process, that were the locations where the crack nucleated. A quite evident example can be seen in fig. 8.

3.1.3 - Evaluation of HIP (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 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.

The fatigue test results hereafter reported (fig. 9) were conducted on un-notched specimens machined from cast rods (R=0.1). This type of specimens did not contain flaws or surface defects (practically they were free from defects detectable by x-rays), so that data obtained shall be only regarded as upper limit of what may happen on a complex casting. On the other hand, the tests carried out are able to show the effect of the HIP process by itself, when the healing of unacceptable porosity is not the main purpose.

3.1.4 – Fatigue evaluation of high performance nitriding steels (Agusta)

Carburising and Nitriding Steels are used traditionally in gearboxes, after application of the relevant case hardening process. Nitriding process is usually characterised by a series of general advantages compared to the carburising process, especially because the nitriding process can be applied to the part very near to the final shape. The nitriding takes place at relatively low temperature (500°C-550°C) in dissociated ammonia atmosphere. The part does not need to be quenched subsequently, and the degree of stock removal after nitriding on the hardened surfaces is quite limited. Also the deformations are very low, which is particularly useful on precision transmission parts.

On the other hand, from the metallurgical point of view, some alloy elements which mainly favour the penetration of nitrogen (Aluminium) may also reduce the toughness properties. Toughness is one factor which has so far limited the use of nitriding steels.

Agusta has carried out a comprehensive activity on the Alloy 32CDV13 VIM-VAR (SAE-AMS 6481) to investigate the potential advantages. The basic improvement which was expected, was a substantial increase in the toughness over the typical Al based nitriding Alloy (Nitralloy N AMS 6475); it was expected a similar or better behaviour also in terms of fatigue and surface fatigue. The test programme confirmed the toughness improvement (Charpy V energy from about 12 J to more than 100 J).

From the fatigue point of view, many tests were carried out on the non-nitrided and nitrided conditions. The process was optimised to achieve the best compromise between case hardness profile and residual compressive stresses. Tests on shaped specimens, reproducing the root radius of the gear tooth, but suitable to be tested in axial loading, were carried out to evaluate the performance in fatigue of the materials in the nitrided condition. In such specimens, the root radius is associated with a K_t factor of 2.1.

The high cycle fatigue curves (the tests were run up to 10^7 cycles), obtained from two materials and for two stress ratios, are shown in fig. 10. It can be noted that, for the fatigue life of interest, only R=0.1 tests are able to discriminate between the different behaviour of the two materials, with better performance of the new alloy (the results are for two different processes), while for R=-1 no particular difference can be observed.

3.1.5 - Factors conditioning the fatigue resistance of stainless steel sheets (Agusta)

Recent work carried out by Agusta on austenitic stainless steel sheets has highlighted the considerable dispersion of fatigue limit results.

Stainless steel sheets are generally classified according to the amount of cold working applied in the manufacturing process, which determines the final resistance or to the ultimate tensile strength. During this research activity, 11 different sheets of AISI 301, in the 1/4 hard condition (thickness 0.2 mm), were cut up to obtain a suitable number of fatigue test specimens. The overall result is shown in figure 11, where the data are plotted according to the classic S-N presentation, and are already interpolated by Woehler curves depending on the original metal sheet. The specimen Kt was 1 and the stress ratio 0.1.

Such data have been subsequently analysed considering the different values of yield strength, which had been measured for every single sheet. The observed degree of dispersion of the fatigue test results (as evident from the range of endurance values) is quite high considering the fact that specification, sheet thickness and size are constant for all the tested sheets. On the other hand, the correlation of the results for the specimen coming from the same sheet, if independently considered, was quite satisfactory.

In the effort to reveal the factor that differentiates one sheet from the other, it was possible to prove that the endurance limits were not scattered in the same way if normalised to the local yield strength, as it clearly appears from the plotting in figure 12.

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

The need to introduce also in rotorcraft components design substantiation criteria based on damage tolerance and flaw tolerance, is driving the attention to materials with better crack propagation characteristics.

The nested metallurgical microstructure of Ti-6Al-4V alloy solution treated in β phase is considered to be useful to hinder the propagation of fatigue cracks. The material in most of the application in structural parts has been used so far in the α/β forged + α/β annealing condition. Recently, some preliminary testing has been carried out to investigate the behaviour of the same basic alloy in the β solution treated and over aged condition. The testing was limited to examination of specimens cut from bars of various diameter which were preliminarily heat treated. Solution treating in β phase requires a quite immediate quenching, which limits the possibility to apply this process only to relatively thin sections achievable after preliminary machining.

Fatigue tests were carried out in rotating bending on un-notched specimens and the results are shown in figure 13. The various Woehler curves show that the high cycle fatigue is beneficially affected by the tested heat treatment; due to the cross section sensitivity of the process, some lower data are obtained from a larger cross section. In addition, crack propagation tests were performed applying decreasing K procedure in order to determine crack growth rates in the order of 10^{-5} to 10^{-8} mm/cycle. An improvement in terms of propagation threshold was observed.

3.1.7 - Application of surface coatings for anti-wear purposes (Agusta)

Fretting fatigue conditions are seriously detrimental to Titanium components. This kind of problems can easily appear at the interface between lugs and shafts or bushings, which is, on the other hand, a quite typical situation in dynamic components. Previous work has shown that the application of surface coatings of various types can beneficially reduce the fretting effect and positively affect the fatigue endurance. Among the coating processes, thermal spray is the most frequently used by Agusta and particularly the Detonation Gun process, which is also covered by an Agusta process specification.

However, as experimentally shown in the past, this and other thermal spray coatings are detrimental to the non-fretting fatigue behaviour; in other words, in absence of fretting conditions, the fatigue endurance is decreased by this kind of coating process. Then, the choice whether to apply the coating or not must be carefully evaluated, bearing in mind these two aspects of the problem. In the period of the present Review, fatigue tests of “structural elements” type specimens were carried out with the main purpose to estimate the negative effect of a specific D-Gun process (86% of WC in Co matrix) at the border of the coated area, in absence of fretting conditions.

The tests were carried out on non-coated and coated specimens, the latter with three different coating thickness values (0.10, 0.15 and 0.20 mm). Whereas the coated specimens appear on a distinct and lower fatigue curve with respect to the non-coated, an effect of the coating thickness in the mentioned range was not found. Test parameters and results are shown in figure 14.

3.1.8 - Durability and damage tolerance characterization of the Force Mate bushing installation process (Aermacchi)

For fatigue and fracture critical parts requiring good Damage Tolerance characteristics, apart from the usual material careful selection (good balance between static, durability and DT capabilities), the main fatigue enhancement processes and solutions have been widely used in the design of the airframe of the M346 trainer developed by Aermacchi. In particular, the FTI ForceMate bushing installation process has been introduced in the wing main spars lower lugs connecting the wing box to the fuselage frames.

Their beneficial effects have been experimentally investigated with simple and more complex tests, carried out on different coupons sizes and joints specimens (lugs). Figs. 15 shows an example of initial artificial defect introduced in a double bushed lug thick coupon, while the test rig is shown in fig. 16.

Classic crack initiation tests have been performed, followed by DT tests, applying different load spectra and introducing different flaws, as far as sites and shapes are concerned. Ranging from CA crack initiation tests on double bushed lug thick coupons to Flight by Flight DT development tests on complex joints simulating the wing to fuselage main fittings, a series of tests have been completed in order to assess the durability and DT behaviour of the wing to fuselage connection system. Part of the experimental activity has been carried out at the Department of Aerospace Engineering of Pisa. Extensive use of split sleeve CX on the main wing box joints, of rivetless nutplates on structures surrounding load-bearing access panel doors and of shot peening on shoulder and corner radii has been adopted.

3.2 - Crack propagation and fracture mechanics

3.2.1 - Fatigue crack propagation under helicopter spectra (Uni.Pisa)

Within the framework of a collaboration with Agusta, a research activity has been carried out for the assessment of the accuracy and reliability of current models used for fatigue crack growth predictions. There is an increasing interest on this subject, since current Airworthiness Requirements are fostering the application of damage tolerance philosophy in metallic helicopter structures, while the most known models have been developed and set-up for fixed wing applications.

An experimental activity has been carried out on simple M(T) coupons, made of thin Aluminium alloy, 2024-T3 and 2024-T42. The thickness was 1.0 mm and the sheet orientation was L-T. Constant amplitude tests have been carried out for the assessment of the basic crack growth behaviour of the two alloys (the –T42 temper is less common than the most used –T3), including also threshold tests. Also variable amplitude tests have been carried out, using spectra defined by Agusta according to typical sequences for fuselage panels, recorded in flight. In total, three sequences have been utilized in the test activity: a passenger transportation mission (relatively mild), a patrol mission (with a high number of manoeuvres) and a global mission, that is not a real typical flight but simply an averaged mission, deduced from the cumulative distribution of stress levels relevant to all the missions examined. As an example, the spectrum relevant to the Passenger transportation mission is shown (with maximum stress equal to 100 MPa) in Fig. 17. In total, 8 VA tests for each material were carried out, since two replicates were performed for each mission, and for the passenger load sequence two stress intensities were studied.

The CA activity produced results very consistent with those available in the literature for the –T3 temper, while the –T42 treatment, not so common, showed as good results, and sometimes even slightly better. The CA data were used to evaluate the accuracy of the Nasgro equation, available only for the –T3 material, for the description of the da/dN – ΔK curve.

For the VA predictions, AFGROW, CORPUS, FASTRAN and the strip yield model implemented in the Nasgro code were used. The tests carried out using the patrol spectrum resulted to be very difficult to be predicted, since the spectrum is characterized by a high number of changes in stress amplitude and average stress, with a long cruise with small amplitude cycles. The test results show clearly that in some mission segments the crack is propagating and in some other not. As a consequence, it is very crucial to evaluate accurately the opening stress, since a high number of cycles are applied in a flight. This peculiarity of the helicopter spectra is the major difficulty in applying damage tolerance principles to helicopter structures, in practical.

Fig. 18 shows the test results obtained under the Passenger transportation loading, compared with the predictions, obtained for the -T3 material.

Other details about this activity can be found in [1].

3.2.2 - Fatigue crack propagation of through cracks in thin sheets under combined traction and bending stresses (Uni. Pisa)

To better understand the role of bending stress superimposed on membrane stress on the fatigue resistance of riveted joints, crack propagation tests of through cracks in 3 mm thick aluminium alloy 6013-T6 sheets were carried out, under combined membrane and bending stresses. Five different values for the secondary bending (SB), i.e. the ratio of bending to membrane stresses, were examined: 0, 0.55, 1.25, 1.8 and 2.23. The tests were performed with a 0.1 load ratio (the load ratio was evaluates on the bases the membrane stress only; the bending stress was a non-linear function of the applied load so the stress ratio evaluated on the bases of the combined stresses was slightly different).

At first, the results were elaborated evaluating the stress intensity factor range by considering only the membrane stress and the dimension of the crack measured on the front side, that is the face of the specimen where bending induces tensile stresses. The back side is the other. The results relevant to low SB values, evaluated in this mode, show good agreement with the results obtained when only the membrane stress was applied, fig. 19, so the two hypotheses: straight from and only membrane stress acting tend to counteract. The same approximation is not still valid for the results obtained at higher SB values which exhibit a remarkable increase in the crack propagation rate, fig. 20.

The results were successively evaluated on the basis of stress intensity factor solutions tabulated in [2], relevant to part elliptical through cracks under combined bending and membrane stresses. In [2] the stress intensity factor is given in eight points along the crack front; the characteristic feature of a part elliptical crack is a very high gradient of the stress intensity factor on the back face of the plate, so by using all the data relevant to the eight points a non elliptical front is generated. On the contrary, only two values are necessary to predict the crack growth of an elliptical crack. In this analysis, the two values were those on the outer faces and were calculated in an approximate mode so to produce, in a given number of cycles, the same cracked area estimated using the solutions of [2]. The agreement between this prediction and the experimental results was good when these values of the stress intensity factor were used to counteract the high stress intensity factor gradient present on the back side of the plate. Some results are shown in figs. 21 (different crack front positions) and 22, relevant only to the front crack length. A detailed description of the results obtained and of the analysis methodology utilised is given in [3].

3.2.3 - Experimental determination of fracture mechanics data for the 7050 Al Alloy (Aermacchi / Uni. Pisa)

In a co-operation between Aermacchi and the Department of Aerospace Engineering of the University of Pisa, for the evaluation of DT analysis within the framework of the M346 program, CT specimens have been fatigue tested in order to experimentally assess the crack propagation rate and the Willenborg interaction coefficient of the 7050 alloy in the T7451 condition for appropriate spectra. The CT specimens geometry reference dimension was W = 240 mm.

Three R ratios have been used in the CA tests (R = 0.02, 0.2 and 0.4). The test program included also the evaluation of the crack propagation threshold, while some smaller CT specimens were manufactured for fracture toughness K_{IC} value evaluation. The tests have been carried out in Pisa, using a 500 KN fatigue test machine; the crack growth was monitored with an optical microscope (40 X) supported by crack wires and grid strain gages.

In figure 23 the typical da/dN vs ΔK diagram represents the experimental data obtained from 4 CT specimens, tested at R=0.02, compared with the Nasgro curve suggested for the 7050-T7451 Al alloy in the code material library.

A flight by flight load random sequence representative of 200 flight hours of the M346 design spectrum (fig. 24) has been adopted for the purpose of determining the interaction coefficient (φ) that best tunes the modified generalized Willenborg model predictions. First results seem to indicate that the most appropriate value of φ is greater than 0.5, the default value for the material suggested by the code, indicating significant interaction effects due to the spectrum.

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

The University of Pisa (UP) is involved in ADMIRE (Advanced Design concept and Maintenance by Integrated Risk Evaluation for aerostructures), an European research program whose aim is the research, development and validation of tools for probabilistic analysis in fatigue aircraft design.

In this context, UP has developed a computer code, named PISA, that can simulate the fatigue behaviour of typical aeronautical components, such as riveted joints and stiffened panels or joints, from the beginning of the life up to the failure (see fig. 25). This code has already been introduced in previous ICAF Symposia, but in these last two years its capabilities have been significantly improved. In fact, it uses the Montecarlo method and so it is necessary to perform a lot of computer runs to evaluate the risk assessment. In this context, UP has implemented new analytical expressions for crack growth evaluation and has developed the statistical distribution of the random parameters used as inputs for the PISA code, in particular the distribution of the Equivalent Initial Flaw Size. The use of the EIFS approach is desirable, because it can transform the fatigue phenomenon, that is usually split into a nucleation phase and a propagation phase, into only a propagation phase.

In details,

- ✈ new analytical expressions have been implemented, i.e.
  - the effect of a stiffener on the stress intensity factor K has been evaluated by means of a FEM analysis for realistic geometrical cross section shapes and then implemented into a simple analytical expression for K, as a function of crack dimension and geometrical shape
  - the effect of countersink at holes has been translated into another analytical simple expression for K obtained from a deep critical review of general data available in literature; this has been introduced either for corner crack or through crack
- ✈ to evaluate the distribution of the EIFS, a draw back procedure has been developed, that allowed to start from experimental data of crack dimensions and “virtually” draw them back to their initial size. The tool used for this draw back procedure has been the FASTRAN code, in-house modified to try to take into account the effect of countersink (in this context, the above mentioned expressions for K were used) and of the load distribution inside the joints, i.e. the membrane stress, the by-pass loading, the secondary bending, the pin loads and the interference effect due to the rivets. The rationale was to evaluate the EIFS distribution by using data from simple open hole specimens and then to validate it, by predicting the crack growth in experimental specimens of increasing complexity such as countersunk holes and filled holes coupons, lap-joint panels and stiffened panels. This validation activity has been supported by a large amount of experimental tests and it is already in progress on 2024-T351 aluminium alloy, tested under CA loads at different S_{max} (R=0.1). Unfortunately, this procedure was not able to predict the effect of the load distribution, particularly the bending effect and the interference effect. Research effort is dedicated to improve the model in these aspects.

4. COMPOSITES

4.1 - Fatigue Behaviour of Hybrid Titanium Composite Laminate (Uni. Rome)

The Hybrid Titanium Composite Laminate (HTCL) incorporates the mechanical advantages of existing Fibre Metal Laminates, such as ARALL and GLARE, while extending their application to aggressive environments. Hybrid composite laminates, consisting of layers of Titanium Ti-40 foils bonded together with fibre-reinforced prepreg plies, have been prepared and their mechanical properties evaluated, including fatigue behaviour.

Static tensile and uni-axial fatigue tests have been performed on both MAT/Epoxy composites specimens and Ti-MAT/Epoxy hybrid laminates: MAT/Epoxy specimens were manufactured using the resin Ciba Geigy EC130 LV reinforced by in-plane randomly oriented Fiberite Glass E Chopped Strand MAT 300. The final composite laminate had 16 layers and a total thickness of 3.0 mm. The same composite material was used to manufacture the hybrid laminate, for which two external metallic layers were made of sand-blasted Ti-40 (0.5 mm thick): also in this case, 16 layers of composite have been utilised. Both composite and hybrid laminates were manufactured by an industrial process, involving a pre-curing at room temperature, for 24 hours, and a final reticulation under an hot press at 80 °C, applying a pressure of 12.95 MPa for 15 hours. A summary of the mean results of the static tests is presented in Tab. 1

Material	E (Gpa)	ν	$\sigma_Y^{(a)}$ (Mpa)	$\sigma_u^{(b)}$ (Mpa)
MAT/Epoxy	6.3335	0.3	36	96
Ti -40	104	0.33	280	345
Ti-MAT/Epoxy	26	0.31	110	130

Tab. 1: Static results. (a) Yield strength – (b) Ultimate failure strength

The stiffness properties of the assembled hybrid laminates agree with the ones from classical laminate theory, showing that a good adhesion was achieved between the metallic layers and the composite plies. The static strength of hybrid laminates is lower than the one of bulk Ti-40, since the failure mode is due to a delamination of composite plies.

