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 May 1999 - April 2001

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This document summarizes the main research activities carried out in Italy about aeronautical fatigue in the period May 1999 – April 2001. The main topics covered are: load measurement actions, fatigue and fracture mechanics of composites, probabilistic design methodology, joints, full scale testing.

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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 - MB-339CD service life management (Aermacchi)

The Aermacchi MB-339CD is the latest and most advanced version of the MB-339 family of jet trainers. It has been designed for advanced and fighter lead-in training and optimised for pilot's conversion to the latest generation of operational aircraft. The MB-339CD is currently operated by the Italian Air Force in the Lead-In Fighter and Operational Conversion Unit roles.

Although not specifically designed to MIL-STD-1530A, the structural integrity of the MB-339CD, in agreement with the requirements of ASIP TASK V, is monitored by:

- Implementing a Load/Environment Spectra Survey (L/ESS) program by means of an Airborne Strain Counter (ASC)
- Performing an Individual Aircraft Tracking (IAT) program, according to the already existing methodology validated with the MB-339A fleets, i.e. by means of fatigue meters data

Only the L/ESS aspects will be reported in the present paragraph.

Each MB-339CD has been equipped with an ASC equipment which records in flight the signal time histories of seven strain gages and one C.G. accelerometer. A description of the equipment performance and of the location of the instrumentation has already been given in previous editions of the National Review. The time histories are processed on board with a rain-flow algorithm and stored in matrix form spectra. The data are downloaded from each aircraft periodically (or in a query mode procedure).

In May 2000 the first set of ASC data relevant to the MB-339CD's in service with the IAF have been downloaded. The data cover an average of 250 flight hours per aircraft.

The fatigue damages accumulated in the critical sections, corresponding to the strain gauges locations, have been evaluated and normalised to the same reference number of flight hours. The relative Miner rule has been used for this purpose, i.e. the results of the fatigue tests carried out on the full scale components were used for tuning the value of the damage at unit for the design life. The results obtained for two fatigue critical locations (the root of the fin main spar and the root of the wing main spar) are particularly interesting and will be discussed here. While the damage in the former location is strictly dependent on the Ny dominated manoeuvres, in the latter case fatigue is mainly sensitive to the Nz vertical load factors.

A statistical comparison has therefore been done between the scatters existing in the two different populations of fatigue damages, i.e. those dependent on the individual Ny spectra and those derived from the individual typical Nz spectra.

a) Fin main spar stress and bending moment spectra

The relationship between fin root bending moment (BM) and strain gauges values has been obtained from the calibration procedure required for the Flight Load Survey activity. The stress spectra have therefore been converted into BM spectra and plotted against the BM spectrum of the fatigue test (all the spectra have been normalised to 1000 hours). The diagrams of figures 1 and 2 show two typical examples (for two different aircraft) of experimental vs. design bending moment spectra. As it is possible to see, with the exception of the case in which it is clear that the measured spectrum is much more severe than the design one (Figure 1), the spectra cross each other and it is not so evident which is heavier (Figure 2).

The Severity Index, defined as the ratio of the fatigue damage relevant to the ASC measured spectrum over the fatigue damage of the reference design spectrum, is a suitable parameter for the evaluation of the usage severity.

The fatigue damage has been calculated for the fin main spar fitting lug, for which the relationship between fin root BM and stress on the lug net section is known from FEM analysis.

Table 1 shows, for each MB-339CD and for each individual measured fin load spectrum, the fatigue damage extrapolated to 1000 hours and the Severity Index (S.I.) with respect to the design spectrum.

FIN MAIN SPAR LUG		
A/C	fatigue damage in 1000 hours	Severity Index S.I.
1	0.0210	1.350
2	0.0023	0.147
3	0.0085	0.544
4	0.0170	1.088
5	0.0051	0.326
6	0.0092	0.589
7	0.0033	0.211
8	0.0360	2.340
9	0.0012	0.077
10	0.0140	0.896
11	0.0031	0.198
12	0.0047	0.301
13	0.0042	0.269

TABLE 1

The Severity Index data reported in Table 1 is well represented by a Log Normal distribution; the mean value of the S.I. is 0.418 and the standard deviation of Log S.I. is 0.4227.

b) Wing main spar stress and Nz spectra

The MB-339CD wing main spar fatigue test article was instrumented on the lower boom with a strain gauge bridge located in the same position as on the monitored aeroplanes and connected to an ASC. The test spectrum was a flight by flight sequence and the "damage model" was determined by "tuning" the fatigue damage calculated from the rain-flow stress matrix spectrum recorded by the ASC with the test result (spar failure time).