Fatigue tests have been performed on the hybrid laminate, using a CA loading, R = 0, with a frequency of 2 Hz. Two load levels were applied, performing 5 tests for each load condition: the results of the tests are presented in Tab. 2, where also the corresponding maximum stresses σ_{MAX} attained both in composite plies and in metallic layers are shown.

Tests	F_{MAX} (N/m)	σ_{MAX} Ti - 40 (Mpa)	σ_{MAX} MAT/Epoxy (Mpa)	Cycles to Failure N_f
I	2.7×10^5	212.2	12.50	48392 ± 452
II	2.75×10^5	222.4	13.20	22002 ± 317

Tab. 2: Results of fatigue tests on hybrid laminates

A second group of 5 fatigue tests was performed on both pure Ti-40 samples and MAT/Epoxy specimens: the loads applied in these tests, on both Ti and composite, were chosen in order to obtain equal stresses as in the case of the tests on hybrid laminates. The results of this second experimental campaign are summarised in Tab. 3: it is worth observing that the fatigue life of bulk Ti-40 specimens is about 35 % shorter than the one for assembled hybrid laminates.

Materials	F_{MAX} (N/m)	σ_{MAX} (Mpa)	Cycles to Failure N_f
Ti - 40	7.64×10^5	212.2	30171
MAT / Epoxy	3.26×10^4	12.50	-

Tab. 3: Results of fatigue tests on bulk Ti Grade II and MAT/Epoxy specimens

The ratio between the applied stress and the yield strength is 0.77 for Ti-40 layers and 0.36 for MAT/Epoxy plies. Therefore the metallic layers are considerably more stressed than the composite ones, so that the fatigue strength of the hybrid laminate is ruled only by the resistance of metallic layers.

The higher fatigue strength of hybrid laminates can be related to the very low damage featuring composite plies, which behave as an elastic foundation for the metallic layers: the fatigue performance of hybrid laminates, particularly regarding stiffness degradation, are considerably better than for bulk metallic materials, provided that the composite used for their manufacturing has a low sensitivity to fatigue damage.

5. JOINTS

5.1 - Fatigue behaviour of adhesive bonded repairs (Agusta)

Recently, the need to apply adhesive bonding repair operations arose and specific tests were then programmed by Agusta to evaluate the adhesives performance when they are not applied and cured in the optimum conditions. In fact, the adhesives in repair operations are applied on blasted or sanded surfaces (i.e. without the prior usual galvanic treatment) and their curing is carried out at lower temperature to avoid problems on the assembled part.

A specific test programme was run to evaluate the loss of properties of adhesives which are applied in those conditions. As far as fatigue properties are concerned, fatigue tests were run on two adhesives with standard curing and lower temperature curing as applicable in repair.

The tests which can only be interpreted in comparison one to the other, were run on single lap joint specimens. Those specimens, though quite easy to manufacture and to test, do not load the adhesive in pure shear conditions, since the peel component is generated as a consequence of the asymmetric loading. The test is however valid as relative evaluation of the two conditions. Under this hypothesis, the test results were meaningful to show 1) how the adhesive performance decays due to curing at low temperature and 2) how different adhesives behave differently in those conditions. The results are summarised in figure 26.

6. INTERNATIONAL RESEARCH PROGRAMS

6.1 - ADMIRE Brite Euram Research (Alenia Naples)

The ADMIRE (**A**dvanced **D**esign concepts and **M**aintenance by **I**ntegrated **R**isk **E**valuation for aerostructures) programme aims at the development and validation of advanced design tools for the simulation of the structural behaviour in the presence of manufacturing damage.

The programme is co-ordinated by Alenia and the major partners are University of Pisa, Naples and Queen Mary Institute, DASA, BAE, CASA, Aerospatiale Matra and INASCO industries and NLR and ISTRAM Research Institutes. It has already passed half of its life and part of the technical results have been presented in a previous paragraph of this same review.

6.2 – 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).

6.3 - COMPRES Brite Euram Research (Alenia Naples)

The main goal of COMPRES (**Comp**osite **Re**pair of Metallic **S**tructure for Ageing Commercial Aircraft) is to define advanced structural repair techniques of in service damaged components, keeping static, fatigue and damage tolerance performances into account.

The selected bonded composite material repairs are excellent candidates to be used both as preventive measures to ensure that damage will not initiate at critical locations, as well as a proven method for retarding future growth of existing damage and for restoring the strength where the structure was removed.

The Project Co-ordinator is HAI (Greece) and the major Alenia partners are: IAI (Israel), OGMA (Portugal), CITEC (UK), NTUA (Greece-University), DUT (The Netherlands-University). The research programme started on February 1999 and was concluded on July 2002.

6.4 - TANGO Brite Euram Technology Platform (Alenia Naples)

Basic information about Tango (**T**echnology **A**pplication to the **N**ear-Term Business **G**oals and **O**bjectives of the Aerospace Industry) were already provided in the last National Review, with emphasis on the objectives and on the technologies that were to be applied for the manufacturing of the demonstrator items.

Alenia main activities are the design, manufacturing and testing of metallic and composite fuselage panels, composite upper wing panels and ribs. Before to freeze the design of the above components, Alenia performed a development test phase as highlighted on Table 4 and on figures 27 and 28.

Technology	Id	Test Type	Qty	Completed
Fiber Metal Laminate	FML 1	Ultimate Compression	3	3
	FML 2	Two Bay Crack Growth (Circumferential)	3	2
	FML 3	Two Bay Crack Growth (Longitudinal)	3	0
Metal Bonding	MB 1	Ultimate Shear	2	0
	MB 2	Fatigue (Shear)	2	0
	MB 3	Ultimate Hoop (Tension)	2	1
	MB 4	Fatigue (Tension)	2	0
Laser Beam Welding	LBW 1	Fatigue (Shear)	3	2
	LBW 2	Fatigue	3	0

Tab. 4 – Tests on components carried out by Alenia within TANGO technology platform

6.5 - "Materials Systems for Surface protection and Sealing" Brite Euram Research (Agusta)

As part of an European Research project (Materials Systems for Surface protection and Sealing), a number of specimens summarizing all the features of an optimised protection were tested at Agusta, according to a complex sequence of environmental exposure and fatigue loading. Within this programme, the introduction of Chromium free coatings, primers and sealants was considered.

The specimens are riveted single-strap butt joints and contain all the features typical of possible airframe configuration and provide potential areas of corrosion attack: namely coupled surfaces of similar metals, exposed edges rivets chamfers, rivet holes internal surfaces non protected with inorganic coating and primers. The specimen reproduce the typical assembling where all faying surfaces are wet assembled with sealant.

The testing method consisted in four phases:

1. Cyclic loading at low temperature (-54°C) in cycles blocks with increasing max load in order to obtain a significant failure on the sealant.
2. Exposure to fluids and salt water
3. Exposure to salt fog
4. Fatigue testing at various loads

The test results in general show that the sealant performance is fundamental for the ability to withstand the environment. After applying in the first phase 10 times the cycles defined by MIL-S-81733 standard, there was just some suspect of sealant loss of adhesion. Nevertheless, the fatigue behaviour after exposure to various corrosion environments did not show (figure 29) any difference with respect to the reference specimens (subjected only to mechanical fatigue loading).

Although the test was not suitable to show possible differences among various primers in the way to withstand the environment in real conditions, it was able to show how effective can be a properly made protection.

6.6 - Influence of processing and manufacturing parameters on the structural integrity of engine rotating parts (Uni. Pisa)

The most common hazardous effect for aircraft engines, as defined in the Joint Aviation Regulations (JAR-E), is ejection from the engine of uncontained high-energy debris. Critical parts mostly consist of rotating high-energy discs and spacers. An European funded research programme (MANHIRP) addresses the reduction of risk of disc burst from manufacturing anomalies, which has become the largest cause of disc failure in the 1990s. The main gas turbines European producers are involved in the research, together with research institutes and universities. The Department of Aerospace Engineering of the University of Pisa (DIA) acts as subcontractor of Fiat-Avio (Turin).

Three geometric features in disc components and three different processes (drilling, broaching and turning) will be systematically examined. The processes for each feature will be evaluated to establish which anomaly types can be produced and which Process Monitoring (PM) techniques will be effective in detecting them. The main part of the programme comprises manufacturing trials using two disc materials, a titanium and a nickel alloy. Blocks of material will be systematically abused to develop the means of producing damage in a controlled manner. Once this has been established, fatigue specimens of various sizes and manufacturing anomaly type will be manufactured, and process-monitoring techniques will be used. The specimens will be made in two batches, where the first batch will examine a wide range of anomalies and the second batch will focus on a few key anomalies, which adversely affect fatigue life.

These specimens will be examined using both current and near term NDI methods to establish the capability of such inspection methods. Finally, they will be tested to determine the fatigue penalty. Metallographic examination of the specimens after testing will allow a correlation between the size of the anomaly and the fatigue capability. Such a relationship has not been available before. These results along with industry data may then be used to calculate the probability of creating a life-limiting anomaly. Hence a probabilistic method which combines the statistical relation between anomaly size and detection capability and the probability of a fatigue life not being achieved will follow. This will allow a probability of burst from a manufacturing anomaly to be calculated for any specified component, and should indicate what PM and NDI would be required to reduce this probability of burst to the required level. The development of quantitative methods for specifying methods and controls is totally new to the gas turbine industry.

Fiat-Avio is investigating the nickel alloy IN718 and the machining process of turning. It produced the specimens from two disc forgings (Fig. 30a). As far as the first batch of specimens is concerned, four raw disks were machined from the forgings by wire EDM (two disks for each forging, outer diam. 377 mm, inner diam. 165 mm, thickness 8 mm, Fig. 30b). The discs were then machined by turning on both sides, using a vertical lathe CNC, to a final thickness of 4 mm. Each of the four discs was machined using two sets of turning parameters, obtaining two ”annuli” of the same radial extension. From each ”annulus”, eight test specimens were machined according to the cut-up scheme of Fig. 30c. The drawing of the axially-loaded specimens is shown in Fig. 30d.

Three machining parameters were selected and two conditions were chosen for each parameter:

- Depth of cut: 0.3 mm and 0.03 mm
- Speed of cut: 35 m/min and 70 m/min
- Tool wear: new insert and worn insert

For each condition, two fatigue-loading stress levels (Smax=1150 MPa and Smax=1110 MPa, R=0) were chosen and two specimens were tested for each stress level.

Special loading bars and grips were designed to ensure the load transfer by friction avoiding fretting failures. A resistance split furnace was used to reach the test temperature of 500 °C. Alignment tests were performed using a specimen with strain gauges. The temperature distribution on the specimen was checked using thermocouples. The test set-up is shown in figs. 31.

The fatigue tests are in progress in the Laboratory of DIA and all the results are not yet available. However, some preliminary comments can be drawn from the results obtained from specimens machined with a new insert, when compared with the standard machining conditions (depth of cut 0.3 mm, speed of cut 35 m/min):

- a low depth of cut increases the life by a factor ranging between 11 and 17, depending on the load level;
- a high speed of cut seems to have no effects on the life;
- at high speed of cut, the beneficial effect of the low depth of cut is reduced to a factor ranging between 2 and 4.

7. COMPONENT AND FULL-SCALE TESTING

7.1 -Helicopter EH101 (Agusta)

A fatigue test was performed, using appropriate spectrum loading, on the Rear Fuselage in the configuration with rear ramp and folding tail for the Navy variant for the MMI (Italian Navy).

The EH101-511 variant for Canada is now fully operative. Fatigue lives were recomputed according to the improved usage spectrum provided by the customer.

Complete fatigue life calculations were carried out for the Royal Air Force (UK) variant. Specific missions were evaluated, like Cargo and Nap-Of-the-Earth (NOE). Improved variants of some tail rotor components were successfully developed and tested to increase their fatigue lives even for the most severe usage.

7.2 – Helicopter NH90 (Agusta)

Fatigue and flow tolerance tests for the qualification of production main gearbox and main rotor mast were successfully carried out. The basic qualification of the Tactical Transport Helicopter variant is scheduled in 2003.

7.3 - Fatigue test of the M346 stabilator structure (Aermacchi)

The stabilator of the M346 trainer has been designed as all moving tail and has a particular manufacturing solution, whose main feature is the adoption of a metallic honeycomb core bonded to the skins and to a steel trunnion carrying the bending and torque loads. The need for a preliminary fatigue test arose from the necessity of gathering data on its fatigue behaviour while subjected to ordinary variable manoeuvre loads and induced buffet phenomena.

The rig of the static test was adopted as fatigue test rig as well (figure 32).

A simplified Lo-Hi-Lo block program test spectrum was defined according to the equivalent damage approach envisaging both manoeuvre and buffet loads effect on a particular assumed critical point.

As far as the buffet loads are concerned, those associated with high manoeuvre loading have been considered as part of the test program (thus included in the equivalent cumulative damage evaluation), while those relevant to smaller loads will be realised by the excitement of 2 modal responses separately from the fatigue block program.

Two lifetimes of testing will be realised, followed by a residual static strength test up to failure.

7.4 - EF Typhoon (Alenia Turin)

After the successful completion of the Major Airframe Fatigue Test on the prototype structure, a production aircraft structure is going to be submitted to a fatigue test (PMAFT). The test is under preparation; a great effort was dedicated to the study of the theoretical buffet spectra and particular care is being devoted to the preparation of the test spectra. The comparison between the manoeuvre spectrum and the buffet spectrum brings to the identification of four wing sections, in the tip region, where buffet is significant. Fig. 33 shows such region, where buffet loads will be applied in the test.

The loads will be applied in a simplified quasi-static manner, using an equivalent damage approach for defining them. In the test, for each wing station, two locations have been chosen to calculate the equivalent load spectrum: one mainly affected by the vertical loading, the other one mainly by the moment. Using an S-N curve with a representative stress concentration factor, the damage of the original sequence is calculated. The simplified spectrum is then obtained, identifying a few cycles giving similar damage in the two locations.

In the meantime, some significant component tests are in progress:

- outboard flaperon, that is currently running (and has reached so far 3000 simulated flight hours). The spectrum was calculated using loads for manoeuvres (symmetric and asymmetric), gusts, landings and buffet. In addition to the loads, deformations imposed by the wing were calculated, to be simulated in the test by means of an actuator applying a displacement to the central support hinge of the flaperon. The test set-up (fig. 34) includes 7 actuators that apply the load through pads on the flaperon surface, plus the actuator applying the displacement.
- the outboard region pressure box (a carbon fibre composite component, successfully tested for 18000 simulated flight hours, after impact damage having been inflicted); aerodynamic and inertial loads were applied to this component, as well as fuel pressure (see fig. 35). The specimen is now being subjected to environmental conditioning, before to perform the residual strength test.
- central pylon housing box (a composite component, successfully fatigue tested for 18000 simulated flight hours, after application of impact damage, fig. 36); a residual strength test is planned after environmental conditioning.
- inboard pylon; the spectrum has been defined, but the test is still in preparation.

8. FATIGUE SUBSTANTIATION OF NEW DESIGN AIRCRAFT

8.1 - C 27-J JAR 25 civil certification

The C-27J 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.

Structural Test Status (Post TC Items)

<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 is oriented 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 in progress and has reached 27,000 Simulated Flight Hours.

<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 is oriented to demonstrate:

- Five Lifetimes (73530 FSLs) for Fatigue assessment of NLG 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)
- Five Lifetimes (73530 FSLs) for Fatigue assessment of 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 (see fig. 37); the MLG Full Scale Fatigue Test started on October 2002 and has reached about 3677 Full Stop Landings corresponding to 5% of total life (see fig. 38).

8.2 - ATR 42- ATR 72 cargo conversion - Damage Tolerance assessment

On the ATR 42 and the ATR 72 Basic Versions (Passenger) the modifications BFC (Bulk Freighter Conversion) and LCD (Large Cargo Door) have been implemented. These modifications allow the ATR family to operate as Cargo Aircraft and new performances, as determined primarily by Customer needs, were certified according to the JAR 25 Certification Basis, Change 15.

Fatigue and Damage Tolerance Issues

For modified and unmodified structural components, the Structural Integrity Assessment was based on:

- Demonstration of ATR Passengers / ATR Cargo Fatigue Spectra Equivalence;
- Assessment of fatigue capability based on ATR 42 Full Scale fatigue test results for the unmodified structure;
- Fatigue and Damage Tolerance analysis of large cargo door and surround area (based on FEM model tuned by a dedicated barrel test);
- Maintenance plan based on MSG-3 approach

The design objectives were:

- ❑ Economic Repair Life = 70.000 Flights (25 Years)
- ❑ Crack Free Life = 35.000 Flights
- ❑ Inspection Threshold = 36.000 Flights

For the Certification of Modifications, Alenia obtained the DOA Certificate (according to JAR 21 Requirements). The STC (Supplementary Type Certificate) was achieved at the end of July 2002.

8.3 - AB 139 Helicopter (Agusta)

This is a new helicopter of 6000 kg gross weight, twin-turbine, multirole capability. The Civil Certification will be carried out according to JAR 29 Rules (the Civil Type Certificate is expected within the end of 2003) and therefore the fatigue qualification will require compliance with the Flaw Tolerance requirements. Some basic information about the Certification process was already given in the last National Review.