WING MAIN SPAR LOWER BOOM		
A/C	fatigue damage in 1000 hours	Severity Index S.I.
1	0.073	2.710
2	0.013	0.467
3	0.063	2.330
4	0.015	0.569
5	0.041	1.518
6	0.024	0.888
7	0.034	1.258
8	0.037	1.370
9	0.029	1.073
10	0.036	1.330
11	0.033	1.221
12	0.045	1.666
13	0.046	1.703

TABLE 2

Therefore the fatigue damage in the critical section of the spar for the flying aircraft can be evaluated using as an input either the ASC Nz spectra or the ASC local stress spectra. The differences encountered are mainly due to the presence of external stores in some missions and/or to a different fuel mass distribution. In Figure 3 a typical ASC Nz spectrum is shown, compared with the design spectrum.

For each aircraft, the fatigue damage has been evaluated in the spar boom critical section, under the ASC spectra; such values and the corresponding S.I. with respect to the design spectrum are reported in Table 2, referred as usual to 1000 flight hours.

Fitting a Log Normal distribution to the above S.I. values, a mean value of 1.255 is obtained, while the standard deviation of Log S.I. is 0.2151.

Notwithstanding the in-service similar use of each MB-339CD of the fleet, in terms of training missions typology, a greater scatter can be observed for the fatigue damage indexes (S.I.), derived from in flight measured Ny dominated stress spectra with respect to the S.I. values calculated on the basis of in flight collected Nz dependent stress spectra.

The fatigue damage status of the vertical empennages is much less homogeneous with respect to that of the wings, even if the types of mission could be considered quite similar and repetitive.

Furthermore it can be seen that a correlation between the fatigue consumption rates of the two components is very difficult and could be misleading in the framework of a monitoring based only on typical fatigue meters data.

2.2 - TORNADO life monitoring (Alenia Turin)

As already outlined in previous versions of the Italian National Review, the structural fatigue life of g-sensitive components, applied to the entire Italian fleet, is managed by Alenia using its own computer program, that utilises g-meter readings and configuration/masses control. This activity is performed in parallel with the Maintenance Recorder System, that is managed by the Italian Air Force. The Maintenance Recorder System is based on flight parameters recordings on board and fatigue life consumption calculation on ground.

The major progresses in the period of the present Review are relevant to a new updating of the software of the Maintenance Recorder System, that will be released to the customer in the next future; it was now converted from VAX station to a PC, with a significant reduction in computation times.

2.3 - EF TYPHOON (Alenia Turin)

ALENIA prototypes (DA3 and DA7) are performing the flight tests activity.

A simplified procedure for the assessment of the structural fatigue consumption of prototypes is used; the procedure is based on flight test instrumentation and compares design spectra with in-flight measured spectra of some significant flight parameters. A particular attention was paid to monitoring the time spent in flight conditions potentially prone to generate buffet.

As far as the production aircraft is concerned, a revision activity of the fatigue requirement and an updating of spectra started, taking into account updating of aircraft characteristics and the definition of new stores. Great importance was given also to generate accurate buffet spectra, since the phenomenon was identified as significant, mainly in the outboard part of the wing.

After the Major Airframe Fatigue Test (MAFT) performed on a prototype, a production structure is in preparation for being submitted to a fatigue test (PMAFT). For the preparation of this test, again, a deeper analysis of buffet spectra was undertaken, starting from the outboard region of the wing; the study is then examining inboard zones where, anyway, the phenomenon remains significant.

A new more refined method to calculate buffet spectra was used. This method is based on the following steps:

a) evaluation of the power spectral density information for different wing stations; this is accomplished by means of extensive wind tunnel data and by the use of transfer functions that relate the level of buffet intensity with angle of attack and the dynamic pressure; the flight test activity is in progress, as already outlined, for a validation of the load information;
b) finite element analysis of the wing, for the evaluation of bending and shear resultants in given locations, as a consequence of the applied buffet load;
c) conversion of the power spectral density information into load time histories, made of various sinusoidal waveforms, at discrete frequencies, with magnitude equivalent to the root mean square of the signal in an interval centred on the given frequency; the various waveforms are characterised by a random phase lag, but the histories are anyhow subsequently shifted one to the other to obtain an optimum correlation with iso-probability plots for coupling of different load resultants, i.e. Fx, Fy, Fz, Mx, My and Mz;
d) analysis of the damage associated with buffet load conditions with usual fatigue methods.

This activity was performed to better estimate both fatigue lives and spectra to be simulated in the tests.

2.4 - Generation of a Flight By Flight spectrum for the design of a new advanced jet trainer (Aermacchi)

Aermacchi has launched the development of the M-346, its fourth-generation training system, designed to meet the requirements of pilots who will fly the multirole air superiority aircraft of the 21st century. The program utilizes the experience gained during four years of flight tests of the YAK/AEM-130D demonstrator prototype.

A computer program has been developed, in co-operation with the Polytechnic of Milan, to generate a complete Flight by Flight (FbF) load history, that can be used from the initial design phase of the entire airframe or components up to the full-scale fatigue test or fatigue tests on single components.

The data initially required are the aircraft design service life, the mission profiles definition and a detailed configuration and mass distribution description.

The program performs first a FbF spectrum definition, in terms of a sequence of mission segments for each mission profile. Subsequently, the program generates a load spectrum for each segment of each mission type.

Spectra are subdivided into ground (taxi, turning, etc.), flight manoeuvres (symmetric, rolling pull-out, 1 g roll, rudder manoeuvres, etc.) defined as steady or abrupt, gusts (vertical and lateral) and particular events (speed brake extraction, brakes activation, etc.).

Then, the program generates a randomised sequence of the missions and of the so-called "point-in-the-sky" inside the missions segments: only the sequence of the segments and the relevant events are not randomised.

The "point-in-the-sky" is defined as a code containing all the necessary information to compute the loads acting on the aircraft, such as speed, weight, altitude, type of manoeuvre or event, etc. By replacing the codes indexes with the relevant loads values, it is possible to obtain automatically the load history.

In Figures 4 and 5 are reported, as typical examples, graphical representations of the most significant mission spectra, i.e. the Nz spectra and the Ny spectra due to flight manoeuvres. The spectra are referred to each design mission type and their shape is such as to take automatically into account the structural limitations of the airframe, as far as the actual feasibility of some manoeuvre is concerned.

3. METALS

3.1 - Fatigue behaviour of notched and un-notched materials

3.1.1 Influence of hardness indentation on fatigue life (Aermacchi)

In the frame of the Brite Euram Research program ELIM, a campaign of laboratory fatigue tests has been made for the determination of the influence of hardness indentations on the fatigue life of typical alloys used in the manufacturing of aircraft structures. For this purpose, three different materials have been tested: the aluminium alloy 7050-T7451, the low alloy steel SAE 4340 B124 and the 15-5 PH H900 stainless steel. Three different kinds of indentation have been applied to specimens: a Vickers pyramid, a Rockwell conical indenter and the Esatest method, which is an advanced system that uses diamond indenters to evaluate the hardness of electrically conducting surfaces.

The Esatest instrument is proposed to determine the material hardness not only on specimens and raw materials but also on finished parts. The aim of this research was to determine if the indentation produced by this instrument has any influence on the fatigue behaviour of materials typically used in aircraft components. For this reason, Aermacchi performed comparative fatigue tests on smooth specimens and on specimens with hardness indentations, produced by the three methods above specified.

The Aermacchi's Laboratory carried out in total 180 tests (45 specimens were tested for 7050 and for 15-5 PH, while 90 tests were carried out for the 4340 steel). In the case of 7050 and of 15-5 PH materials, 5 specimens were subjected to static tensile tests, while the remaining were all fatigue tested, divided into 4 groups, each one composed by 10 specimens: no indentation, Vickers, Rockwell and Esatest indentation. In the case of 4340steel, all the numbers were doubled.

The 7050-T7451 alloy specimens were machined from plate while the 4340 B124 and 15-5 PH H900 steels alloy specimens were machined from a round bar. Chemical and mechanical characteristics of materials were checked, and the materials were found to be compliant with the applicable specifications.

Each specimen was polished, had dimensional checks and its surface roughness was measured less than 0.6 µm. Four hardness indentations were applied, equally spaced, in the central section of each specimen.

The fatigue tests were performed by means of an "Instron Dynamic 8501" machine, applying to the specimens an axial loading of constant amplitude, with a stress ratio (R=0.1). The maximum cyclic stress was 85% of the yield stress. The test frequency was 20 Hz. The tests were carried out in air at room temperature.

The average results of the static tests are shown in Table 3.

Material	Yield stress (MPa)	Ultimate stress (MPa)
7050 T7451	461	535
4340 B124	1181	1275
15-5 PH H900	1311	1389

Table 3 – Average tensile static properties.

The fatigue tests results are reported in Figs. 6, 7 and 8, respectively for 7050-T7451, for 4340 B124 and 15-5 PH H900. It is possible to see that the different indentations have no influence on the fatigue strength of the first two materials and a slight effect in the case of the stainless steel.

Table 4 shows the average number of cycles at specimen failure, obtained with all the types of hardness indentations. It is possible to observe that the average fatigue life of the three different materials is hardly influenced by the Esatest and Vickers indentations and a little more by the Rockwell.