During the last two years, more than 200 fatigue tests were carried out. All the fatigue critical parts were evaluated for safe lives and further tests are being carried out to improve this evaluations. Further, tests on flawed parts and/or fracture mechanics analysis have been used to select inspection intervals or retirement times, as applicable, to protect the critical parts from any damage identified by the threat assessment, proving compliance with the Flaw Tolerance requirements. The preferred method for compliance with Flaw Tolerance requirements for dynamic components is “no damage growth”. 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. An efficient method to determine the threshold ΔK has been developed, in a co-operation with the Department of Mechanical Engineering of Milan Polytechnic, and will be presented in detail in a paper at the Symposium, [4].

The main full scale tests include main rotor and tail rotor hub, blades, controls, main rotor gearbox. Some test activities was performed in the Alenia (Naples) and in the Aermacchi (Varese) Test Laboratories.

The class of helicopter required the development of two completely new test rigs for the main rotor blade specimen with higher capacity (Centrifugal force up to 100.000 daN).

8.4 - BA609 Tiltrotor (Agusta)

This is the first civil tilt rotor model of 16800 lb weight, twin 3 blade rotors, 9 passengers cabin. The Bell-Agusta BA609 will combine the attributes of a high performance turboprop with the vertical take-off and landing capabilities of a modern helicopter.

The certification will be carried out according to FAA rules. The BA 609 has its own certification basis, that is made up by compiling the different rotorcraft and airplane FARs into the BA609 Certification Basis.

The first Ground Run took place in December 2002, while the first flight of A/C 1 (Aircraft 1) took place in March 2003.

The relevant test activities on primary structures have already required the design of dedicated rigs for the wing, blade, prop-rotor mast, flaperon, vertical and horizontal stabilizer. A set of fatigue tests of all critical components was carried out for flight clearance in about 1 year. The most significant tests were carried out on the Wing, the Prop-Rotor Mast and the Blade. Load and strain surveys were carried out on the test articles to verify FE models, to calculate preliminary fatigue lives and to determine monitoring limits during the flight tests.

BA609 WING FATIGUE TEST

The rig for the wing fatigue test has required a major improvement in the Agusta Structural Testing Laboratory capability (see fig. 39). During the test, a fatigue spectrum is applied, consisting in a random sequence of typical flights that is repeated a number of time to form the lifetime of the aircraft. The fatigue spectrum includes ground manoeuvres, take-offs, helicopter manoeuvres, conversions, airplane manoeuvres and landings.

The control system manages 48 control channels (input loads) and 256 monitor channels used for strain gages and displacements transducers. During the test, all the parameters are continuously recorded and automatically monitored, permitting an unattended run of the test for 24 hours a day.

BA609 BLADE FATIGUE TEST

A dedicate rig was developed for the blade fatigue test. The main characteristics of the rig for the blade are:

- Adjustment of the centrifugal force load direction;
- Double way of application of the centrifugal force (hydraulic or pneumatic actuator)
- Adjustable pitch angle attachment to the blade root to meet better load setup.

8.5 - 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. The M346 is a fracture based designed aircraft, where durability and damage tolerance issues have been addressed during the fatigue design process.

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

1. Development of local refined FEM models for fatigue and DT analysis
2. Experimental determination of fracture mechanics data for the 7050 Al Alloy
3. Durability and damage tolerance characterization of the Force Mate bushing installation process in the wing-fuselage joint
4. Assessment of buffet load spectra and their fatigue impact on the empennages
5. Development of a fatigue test on the stabilator structure

In the following some information will be given about the first point, while the others are treated in the appropriate chapter of the National Review.

8.5.1 - Development of local refined FEM models for fatigue and Damage Tolerance analysis

The M346 airframe is designed to meet demands on both durability and damage tolerance.

For the critical parts, the main goal is a slow crack growth structure not requiring any major inspection during its full life. A small compact aircraft such as the M346, in fact, would require very expensive disassembly in order to allow reliable inspections.

For the above reasons, very accurate DT analyses are performed with as much precise as possible stress spectra and Stress Intensity Factors solutions. Crack propagation analyses are carried out by means of the NASGRO code, using the modified generalised Willenborg model.

Complex shape structural solutions, particularly for heavily loaded thick machined components, are somehow difficult to be idealized for correct stress distribution and SIF evaluation. The standard SIF solutions available in NASGRO are not always suitable to easily analyse real structural situations and therefore it is necessary to carry out a refined FEM stress analysis. The output of such FEM analysis is an accurate estimation of the Stress Concentration Factor and of the reference stress, to be used for fatigue and DT analysis.

As an example, fig. 40 shows a FEM model for the analysis of the most critical areas of the fin - fuselage attachment fittings. The DT assessment is carried out using the reference stress so identified, in conjunction with a standard crack solution available in NASGRO, as appropriate.

As a result of the analyses, typical design damage tolerance curves have been drawn for the most significant typology of structural solutions relevant to riveted joints, lugs, spar caps sections, skin and various types of cut-outs. An example of such curves is presented in fig. 41 in which the design curves refer to a typical spar cap and have been obtained from Nasgro with different initial flaw sizes.

DT design curves have been used in the weight optimization process and for the final Durability And Damage Tolerance Assessment of the most significant structural items of the airframe, involving both safety and economic maintenance aspects.

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

9.1 - Mechanical properties of Friction Stir Welded aluminium 6082-T6 joints (Uni. Pisa)

Several tests were carried out on aluminium alloy plates, 6082-T6, Friction Stir Welded. Different aspects were investigated, such as hardness of the material, static resistance, residual stresses, fatigue resistance and stress corrosion resistance. Even if the process was not fully optimised, since some defects were present in the welded joints, the results obtained compare well with the results of tests carried out previously on the same material, MIG welded, fig. 42. Friction Stir Welding could be a useful alternative to MIG welding for joining the large extruded aluminium elements which are used in some railway construction. A detailed description of the results obtained is given in [5].

9.2 - Fatigue qualification of welded joins in thin steel sheets (Uni. Pisa)

The objective of this research activity, carried out in collaboration between the Department of Aerospace Engineering of Pisa and Piaggio, is the fatigue characterization of welded joints made of thin steel sheets, typically used for the manufacturing of motorcycles frames. In the literature, an adequate number of technical documents is not available on this subject.

During the research activity, a few joints types, defined starting from typical Piaggio production frame solutions, have been characterised numerically and experimentally, and a complete detailed stress analysis study has been carried out for the Liberty motorcycle frame, subjected to the loading systems applied by Piaggio for its qualification. This last study, carried out numerically and experimentally, has allowed the determination of the correlation of the test results from specimens and the stress field in the frame.

Three specimens, representative of typical fatigue critical details, have been identified, mainly made of a tube with three different types of weldings on it. The material is Fe 510 steel for the tube and Fe 355 HF for the parts welded to it; the process is MAG, applied automatically. The S-N curves of one of the details can be seen in fig. 43, where the local equivalent stress, evaluated by means of a Finite Element analysis, has been plotted.

More details of this activity can be found in [6].

9.3 - Fatigue Resistance of Flat Specimens Containing a Central Hole Obtained by Nibbling (Uni. Pisa)

Fatigue tests on stainless steel specimens, AISI 304 annealed, thickness 5 mm, containing a central hole obtained by nibbling were carried out. The stress ratio was R=0.02. The activity was performed in consequence of some un-expected fatigue cracks, which nucleated from some holes obtained by nibbling, in the beams of large machines involved in the handling of objects. The results of the tests clearly demonstrated the low fatigue resistance of these specimens when compared with the results of specimens in which the holes were reamed, fig. 44. Additional fatigue tests were carried to evaluate possible repairing techniques of the fatigue cracks, to be applied in the field. A detailed description of the results obtained is given in [7].

10. EVENTS

10.1 - Workshop on “Fatigue Design of Helicopters”

An international Workshop on “Fatigue Design of Helicopters” was held in Pisa on September 12-13, 2002. The Workshop was organised under the auspices of the U.S. Army European Research Office, the U.S. Navy Office of Naval Research – International Field Office, the U.S. Air Force European Office of Aerospace Research and Development, the Federal Aviation Administration and the Department of Aerospace Engineering of the University of Pisa. The workshop was on invitation only, and was attended by about 50 delegates. In the two days, 22 presentations were given by fatigue specialists of the major industries, airworthiness authorities and research centres. The Proceedings have been edited in form of a CD, with the collection of the presentations, and can be obtained from the local organizers (Prof. Luigi Lazzeri, E-mail: aero.lazzeri@ing.unipi.it, fax: +39.050.2217244).

REFERENCES

[1] L. Lazzeri, G. Ratti: 'Fatigue crack propagation in thin 2024 sheets under typical helicopter spectra', in "Fatigue 2002", vol.1/5, Proc. Eighth International Fatigue Congress, EMAS Publ., pp. 585-592.

[2] S.A. Fawaz: "Stress Intensity Factors for Part-elliptical Through Cracks", Engineering Fracture Mechanics, n. 63, 1999, pp. 209-226.

[3] A. Lanciotti, C. Polese: "Fatigue crack propagation of through cracks in thin sheets under combined traction and bending stresses", accepted for publication on "Fatigue and Fracture of Engineering Materials and Structures".

[4] S. Beretta, M. Giglio, U. Mariani, M. Vicario: "Flaw Tolerance evaluation of helicopter rotor parts", to be presented at the 22nd ICAF Symposium, Lucerne, 7-9 May 2003.

[5] A. Lanciotti, F. Vitali: "Characterization of Friction Stir Welded joints in 6082-T6 aluminium alloy", Rivista Italiana della Saldatura (in Italian), n.4/2002, pp.467-474.

[6] M. Chiarelli, R. Hippoliti: "Fatigue qualification of steel welded frames: an example from the motor scooter industry", to be presented at Fatigue 2003, "Fatigue and Durability Assessment of Materials, Components and Structures", Cambridge (UK), April 2003.

[7] A. Lanciotti: "Fatigue Resistance of Flat Specimens Containing a Central Hole Obtained by Nibbling", Engineering Failure Analysis, vol. 9/3, Feb. 2002, pp. 245-253.

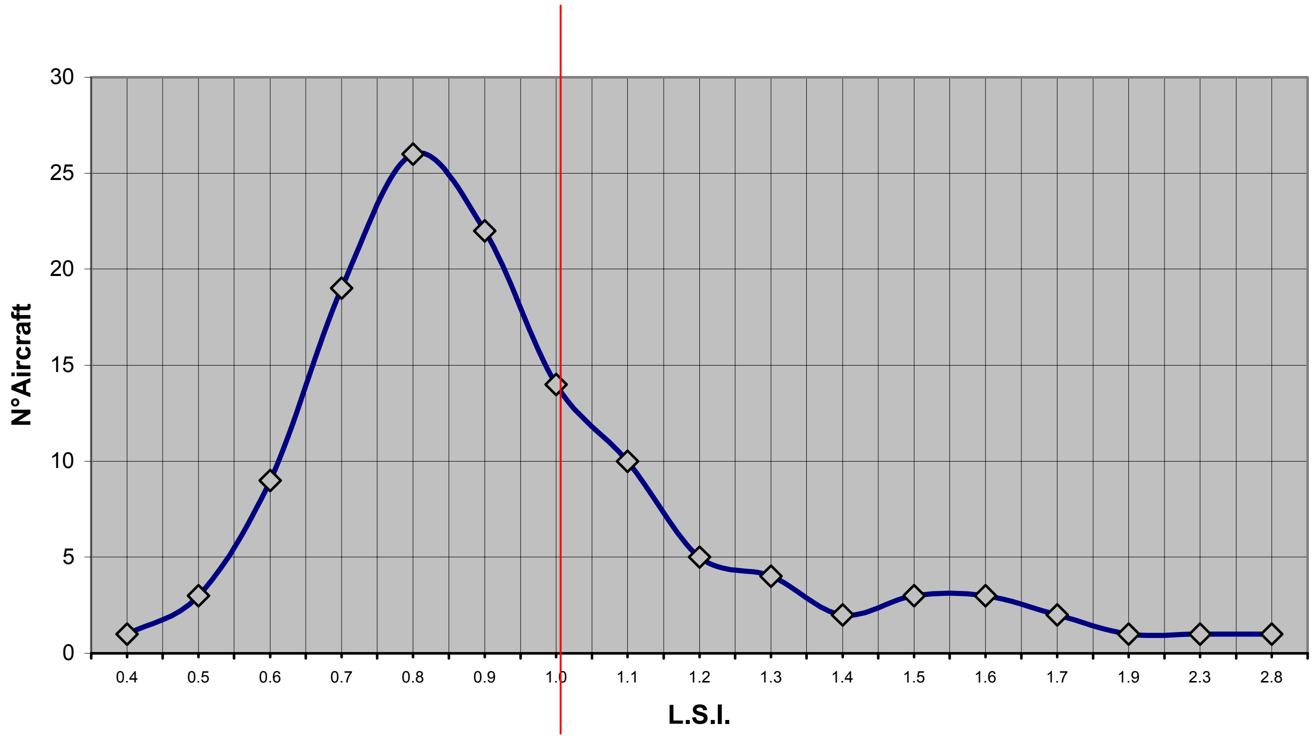

Fig. 1 – Load Severity Index distribution for the AM-X fleet.

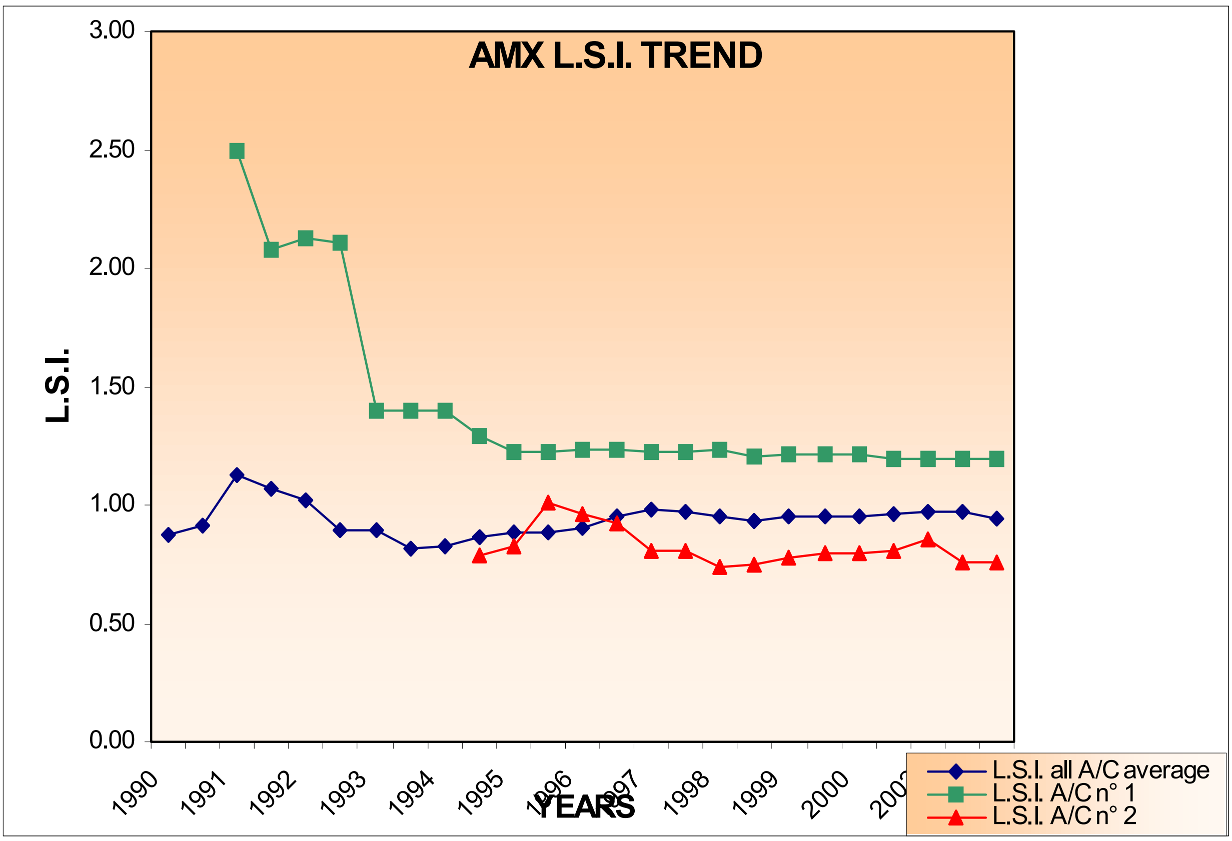

Fig. 2 – Examples of different fatigue life consumption rate for different AM-X aircraft.

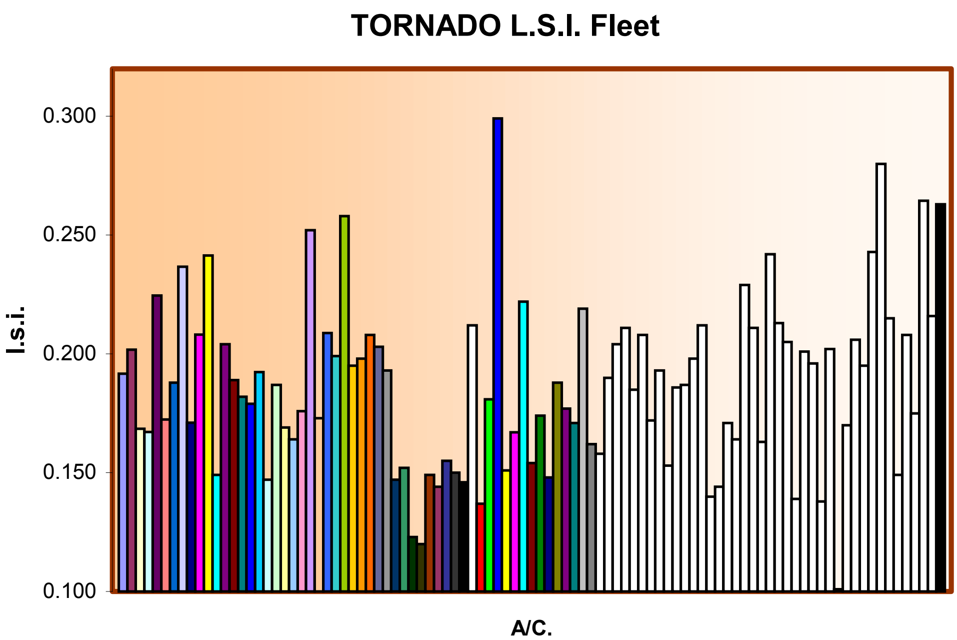

Fig. 3 - Load Severity Index distribution for the I.A.F. Tornado fleet.