Table 4

Material	Average Number of Cycles at Failure			
	Specimens without hardness indentations	Specimens with hardness indentations		
		Vickers	Rockwell	Esatest
7050 T7451	23292	24242	17176	25705
4340 B124	103668	67710	77391	61534
15-5 PH	79839	75427	34145	42946

In Table 5 are summarised the failure locations, whether in correspondence of indentations or not, observed with all the types of hardness indentation. It can be noted that the Esatest and Vickers indentations have practically no influence on the specimen failure for the three different materials. On the contrary, in the specimens with Rockwell indentations, 25% of fatigue failure surfaces interested an indentation mark, and for some of them the crack initiated from one of the four indentations on the boundary of the cross section.

Table 5

Material	N° of Specimens Failures In correspondence of Indentations (IN) or not (OUT)					
	Vickers		Rockwell		Esatest	
	OUT	IN	OUT	IN	OUT	IN
7050 T7451	9	1	9	1	10	0
4340 B124	19	1	14	5	19	0
15-5-PH H900	10	0	6	4	10	0
Total	38	2	29	10	39	0

The results shown verified that the indentations produced by the Esatest Instrument indenter do not influence the fatigue life of the materials evaluated. Moreover, the indentations are so small that it is possible to use the Esatest instrument also on finished elements and parts. This is a very important characteristic because it allows to measure the hardness of a finished part without disassembling the element, as it is usually necessary if a traditional hardness tester is used.

3.1.2 Fatigue behaviour of superplastic formed Ti-6Al-4V (Alenia Turin)

Some components made of Ti-6Al-4V of the EF Typhon, such as the keel beam, are manufactured by means of the superplastic forming technique. This process is very critical because of the risk of a change in the metallurgical characteristics of this alloy, that is an alpha-beta alloy: a common defect is the increase of the alpha phase, that may occur mainly on the outer surface. An experimental investigation on the influence of alpha phase presence was initiated. Coupon specimens, obtained from manufactured items, with different levels of alpha phase contamination in the layers close to the surface, were fatigue tested; the results are plotted in Figure 9, where no difference is appreciated between the fatigue lives of coupons made of uncontaminated material with those of coupons with increasing levels of contamination, cut from production elements.

A further investigation was performed exposing specimens at the temperature of 850 °C, in order to increase the presence of the alpha phase. The specimens were subsequently fatigue tested and the results plotted as a function of time exposure (i.e. percentage of alpha phase); the results are shown in Fig. 10. The data obtained indicate a small influence of the alpha phase on the fatigue behaviour, if the contamination remains confined within 3-4% of the coupon thickness, while a significant decrease of the fatigue resistance is observed, when the alpha phase contamination interests more than 5% of the thickness. Further analyses are on going.

3.2 - Crack propagation and fracture mechanics

3.2.1 Fatigue crack propagation under the combined action of tension and bending (Uni. Pisa)

An experimental activity started at the Department of Aerospace Engineering of University of Pisa about the propagation of cracks subjected to combined tension and bending stresses. This is a contribution to the research on probabilistic design methodology, that has been running for the last 5-6 years at the University of Pisa (see previous Italian National Reviews). The aim is to increase the accuracy of the models for the description of the fatigue crack growth process in a lap joint.

Tests are carried out on 2024-T3 specimens, 250 mm wide. The bending stress is introduced by mounting eccentrically the specimens on flexible grips. Two different values of thickness, 1.6 and 3 mm, and three different bending/tension stress ratios, in the 0.5÷2.5 range, are examined. The activity is still in progress. Fig. 11 shows the results of a test; the data of the test are: axial stress 42 MPa, ratio of bending to axial stress 2.2, thickness of the specimen 3 mm. The start notch was a double corner crack, c=1.8 mm in a hole with a diameter of 4 mm. A good prediction of the crack growth, even if slightly conservative, was obtained by using AFGROW, that implemented the results developed in [1].

3.2.2 Fatigue crack growth characterization of 2195 Al-Li alloy (Uni. Pisa)

The 2195 alloy is a low-density aluminium alloy that may replace 2219 in future aerospace programme, due to its lower density, higher fracture toughness and greater strength at cryogenic temperatures. All these characteristics allow significant weight savings in the design of space structures, particularly those obtained by welding.

An experimental activity started at the Department of Aerospace Engineering of the University of Pisa on 2195-T8, within the framework of cooperation with Alenia, Space Group, to obtain results about the fracture toughness, the crack propagation rate and the susceptibility to stress corrosion cracking of the base material. In the meantime, Alenia is developing two welding processes on this material, variable polarity plasma arc welding and friction stir welding, which will be evaluated from the fatigue/fracture mechanics points of view.

At present, fatigue crack propagation tests are concluded; tests were carried out on 7 mm thick plates, two orientations and two stress ratios. Fig. 12 shows the results of the tests carried out on L-T specimens, for two values of R, the stress ratio.

3.2.3 – Random fatigue accumulation (Uni. Rome)

The aim of this research, developed at the Aerospace Department of the University “La Sapienza” of Rome, was to validate some probabilistic models for the analysis of fatigue cracking in aeronautical structural components in the case of non-deterministic loading.

In collaboration with the Italian Air Force, that provided loading spectra of the AM-X fighter engine (Fig. 13), extensive experimental tests have been conducted on the Nickel alloy Inconel X750 and demonstrated the advantages and disadvantages of each of the proposed models. In particular, several experimental tests demonstrated that Furry-Yule and Poisson distributions do not describe correctly the whole crack propagation process, while a new expression of the calibration parameters, i.e. state transition intensities, was developed, producing a good improvement of the results. As a further evidence of the reliability of the proposed model, the life probability was computed (Fig. 14) denoting a perfect correspondence (failure at 100,000. seconds) with experimental results, despite Furry-Yule and Poisson predictions. More details can be found in [2].

3.2.4 – Probabilistic modelling of fatigue crack growth under sinusoidal loading (Uni. Rome)

This research proposes a critical comparison among three probabilistic models of fatigue crack growth: the first two, already presented in literature, are the one developed by Spencer, Enneking and Tang (SET), based on the randomization of a semi-empirical crack growth law by a gaussian white noise of proper intensity and the one developed by Ray and Tangirala (RT), hinged on a discrete time representation of the correlation functions of fatigue crack growth. The third one, proposed in [3], deals with the Virtual simulation of Fatigue Tests (VFT) performed by a computer: this approach to fatigue modelling allows to obtain the statistical features of damage growth by the direct analysis of virtual generated data.

Fatigue tests, performed on compact type CT samples, made of the Titanium β alloy Ti-15V-3Al-3Cr-3Sn, and numerical results demonstrated that: 1) The SET model has proved to be substantially inaccurate, since it is based on the assumption that the crack growth process is stationary; however, it has the advantage of being based on Crack Mechanics concepts, which help to explain the physical meaning of the model parameters; 2) The RT model shows great analytical simplicity and leads to numerical results which agree well with experimental data; however, from a mathematical viewpoint, it requires to diagonalize a correlation matrix, which can be of considerable dimensions and, in addition, this model does not take into account the physical description of crack growth mechanism and so it does not allow to establish any link with the load features; 3) The VFT model allows reliable statistics of the crack growth process (Fig. 15) to be obtained starting from simple statistical hypotheses and a limited set of experimental data, that is, strictly speaking, a single fatigue test: it is based on the implementation of a generation algorithm and it is very simple from an analytical and a numerical viewpoint.

4. COMPOSITES

4.1 – Fatigue behaviour

4.1.1 Composite degradation due to fluid absorption (Pol. Milan)

The experimental study, carried out at the Department of Aerospace Engineering of the Milan Polytechnic, investigated the combined effects of liquid (water, Skydrol, fuel and dichloromethane) absorption, impact damage and drilling on aramid and carbon fibre/epoxy composites. Fabric material was evaluated, with coupons made mainly with two lay-ups: a fibre-dominated 0/90 cross-ply and a matrix-dominated 45/-45 angle-ply. The static and fatigue behaviour of the composite samples was determined after the treatments. The response to impacts was analysed and elastic and absorbed energy were measured. The mechanism of moisture diffusion into the composites was studied and a method for the accelerated ageing of the composites applied. Penetrant radio-opaque dye and stereo radiography were used to determine the onset and growth of damage during fatigue life and the decay of mechanical characteristics. Optical microscopy was used to investigate the microscopic mechanisms of absorption and damage, in order to propose interpretative models. More details on this activity can be found in [4].

Wet conditioning was found to induce strong matrix plasticisation. For matrix-dominated aramid laminates, this produces a notable reduction of static and fatigue performance, compared to unconditioned (as supplied) laminates. Skydrol conditioning causes similar effects, but quantitatively they are more severe. Conditioning with jet fuel and de-icing fluid generally had negligible effects on laminate characteristics, except that compressive strength was strongly reduced (25%), owing to the severe fibre degradation. Some numerical results of this study have also shown that numerical models for Fickian diffusion are valid for composites. In particular, neither drilled nor impacted laminates showed anomalous diffusion. Greater than room temperature conditioning with water and Skydrol resulted in reduced mechanical performance, while room temperature conditioning with jet fuel, de-icing fluid had little effect. However, whether these differences in results depend on conditioning temperature (as advised by standard procedures) needs to be further investigated. Furthermore, because aramid fibre performance was strongly affected by the conditioning processes, the effects of high temperature conditioning on these fibre-dominated laminates should also be examined.