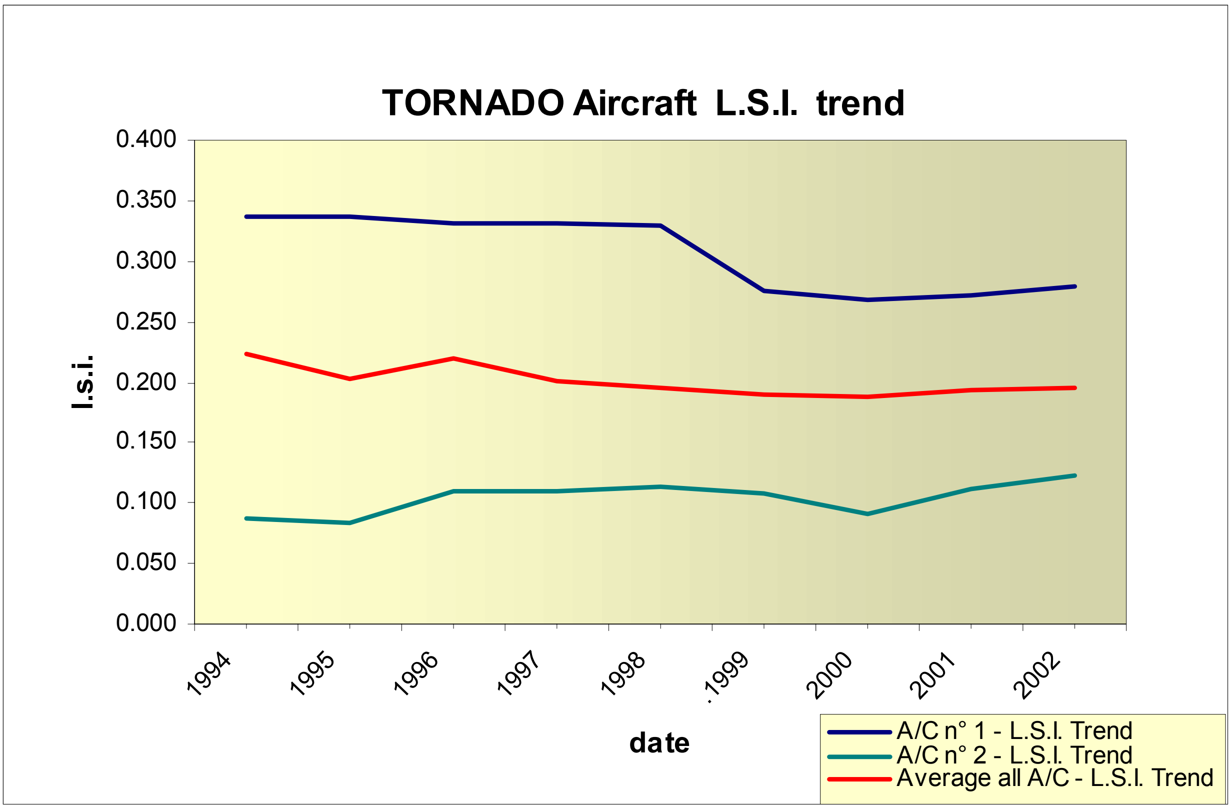

Fig. 4 – Examples of different fatigue consumption rates for individual Tornado aircraft.

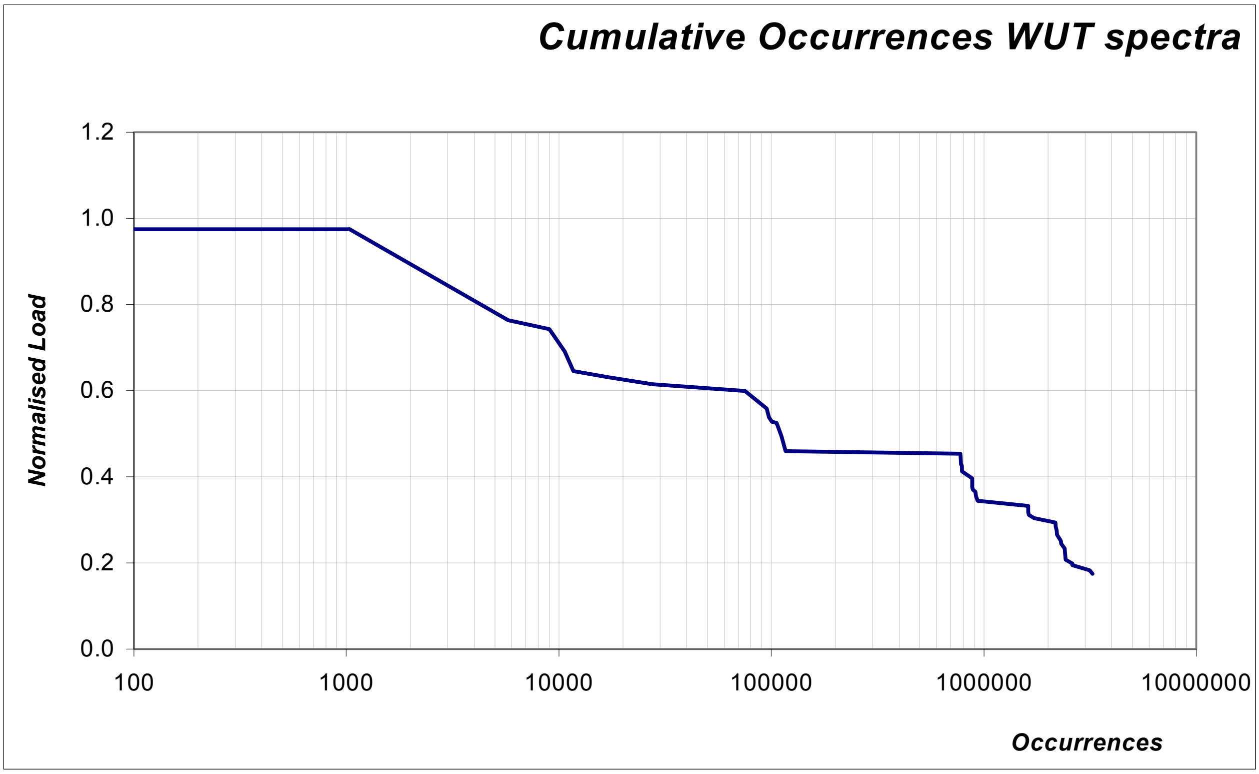

Fig. 5 – Buffet spectrum for the fin of the M346 trainer.

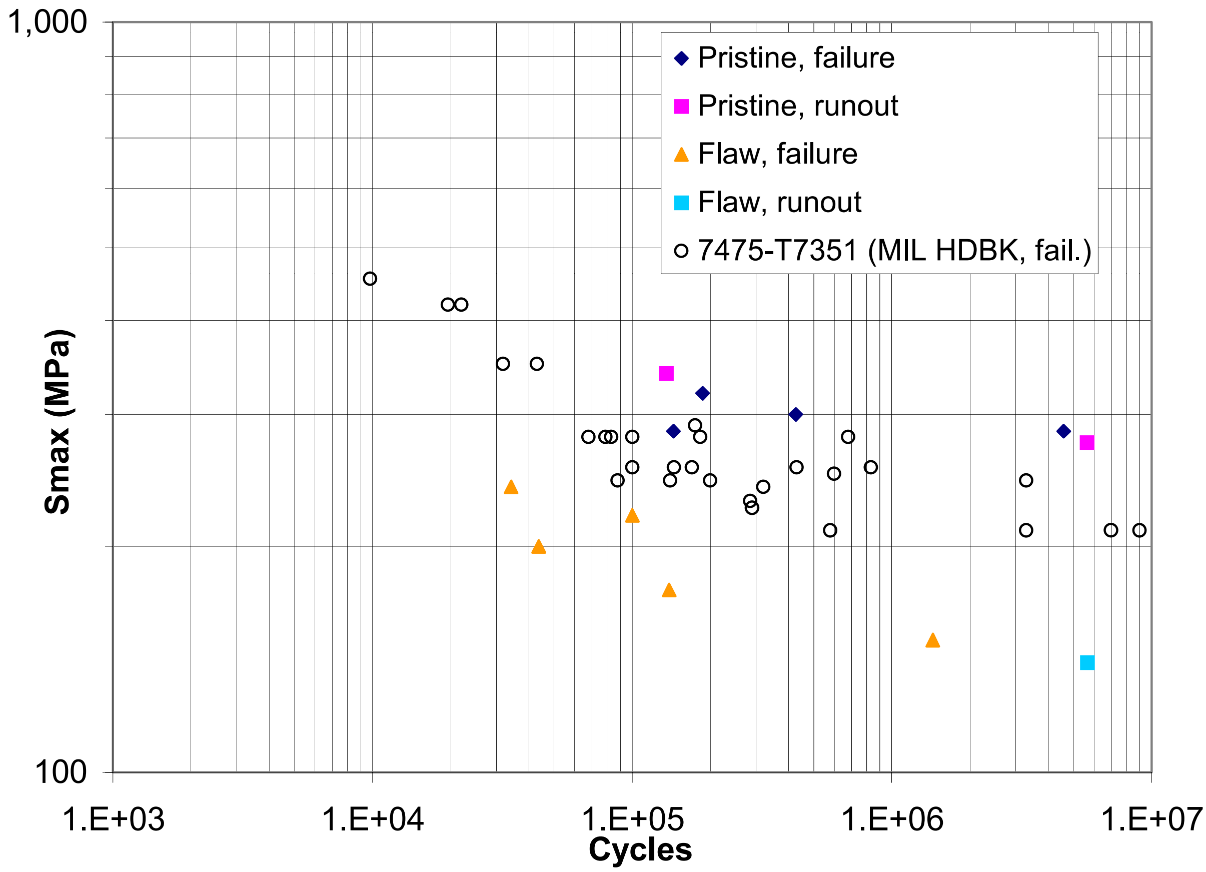

Fig. 6 – CA results for a typical fatigue critical helicopter detail, in 7475-T7351 (R=0.05).

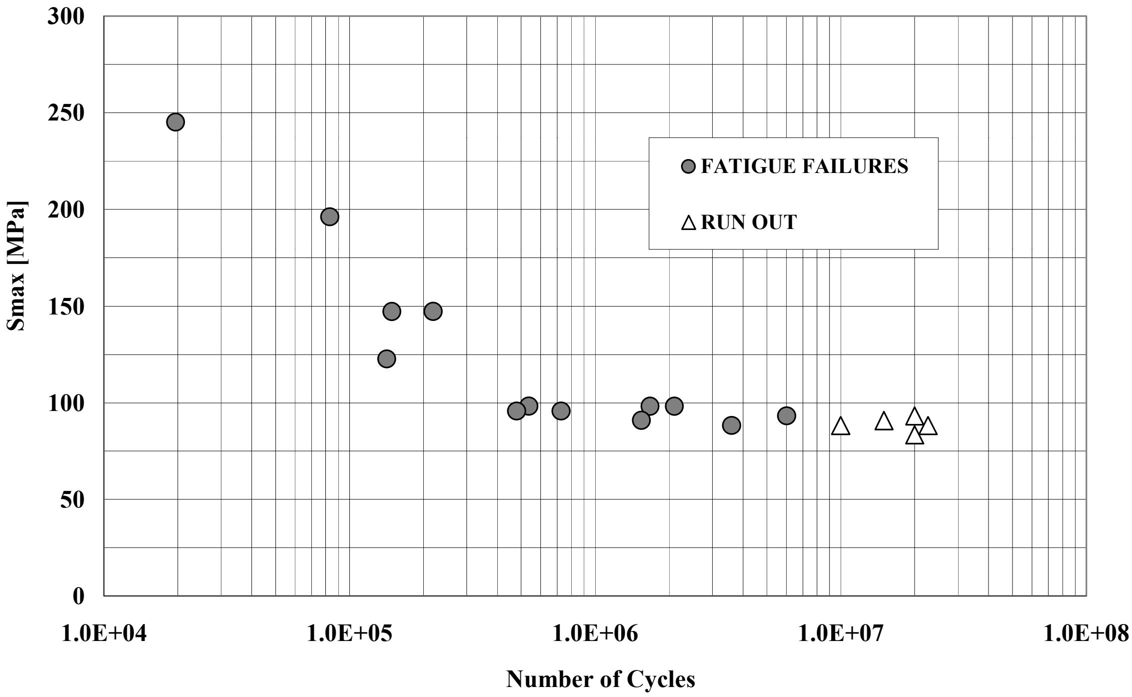

Fig. 7 – Fatigue test results of unnotched coupons of micro cast A357 alloy (R=0.1)

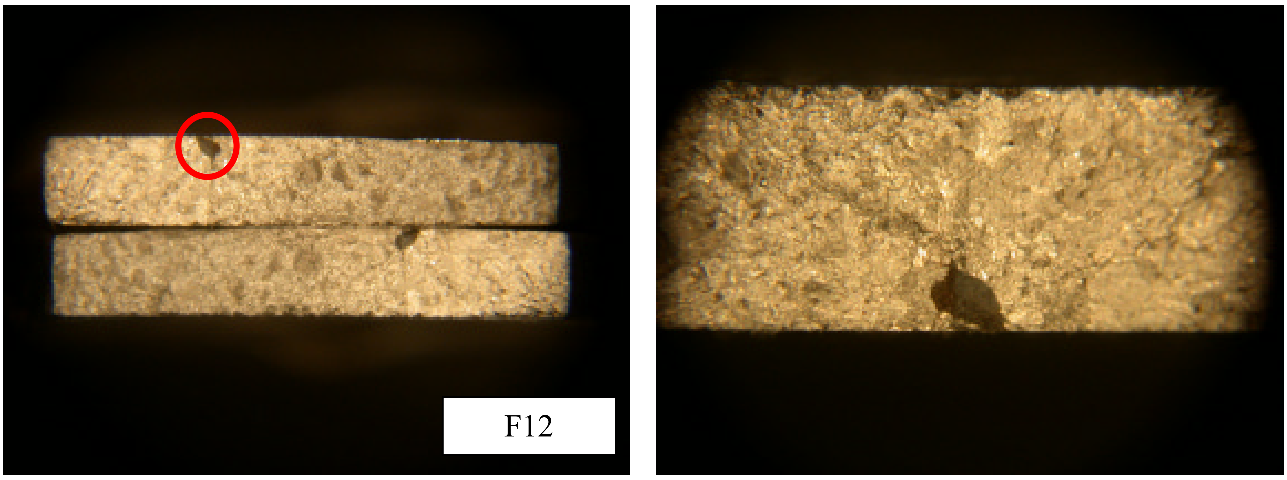

Fig. 8 – Evidence of defects, due to micro casting, in A357 material.

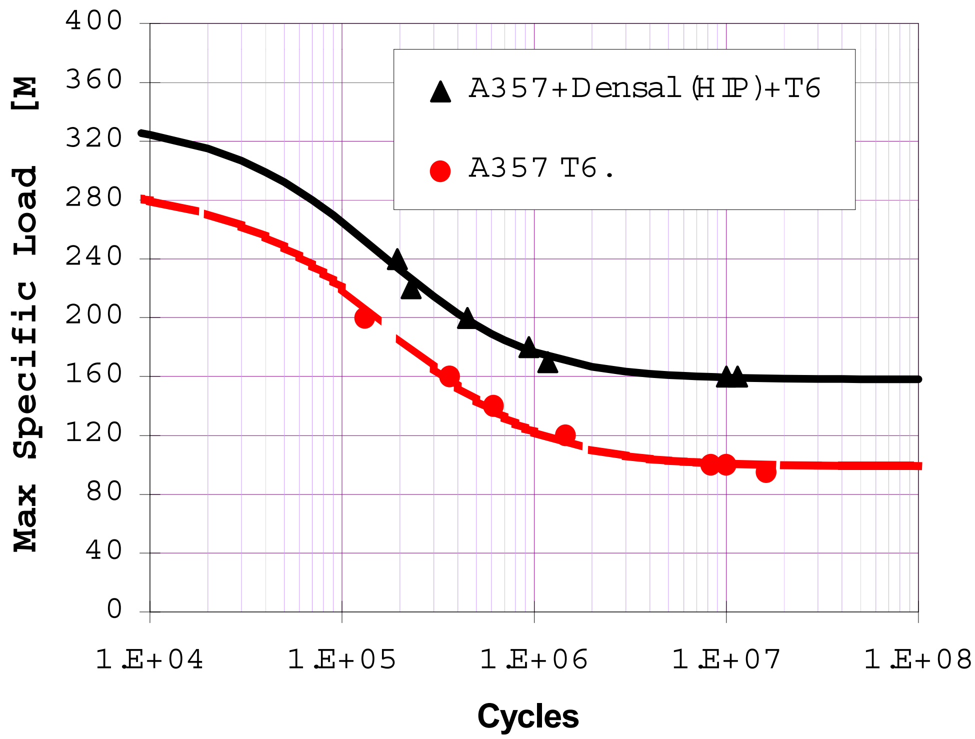

Fig. 9 – Effect of HIP treatment on S-N curves relevant to A357 specimens, cut from cast rods.