Carbon/epoxy laminates responded poorly to impact, with extensive damages produced by low energy impacts. Furthermore, static characterisation showed that impact led to greater damage than drilling, irrespective of the type of conditioning. Fluid uptake led to degraded static mechanical performance in all laminates tested, except that compressive strength reduced less for drilled laminates after water conditioning than for plain laminates. This was due to resin plasticisation and reduction of stress peaks close to the hole. Fatigue characterisation confirmed degraded mechanical performance. Moisture uptake further reduced fatigue life, particularly on impacted laminates. Synergistic effects between impact damage and fluid absorption were observed that were greater than combined effects due to holes and fluid absorption.

Aramid/epoxy laminates were better able to absorb impact energy than carbon/epoxy, so limiting damage extension, and impacts of specific energy for unit thickness in the 1.0-1.5 J/mm range induce barely visible damage in these materials. Moisture absorption occurred as expected indicating that no irreversible absorption phenomena occurred. There was a marked synergy between impact damage extension and fluid uptake, which jointly reduced both static and fatigue material performance. The reduction in performance was proportional to damage extension. Aramid composites absorbed about 70% more water at saturation than carbon-reinforced composites, due to the hygroscopicity of the aramid fibres. In conclusion, fluid uptake always induces resin plasticisation and hence reduces the performance of laminates. This performance reduction is greater in matrix-dominated than in fibre dominated laminates and is always increased by impact damage.

4.2 – Damage mechanisms and damage development

4.2.1 Interlaminar fracture resistance of composites under Mixed Mode conditions (Uni. Pisa)

Within the framework of a collaboration with Agusta, a research activity has been carried out about the delamination growth in composite structures. One of the most interesting observations was that a delamination may grow, under the application of a compressive fatigue load of constant amplitude, with a progressive decrease in the rate; in some cases, when the load range was low, the growth stopped and a sort of stable final shape was reached.

Fracture Mechanics analysis is usually based on G, the Strain Energy Release Rate, and on how G is divided into the contributions according to the fundamental Fracture Mechanics modes, i.e. mode I (opening), mode II (in-plane shear) and mode III (out-of-plane shear), [5]. Since in real structures, delaminations are very often loaded in mixed mode conditions, it has been considered important to carry out the characterization of the material used in the activity, an unidirectional carbon/epoxy system, Cyanamid 985-GT6-135.

For this purpose, the Mixed Mode Bending (MMB) test procedure has been utilised, [6]. This is a test procedure that has the advantage of using only a single type of specimen, i.e. the Double Cantilever Beam coupon, made of 24 plies at 0-degrees, with a Teflon insert as delamination starter. This specimen can be used not only for pure mode I tests, but also for Mixed Mode and for mode II conditions (as if it were a End Notch Flexure coupon). The MMB test set-up has the advantage that only one actuator is required: the force is applied to a lever, that introduces two superposed load conditions (one according to mode I and another in mode II) on the coupon. By changing the position of the specimen with respect to the actuator axis, it is possible to change the mode ratio.

Tests have been carried out in pure mode I, pure mode II and for three different G_I/G_{II} ratios: 4/1, 1/1 and 1/4; Fig. 16 shows the experimental results in terms of G evaluated according to the Kinloch formulation, plotted on the G_I versus G_{II} plane. The bilinear criterion, that currently receives most credit by the scientific community, is capable of describing adequately the material interlaminar resistance.

A similar activity has been carried out, in collaboration with AerMacchi, for the characterization of two unidirectional carbon epoxy systems, produced by Hercules: AS4/3501-6 and IM7/8552.

4.2.2 Damage tolerance of composite sandwich structures (Uni. Pisa/Agusta)

Within the framework of the EDAVCOS Brite-Euram project, a collaboration has been carried out between the Department of Aerospace Engineering of Pisa and Agusta, for the study of the damage tolerance behaviour of selected composite sandwich panel configurations. The purpose of the project was to improve comprehension of the driving parameters in delamination growth, deriving data to reduce the test plans on complex elements and subcomponents.

In particular, the following types of specimens have been considered in the Agusta and Pisa studies:

a) panels containing a delamination and subjected to compression loading;
b) panels subjected to impact damage and tested in shear in a picture frame set-up;
c) panels tested under Four Point Bending (FPB) loading.

Static and fatigue tests have been performed, in order to collect data to evaluate the capability and accuracy of design procedures. In the cases examined in the research, the approach based on the use of the Strain Energy Release Rate has been utilised for evaluating the test results. This requires a non linear analysis of a detailed Finite Element model of the component, since the occurrence of local buckling often must be taken into consideration. The results of the numerical analysis are then used to evaluate G, the Strain Energy Release Rate, along the delamination front, included its mode partition.