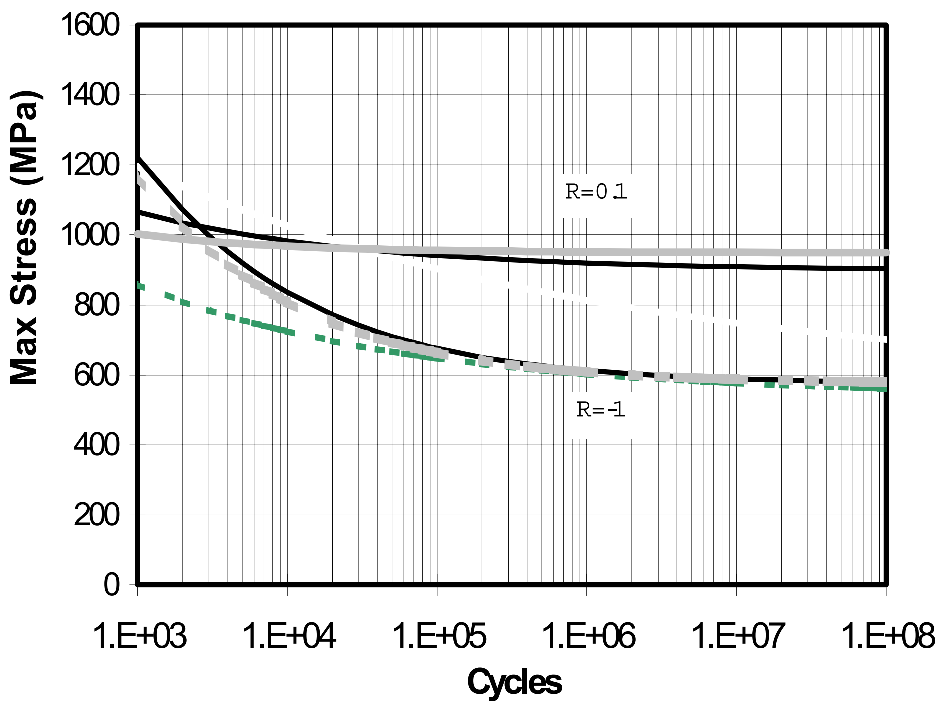

Fig. 10 – S-N curves for different nitrided steels, for two stress ratios. The green lines refer to the Al based Nitralloy (AMS 6475), while the grey and black lines refer to 32CDV13 (AMS 6481) subjected to nitriding under different process parameters.

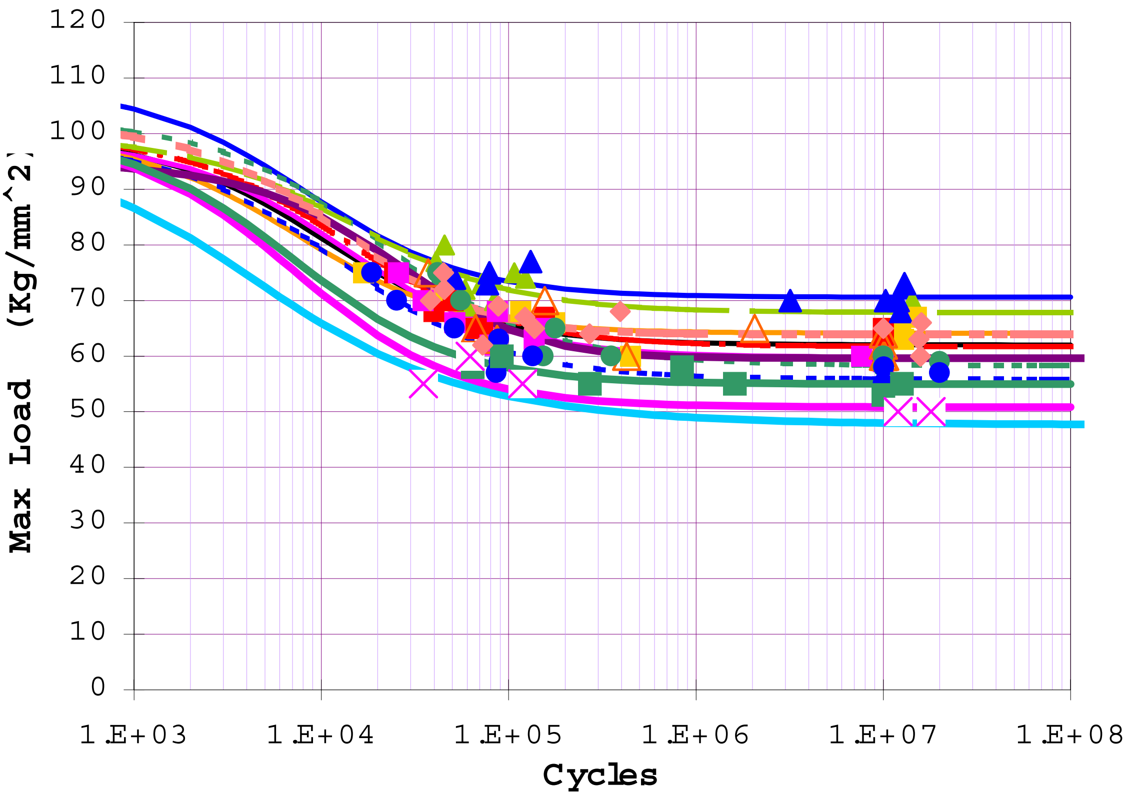

Fig. 11 – S-N curves for different batches of AISI 301 stainless steel, R=0.1, unnotched.

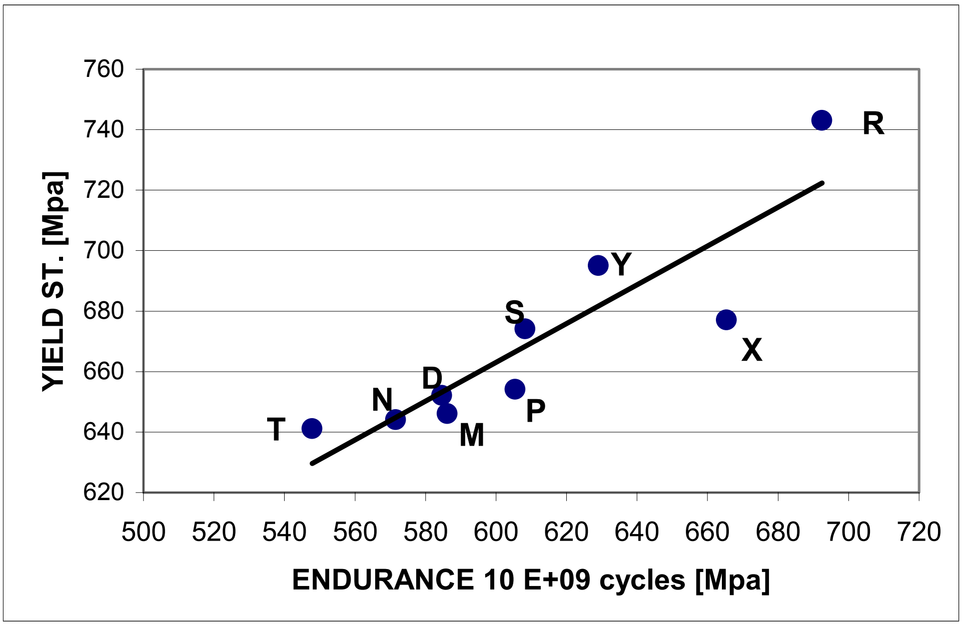

Fig. 12 – Correlation between endurance limit and yield stress for various batches of AISI 301 stainless steel, ¼ hard.

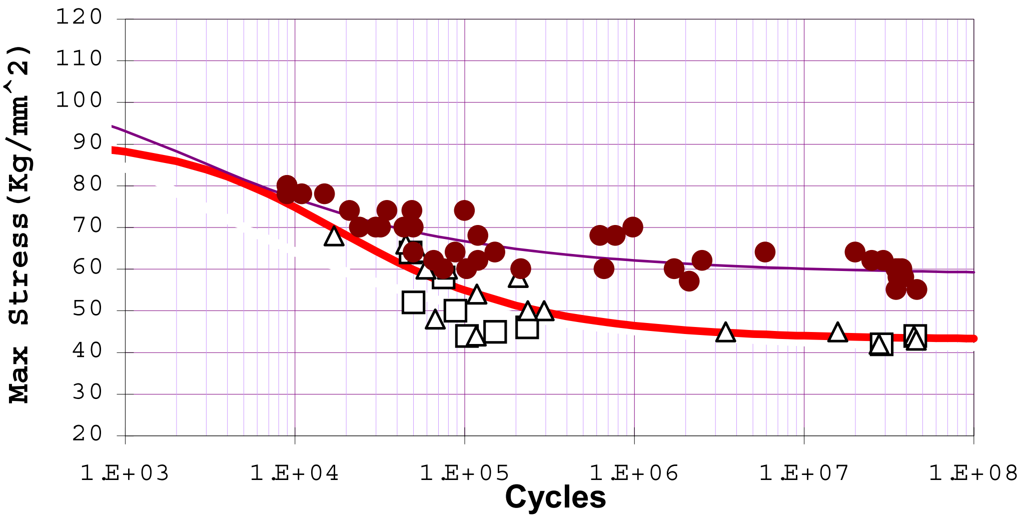

Fig. 13 – Comparison of fatigue results from Ti-6Al-4V (ELI) annealed (triangle), with Beta Solution Treated and OverAged (solid symbols). The open square symbol refers to BSTOA condition applied to a blank of excessive thickness.

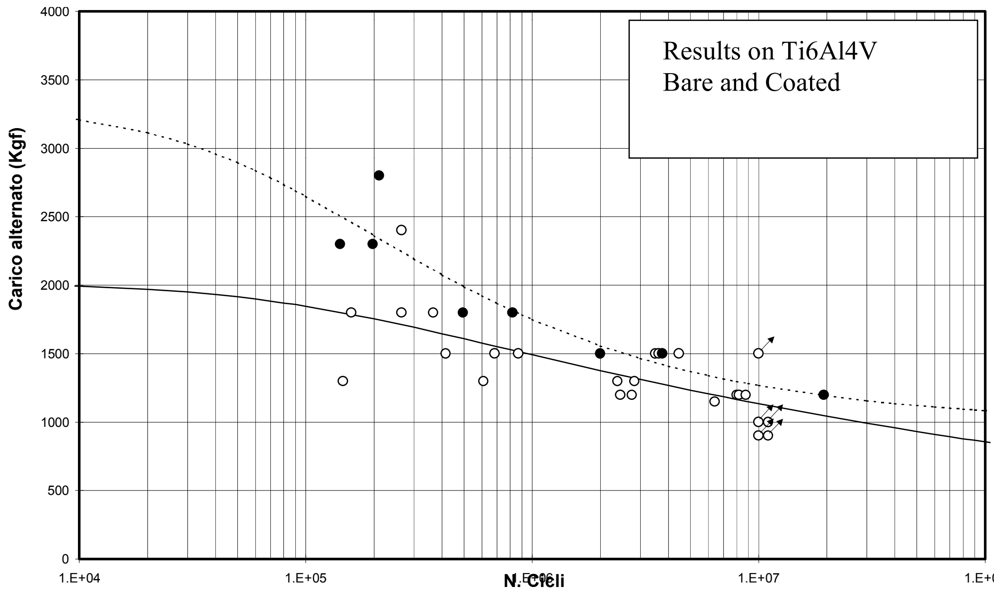

Fig. 14 - Fatigue S-N curves and experimental points relevant to non coated (solid circles/ dashed line) and coated (open circles/solid line). Tests were run at variable R: fixed static load of 2500 Kg_f and various alternating loads as shown on the Y-Axis

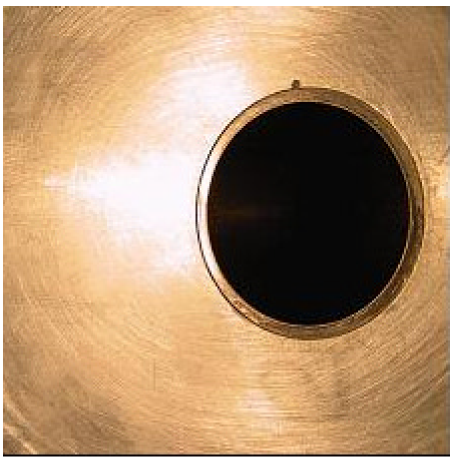

Fig. 15 - Example of the defects introduced into the specimens for a first Damage Tolerance assessment of M346 wing-to-fuselage attachment.
The photo is deformed by the fish-eye lens.

Fig. 16 - One of the 14 joint specimens available assembled on the test machine. The geometry of this specimen is representative of the M346 wing-to-fuselage attachment lugs.

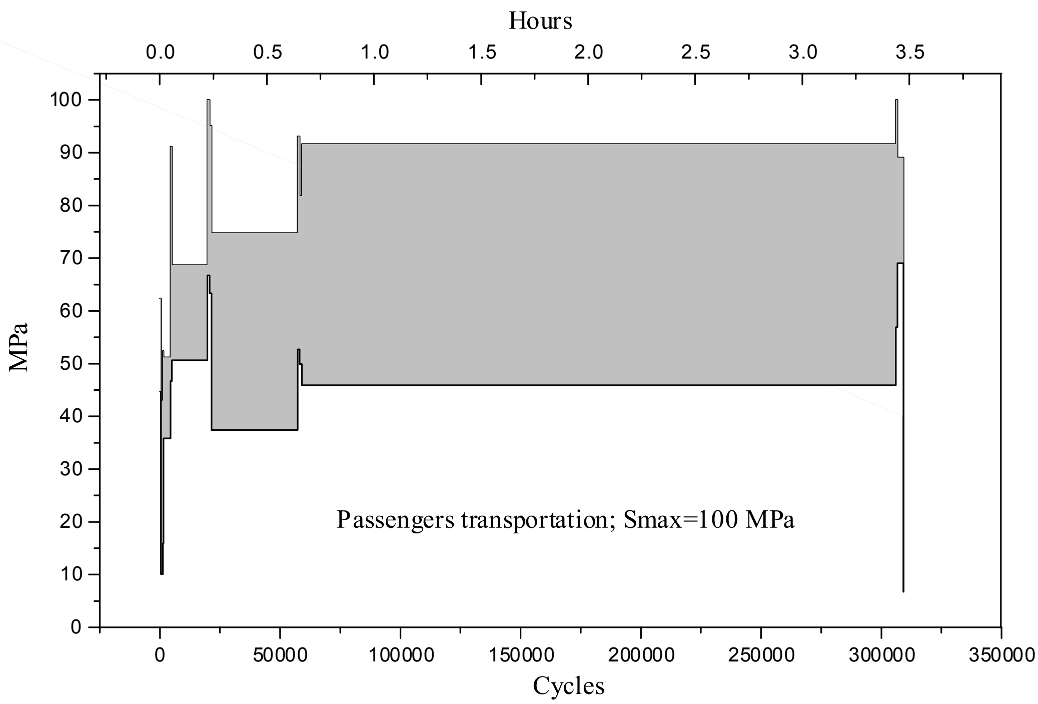

Fig. 17 – Typical helicopter fuselage spectrum sequence.

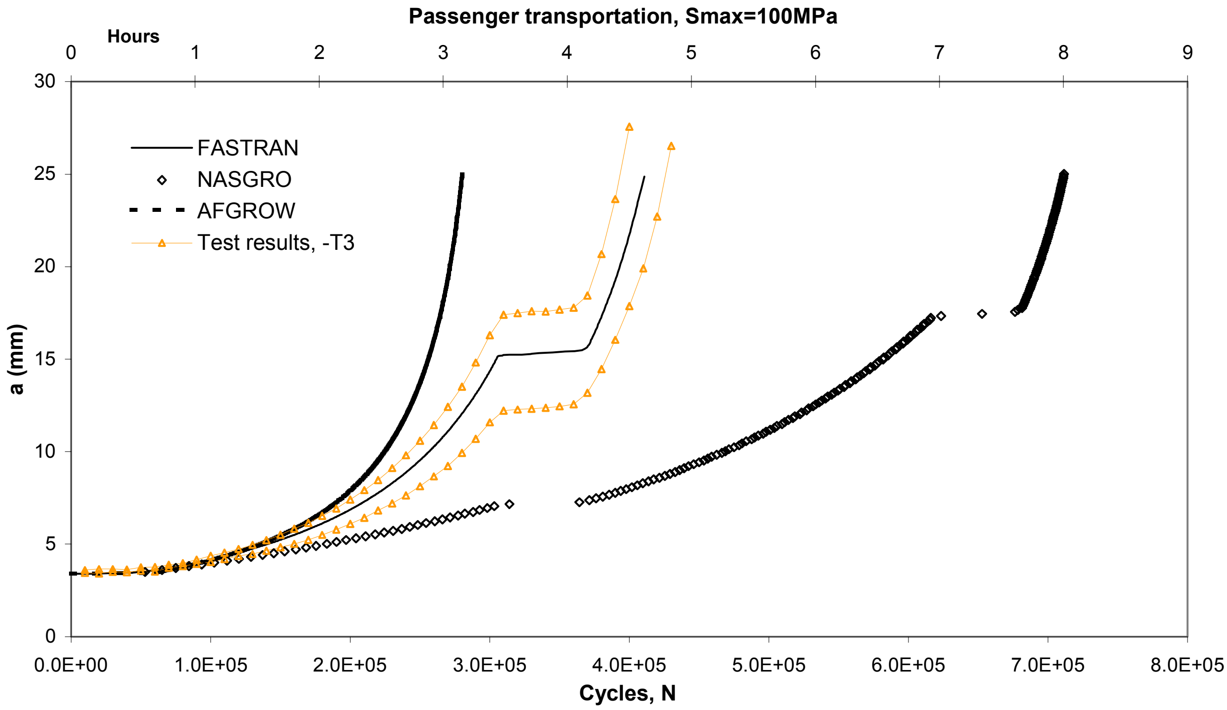

Fig. 18 – Comparison of VA test results with predictions (2024-T3, Passenger transport mission, Smax 100 MPa).

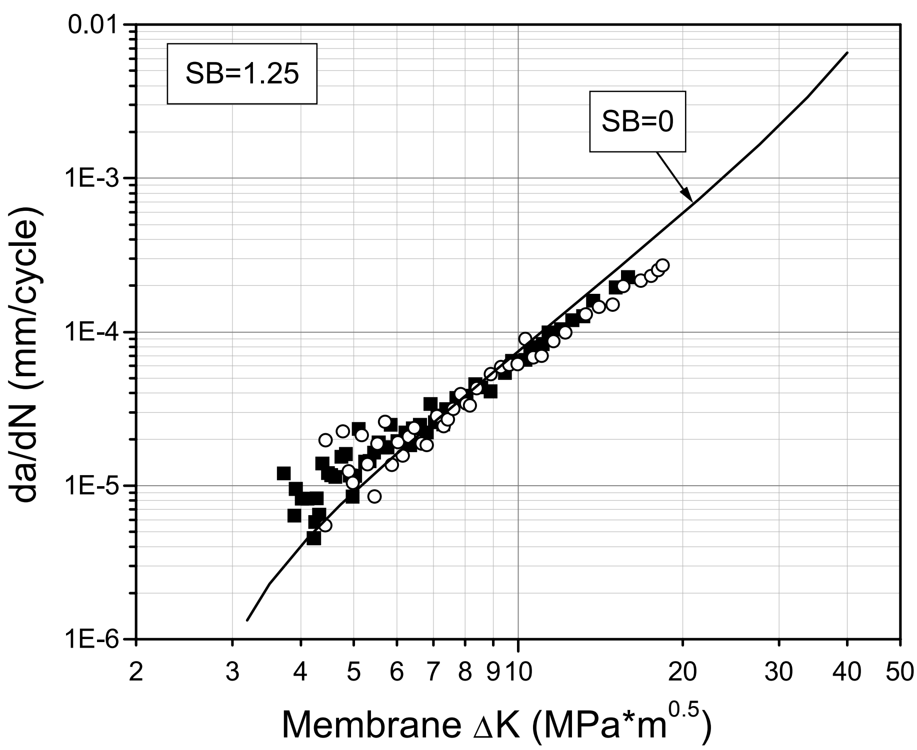

Fig. 19 – Comparison of fatigue crack growth data obtained under tension and bending loads with basic material properties. Case of low secondary bending (SB).

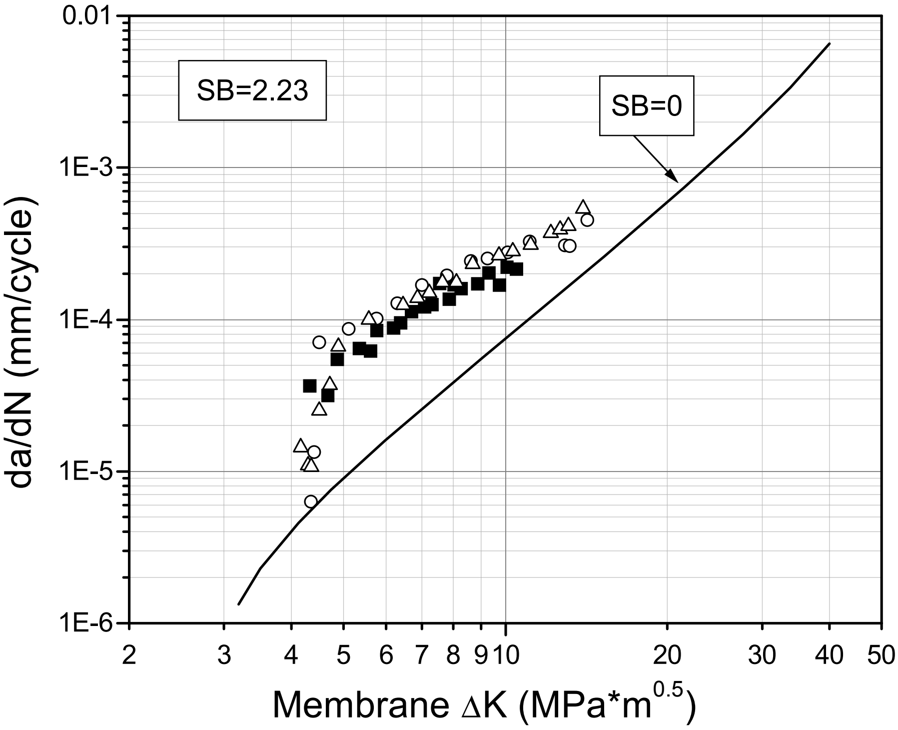

Fig. 20 – Comparison of fatigue crack growth data obtained under tension and bending loads with basic material properties. Case of high secondary bending (SB).

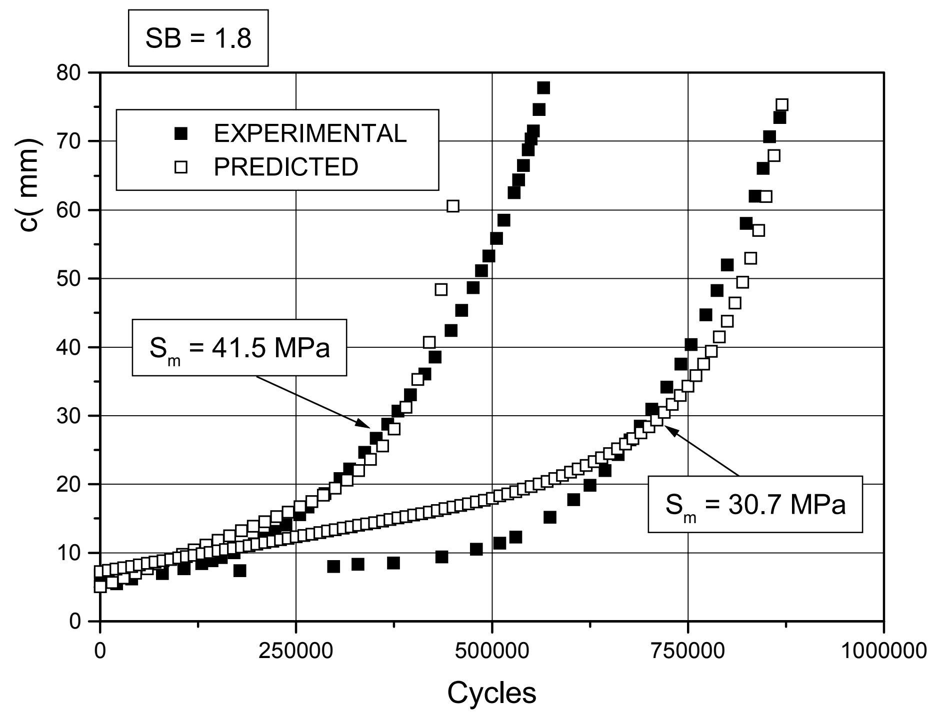

Fig. 21 – Comparison of experimental vs. predicted crack growth under combined tension and bending stresses.

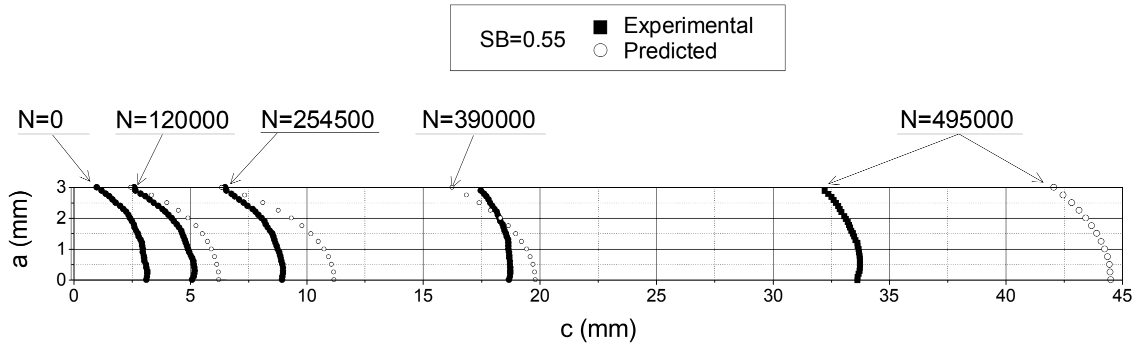

Fig. 22 – Comparison of experimental vs. predicted evolution of crack front under combined tension and bending stresses.

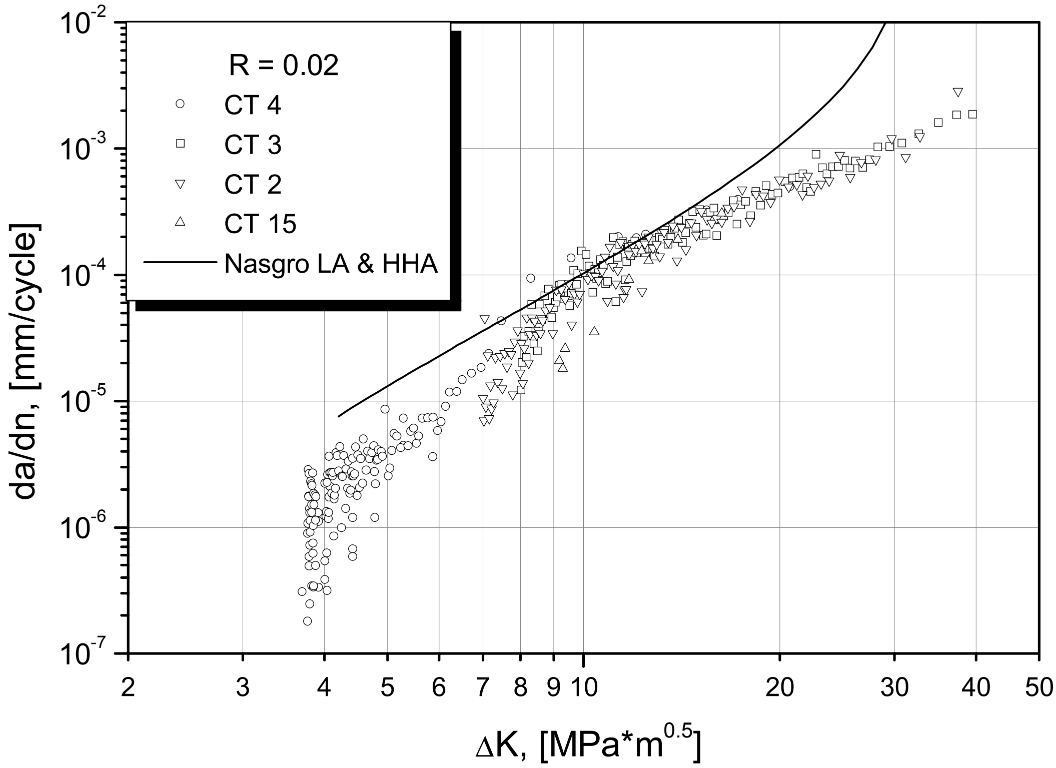

Fig. 23 – Fatigue crack growth results for 7050-T7451, thickness 42 mm.

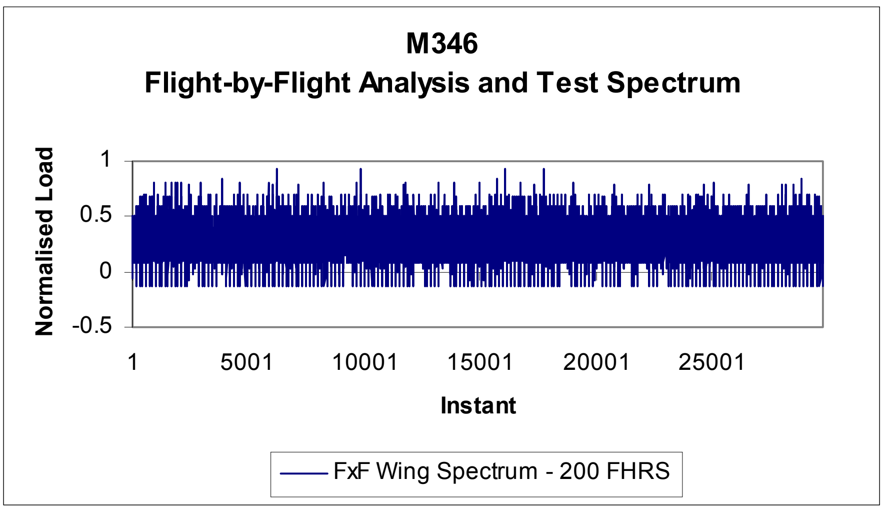

Fig. 24a – Flight by Flight M346 wing spectrum (200 flight hours)

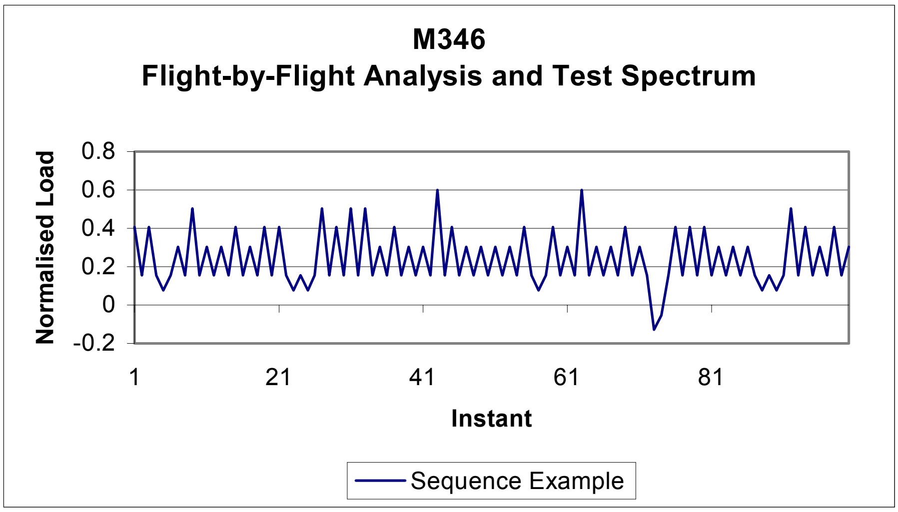

Fig. 24b – Detail of the Flight by Flight M346 wing sequence.

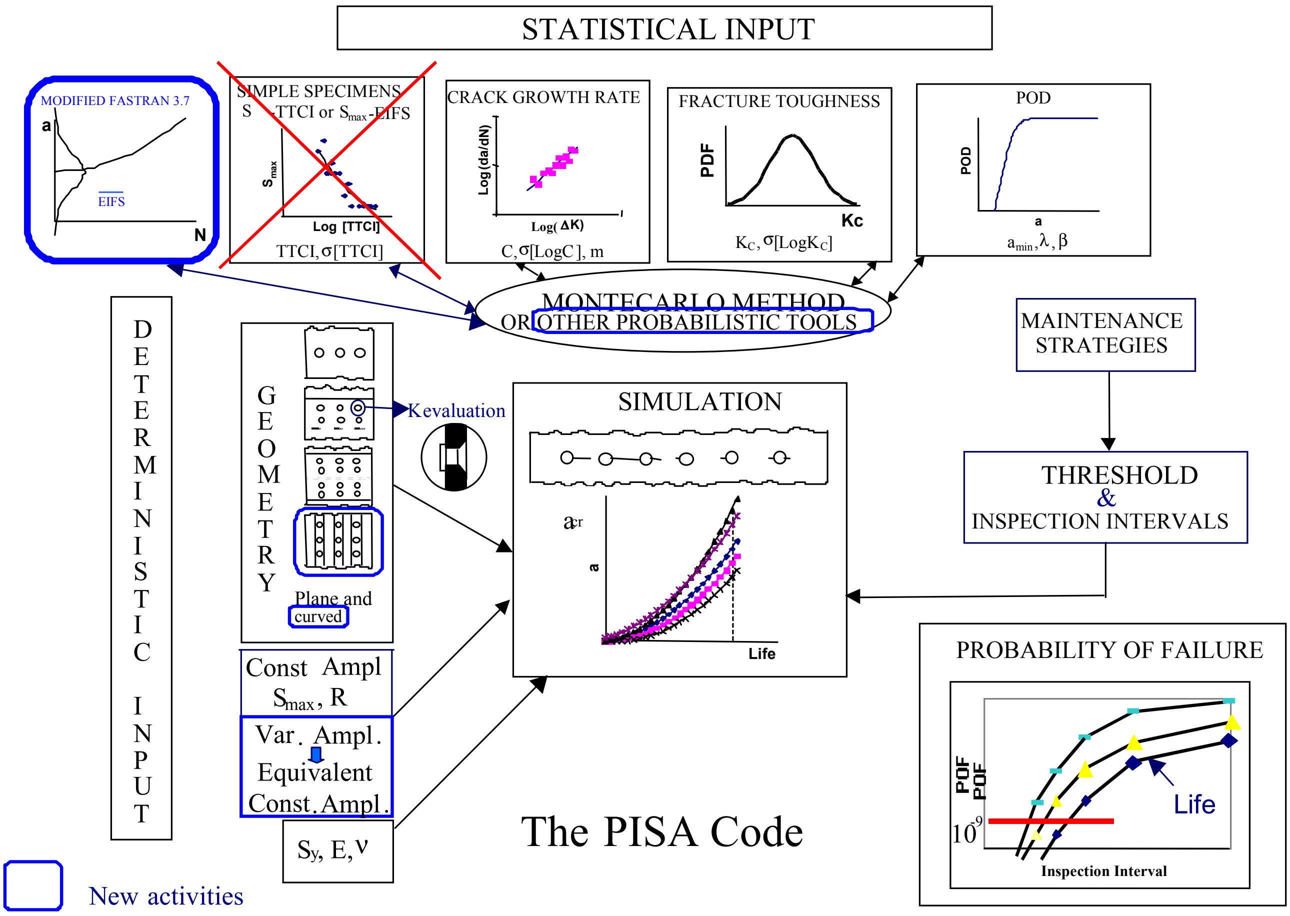

Fig. 25 – Organisation of the PISA code.