The first kind of component represents a classical example, often discussed in the literature. The results of the numerical analysis are in a reasonably good agreement with the experimental results, both for the static and for the fatigue load cases, and are partly reported in [5].

In the second type of component, i.e. the shear loaded panel, one of the major problems was how to model efficiently an impact damage, that was more severe than the BVID level, producing a permanent visible indentation in a skin. Only static tests were carried out to evaluate the residual strength of the panel, after a 30 J impact being inflicted in the centre of a face. The experimental results, in terms of strain distribution and displacements for loads up to failure, have been particularly useful to validate the numerical analysis. The permanent indentation, that interested all the thickness of the impacted skin, was modelled as a cylinder of material characterized by a much lower stiffness than the integer layers, surrounded by larger delaminations at the first two outer interfaces. This model is rather questionable, even if it is supported by predictions in reasonable good agreement with test results.

The third type of specimen, i.e. sandwich coupons tested in FPB conditions, had the same material and lay-up of the previous one. Each skin was composed by six layers of carbon epoxy fabric and the effect of different defects introduced in the compression loaded skin was studied. Three different variants were available: pristine panels, panels with an artificial delamination in the form of a Teflon strip (10 mm long, as wide as the specimen) inserted in a skin, impact damaged specimens (25J). Static and fatigue tests were carried out, with a Compression-Compression loading (R=5) being applied to the critical skin. The fatigue results show that impact damage, that was almost at BVID level (with an indentation of about 0.4-0.5 mm), was very critical, reducing heavily the fatigue strength in comparison with the pristine specimens, as shown in Fig. 17. Numerical analyses are still in progress.

4.2.3 Impact behaviour of heat-resistant toughened composites (Pol. Milan)

The research, carried out at the Department of Aerospace Engineering of the Milan Polytechnic, had two purposes: to measure the influence of toughening on the post-impact residual compressive strength of composites for high temperature application; to check the possibility of studying the problem through experimental tests and numerical simulations.

Three different composites were considered:

a) standard glass fibre/isocyanate-epoxy;
b) glass fibre/isocyanate-epoxy toughened with 15% in volume of polyethylene-glycol;
c) glass fibre/isocyanate-epoxy toughened with 15% of polyester.

The experimental activity consisted in imparting low-energy impacts to produce visible and barely visible damages (BVID) into composite panels, subsequent digital analysis of the damage and final evaluation of residual strength through compression-after-impact (CAI) static testing.

The experimental results show that the toughened composite have the best post-impact behaviour: in fact, the specific total impact energy being equal, the damaged area in polyethylene glycol- and polyester-toughened composites is respectively 12-49% and 12-25% smaller than the one in the standard isocyanate-epoxy composite, the higher differences pertaining to low-energy impacts, leading to BVID. Besides, the post-impact residual compressive strength shown by polyethylene glycol- and polyester-toughened composites is respectively 18-35% and 31-35% higher than standard isocyanate-epoxy; again, the best performances are obtained at low-energy-content impacts producing BVID.

The three materials show the same type of correlation between the total specific impact energy and the damaged area, absorbed energy and residual strength, that is respectively linear, logarithmic and cubic. Owing to the random disposition of the reinforcement, the damage does not assume a well defined shape. Further tests showed that the compressive residual strength is lower for notched specimens (hole diameter equal to impactor diameter) than for damaged ones. These beneficial effects demonstrate the soundness of toughening to reduce the sensitivity of composites to low-energy impacts. However, the influence exerted by toughening on high temperature behaviour and moisture endurance should be analysed in the future.

The feasibility of the numerical approaches was demonstrated as well, making use of two different codes, to model respectively the impact damage extension and the compression-after-impact tests. An appreciable agreement between the experimental and the numerical results was obtained. A particularly good correlation between measured and computed damage area was found, in the case of low and medium energy contents, not leading to through-the-thickness penetration. This does not constitute a limitation to the application of the numerical approach: in fact, in the latter case, the damage is easily detectable and does not constitute a BVID. The numerical simulation allows to identify the damaged area much more easily than through the experimental techniques, like digitised radiographs, being the contours of the former better defined and easily identified. A satisfactory through-the-thickness reconstruction of the damage was performed as well, although the comparisons were made between the theoretical computations and the numerical simulations, rather than with the experimental results.

More details can be found in [7].