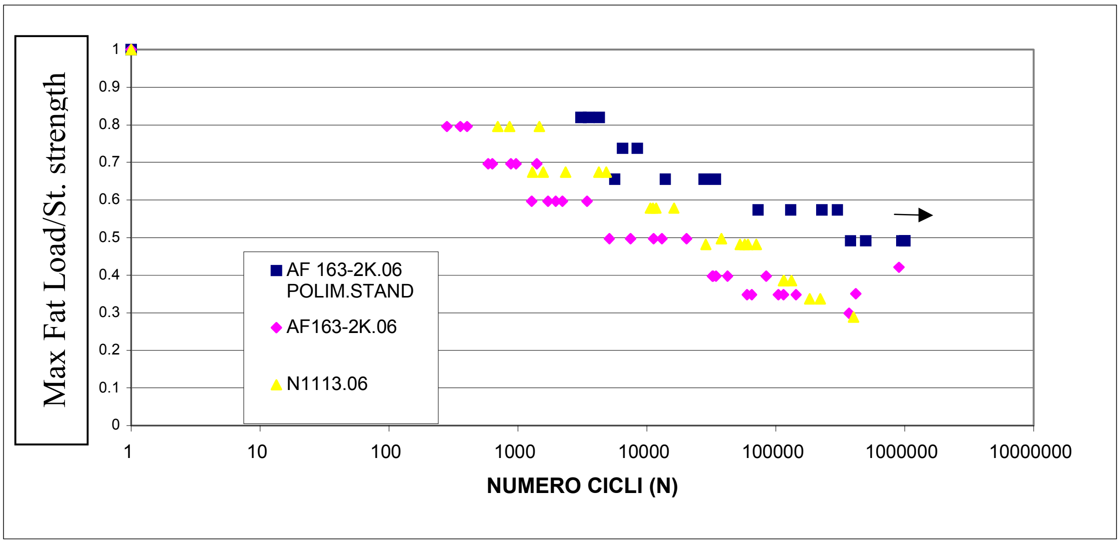

Fig. 26 - Fatigue test results from adhesive bonded single lap joints, obtained with various curing variants. Black square refer to Standard curing, triangles and diamonds data points refer to two different adhesives and curing at lower temperature.

FML 1 – Test article	FML 2 – Test article

Fig. 27 – TANGO development phase test articles, manufactured by Alenia.

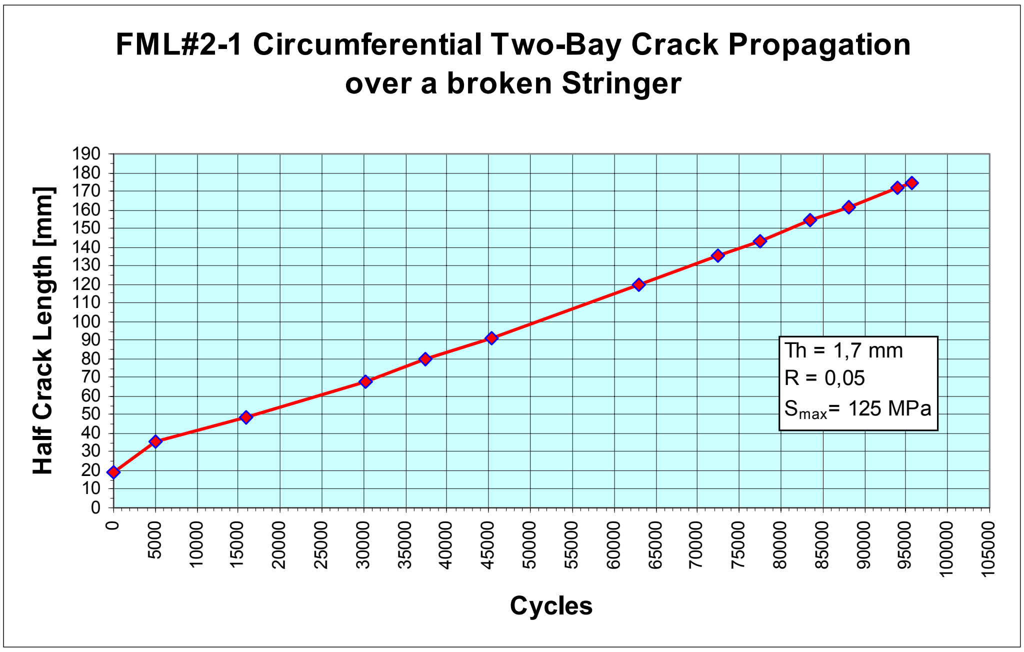

Fig. 28 – Results of a TANGO development test. Fatigue crack growth in a stiffened panel (Alenia).

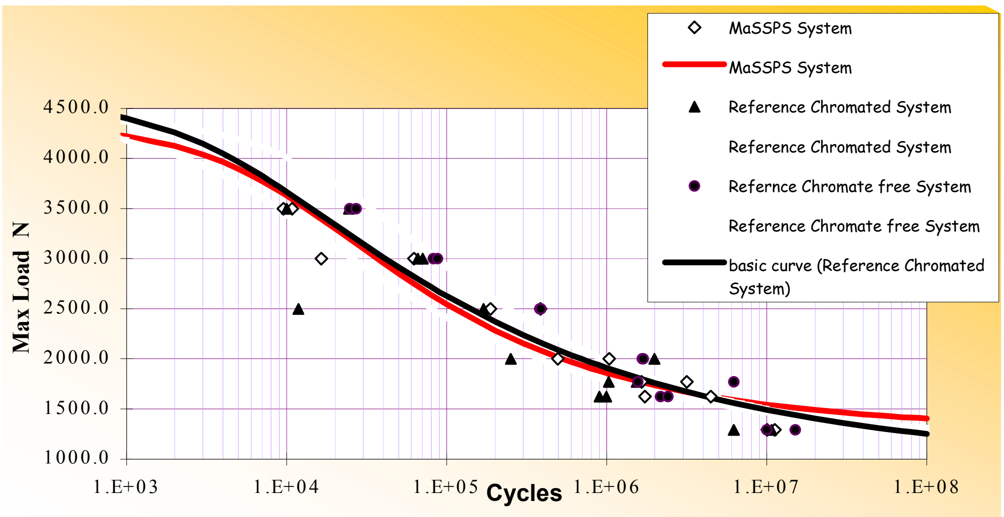

Fig. 29 – Fatigue test results after conditioning of specimens subjected to three protection systems (two chromate free and one with chromate), compared with reference results from specimens not exposed to fluids and corrosion.

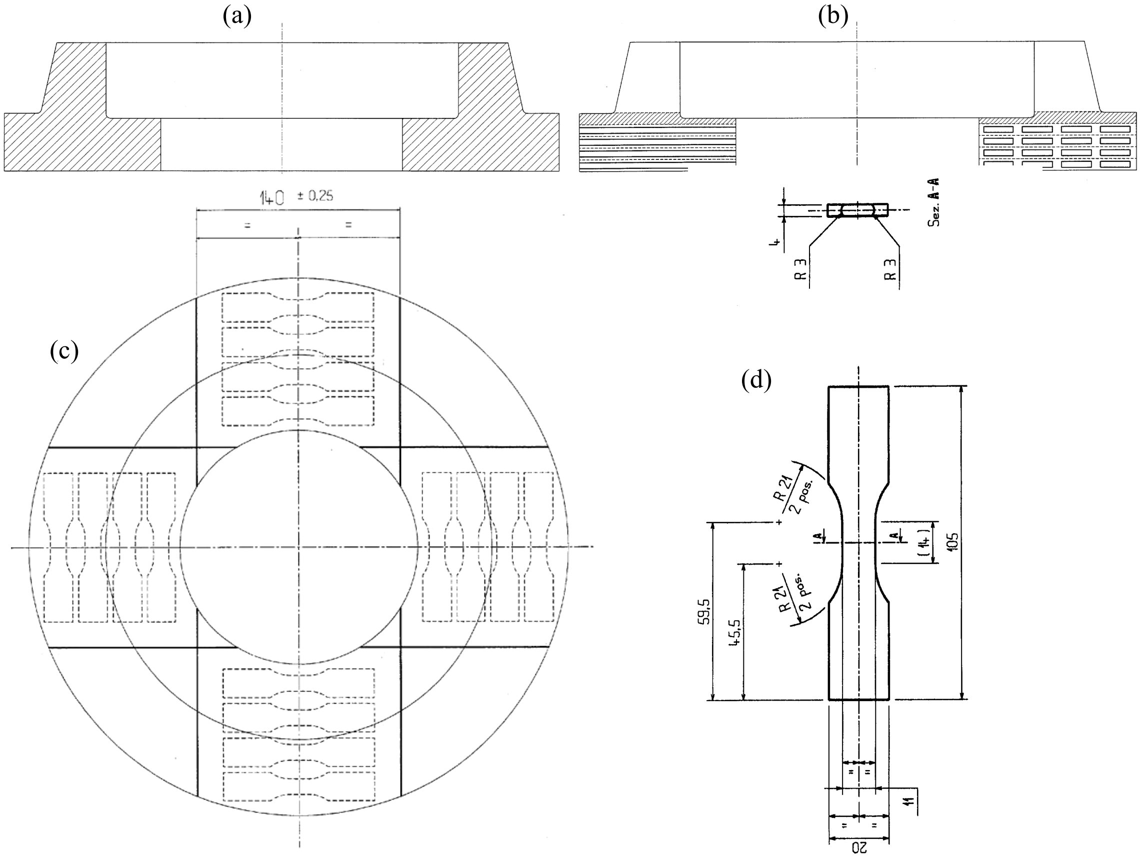

Fig. 30 – Specimen machining from IN718 disc forging for the MANHIRP program.

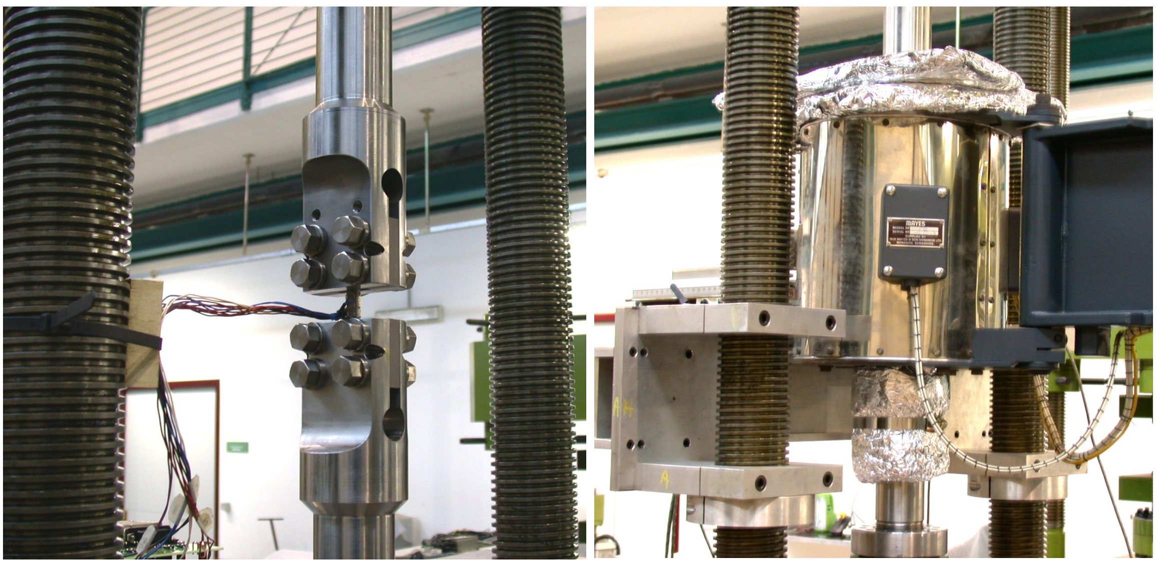

Fig. 31 - Loading bars and grips (a) and resistance furnace (b) of the test set-up for carrying out fatigue tests at high temperature (500 ºC).

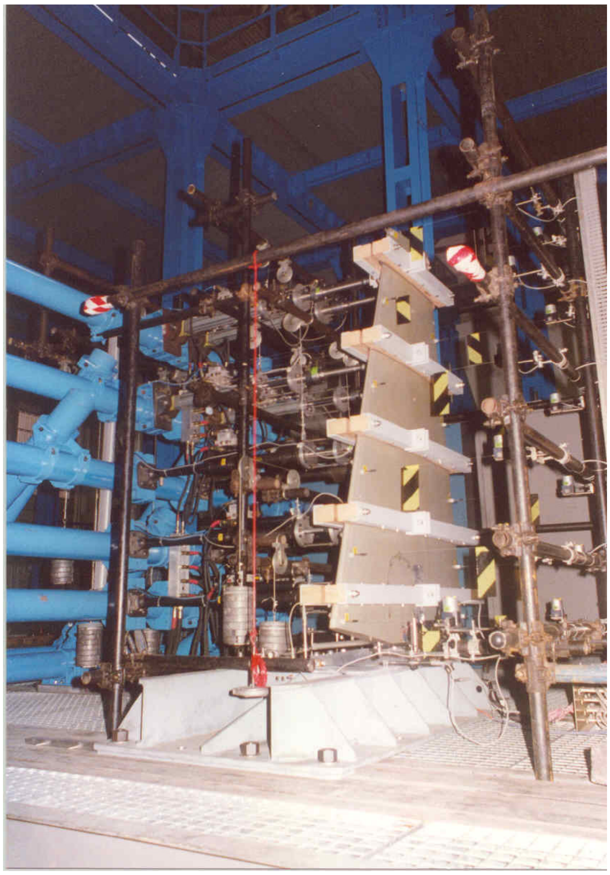

Fig. 32 – Test rig for the M346 Horizontal Tail fatigue test

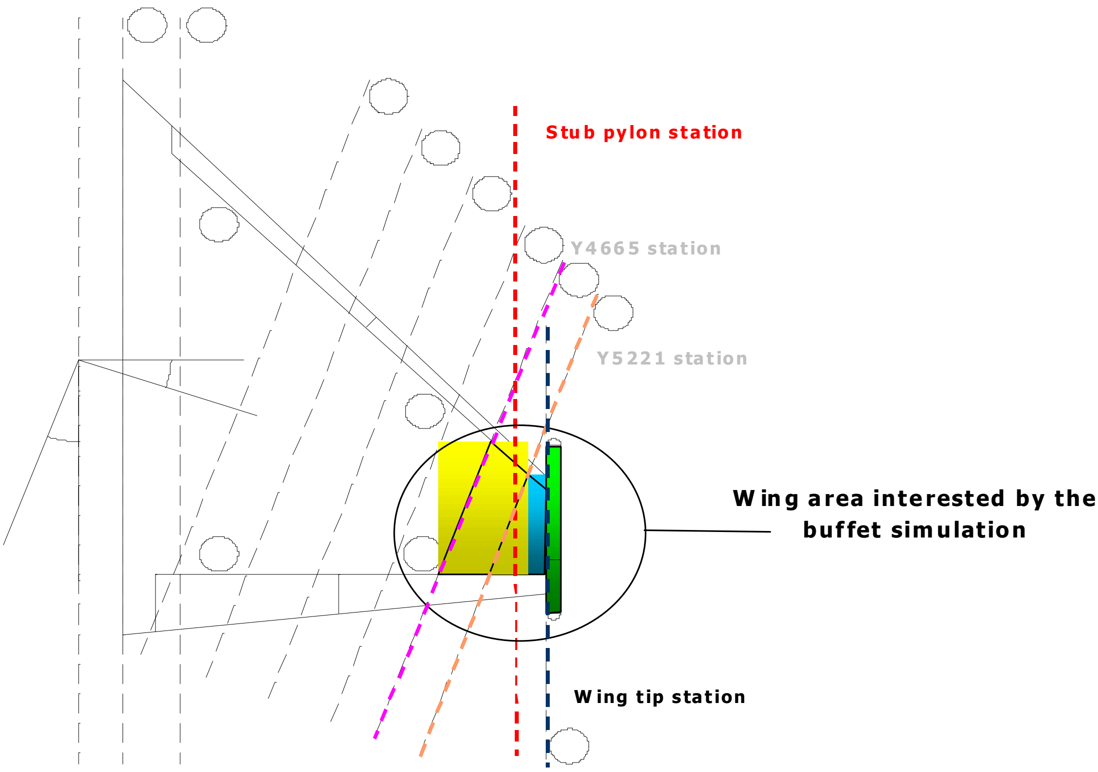

Fig. 33 – Area of the EF Typhoon wing where the buffet loads are significant.

Fig. 34 – Test set-up for the Typhoon outboard flaperon

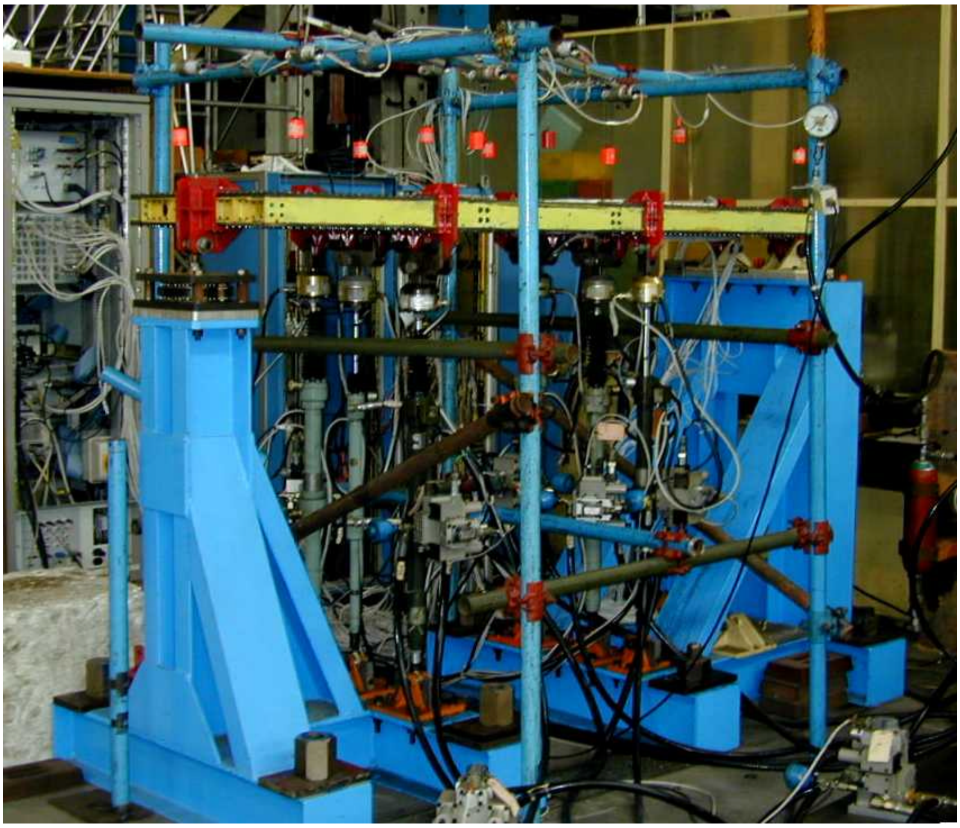

Fig. 35 – EF Typhoon: fatigue test of the outboard region pressure box

Fig. 36 – Test set-up for the central pylon housing box of the EF Typhoon

Fig. 37 – C 27-J Nose Landing Gear fatigue test set-up.

Fig. 38 – C 27-J Main Landing Gear test set-up.

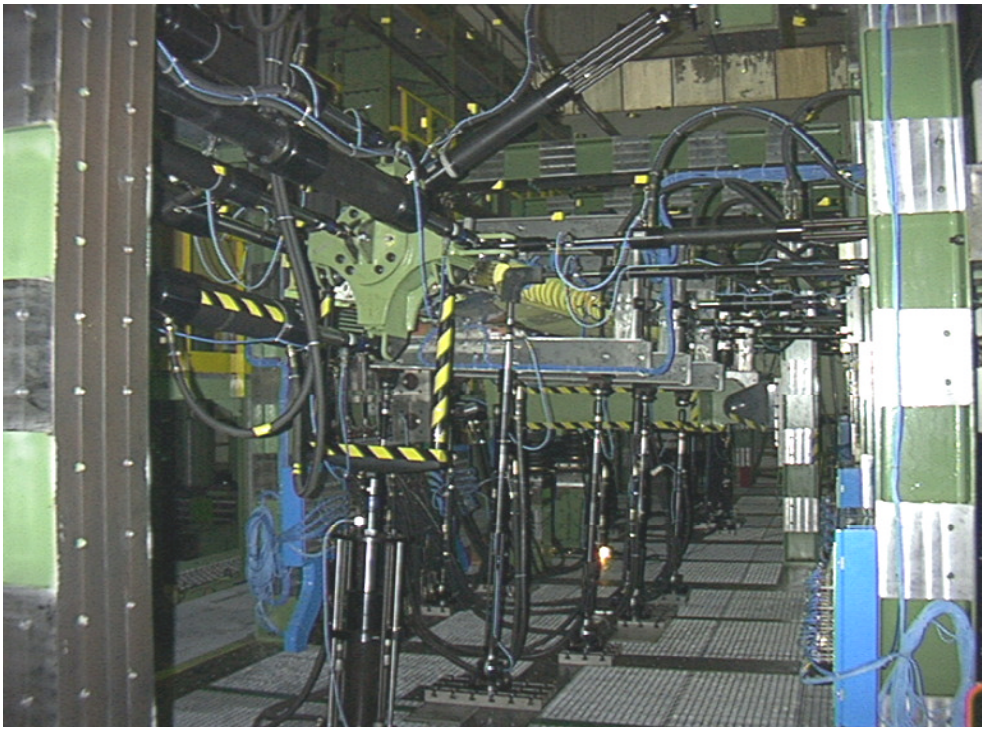

Fig. 39 – BA609 Tiltrotor: wing fatigue test set-up.

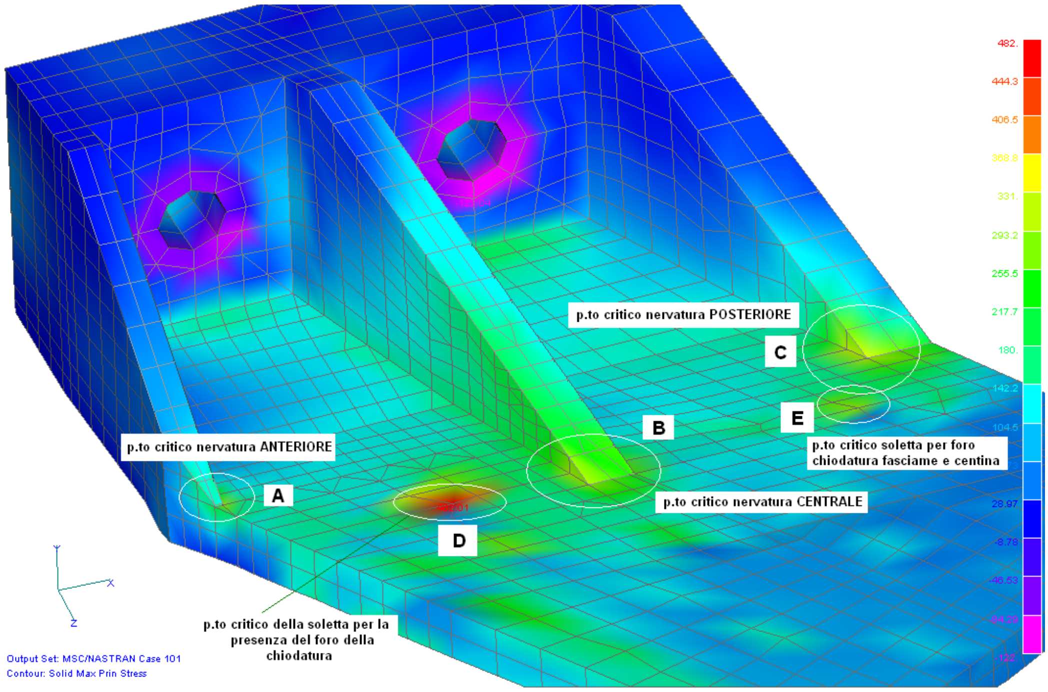

Fig. 40 – Detail of a FEM stress analysis of the fin-fuselage attachment fitting in the M346 aircraft.

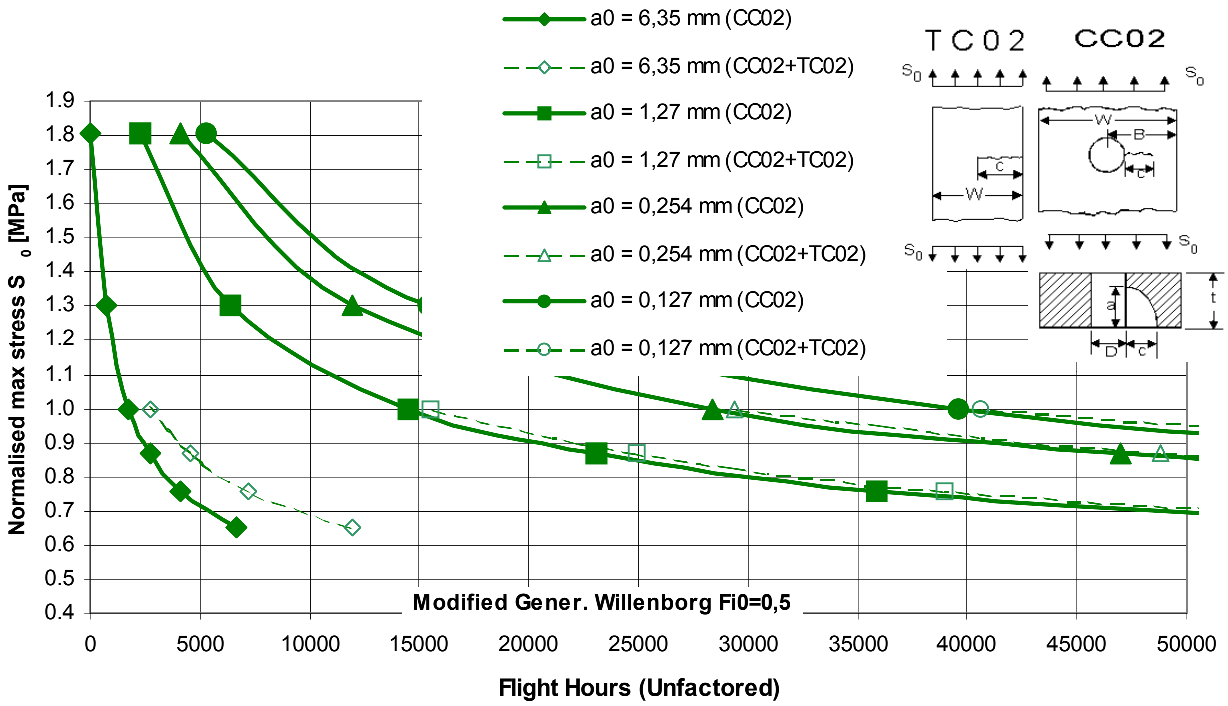

Fig. 41 – Example of damage tolerance design curve for a critical detail of the M346 trainer.

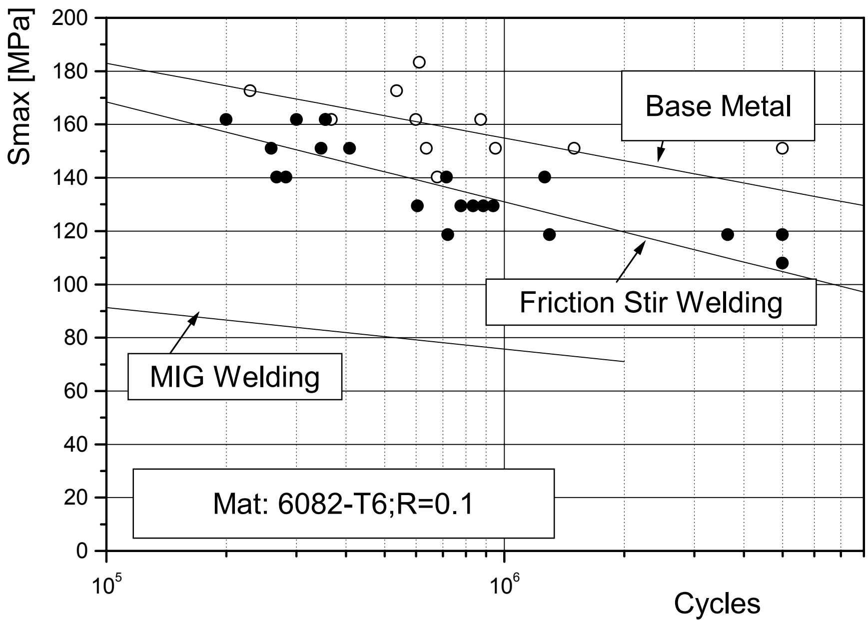

Fig. 42 – Results of fatigue tests on FSW butt joints in 6082-T6.

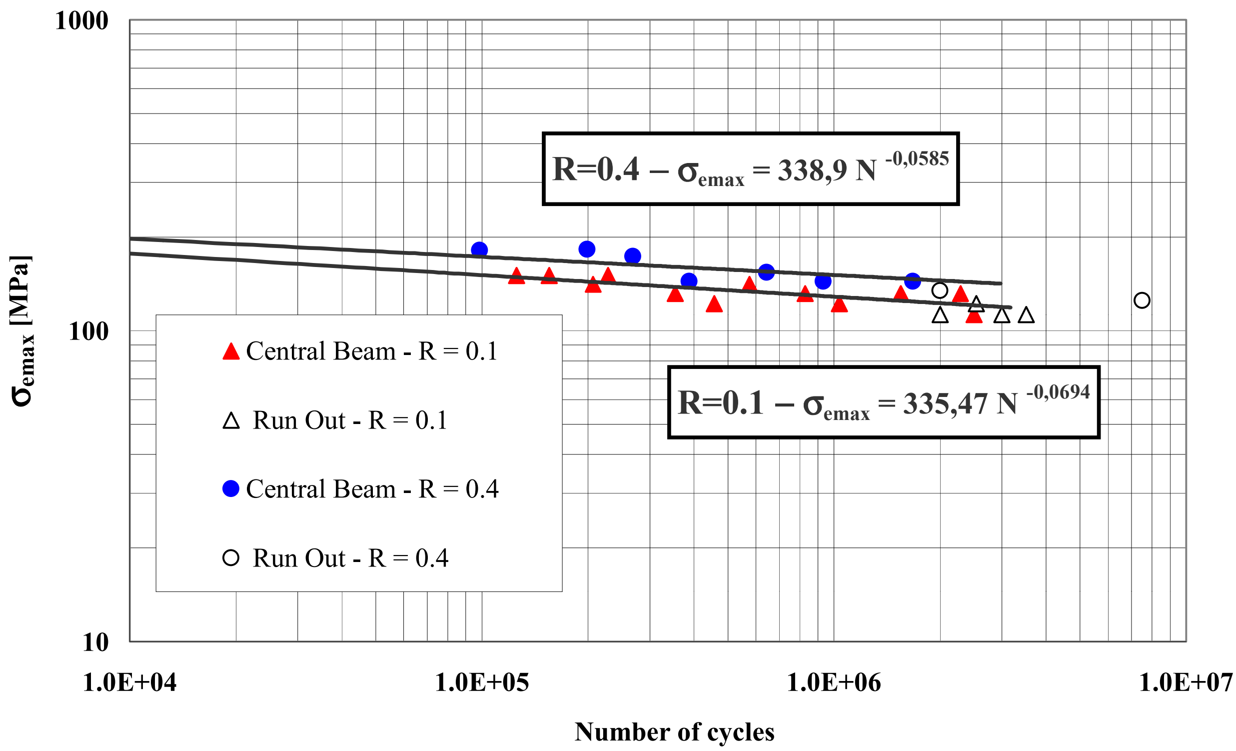

Fig. 43 – Results of fatigue tests on welded specimens made of thin steel sheets.

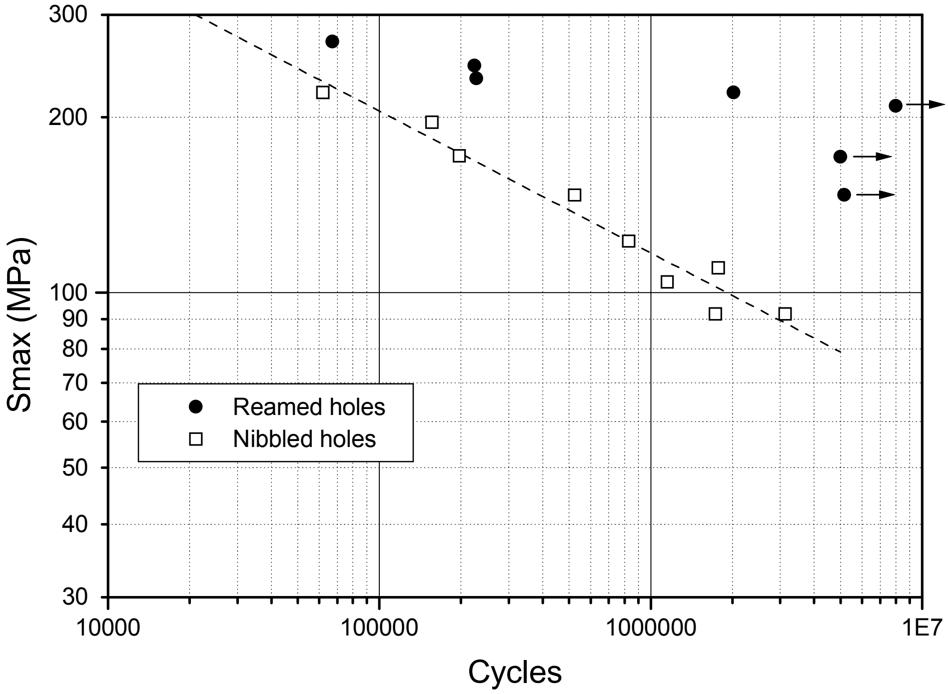

Fig. 44 – Comparison of fatigue test results from open hole specimens in AISI 304, R=0.02; effect of the hole manufacturing technology