5. JOINTS

5.1 - Riveted Joints

5.1.1 Development of a design methodology based on the probabilistic approach (Uni. Pisa)

The PISA (Probabilistic Investigation for Safe Aircraft) code, written in Fortran, studies the modelling of the fatigue behaviour of typical aeronautical structures, such as riveted joints and stiffened panels or joints, in order to evaluate their number of cycles to failure. By means of the MonteCarlo method and utilizing the statistical distribution of the main parameters that influence the deterministic estimate of the component fatigue life, the code is capable to simulate the typical scatter in fatigue life of metallic components. The code has already been the object of presentation at ICAF Symposia, [8] and [9]. A sketch of the organization of the code is shown in Fig. 18; in the last two years the activity has been centered on the following topics:

a) nucleation of single cracks, through the Equivalent Initial Flaw Size distribution;
b) analytical relationships for expressing the Stress Intensity Factor in stiffened panels;
c) possible inspectionability of the structure, at prescribed intervals in terms of number of cycles, through the Probability of Detection curve.

As an example of the major results of the activity carried out in the last two years, Fig. 19 shows a discussion of the determination of threshold and repetitive inspection intervals, based on the risk analysis, for a fuselage joint. Future developments of the research comprise the performance of tests on components, to evaluate the accuracy/reliability of the results and a further development of the code, in order to include a larger number of possible joint geometry.

5.1.2 Equivalent Initial Flaw Size distribution in lap joints (Uni. Pisa)

As a contribution to the development of the PISA code, an experimental research has been carried out at the Department of Aerospace Engineering of the University of Pisa for the assessment of the Initial Flaw Size distribution. For this purpose, riveted lap joints in 2024-T3 alloy, t = 1.6 mm, representative of fuselage longitudinal joints (three rivet rows, countersunk rivets), were fatigue tested with a sinusoidal load (R=0.1). The maximum stress was 100 MPa and the tests were stopped at selected number of cycles; the specimens were subsequently statically broken and the fracture surfaces were then examined at a low magnification microscope (20X) for identification of the already nucleated cracks. The data obtained in this way was then back extrapolated to an initial (0 cycles) defect distribution, by means of the FASTRAN (v. 3.7) code. This code has been considered the most appropriate for this kind of analysis since also short crack effects are kept into consideration. The results, shown in fig. 20, have been subsequently verified by means of other fatigue tests carried out at different stress levels, i.e. 80 and 120 MPa. The EIFS distribution has been utilised to obtain predictions of crack distributions at different number of load cycles, that have been compared with test results. The activity has been carried out for different squeeze forces used in the rivet installation, expressed as the ratio of the diameter of the formed head to the shank diameter: 1.4 and 1.6. Most of the results of this activity constitute the basis of a paper that will be presented at the Symposium, [10].

Another experimental activity is in progress, for the evaluation of the effect of environmental agents on the fatigue behaviour. Lap joints, similar to those tested in the activity previously described, are exposed to the combined action of sinusoidal fatigue loading plus immersion in a 3.5% NaCl water solution.

A supplemental investigation is also in progress to evaluate the effects of the load spectrum, by applying to the joint a sequence obtained from the constant amplitude load case by interspersing a block of many small cycles (at high stress ratio, since the maximum stress is kept constant) between two large load cycles (R=0.1).

6. INTERNATIONAL RESEARCH PROGRAMS

Many internationally coordinated research program are running, mainly within the framework of the Brite-Euram Programme, funded by the European Union, that is a very wide technology research and development programme. In most cases, technology developments have a significant impact and a tight connection with the fatigue behaviour of aircraft structures. In the following, a short description of the major programs in which Italian aircraft industries were involved is given, pointing out the objectives of the research, even if sometimes it is not easy to separate each partner's contribution.

6.1 - ADPRIMAS Brite Euram research (Alenia Naples, Agusta)

This European research program is oriented to the application of innovative material and processes in the design of ADvanced PRImary Metallic Aircraft Structures.

In this program the Durability and Damage Tolerance design, analysis, testing and certification processes were investigated.

The main partners were: University of Pisa, Naples, Dublin, Oxford and Delft, SAAB, BAe, Aerospatiale Matra, Dassault, INASCO, SABCA and Agusta industries and NLR and Institute de Soudure Research Centres.

Alenia main technical role was:

- Design, manufacturing and theoretical analysis of full scale side fuselage panels made in GLARE material (see Figure 21), including both riveting and bonding technologies.
- Design and manufacturing of a tri-axial (able to apply simultaneously bi-axial tension-compression and shear loads) test machine for static and fatigue testing for large scale fuselage panels (see Figure 22).
- Fatigue testing of large scale fuselage panels

The main objective of Agusta was the study of the applicability of Aluminium-Lithium alloys to typical helicopter fuselage structures, with particular attention being paid to the damage tolerance qualification of the structure.

The research activity was successfully completed on September 2000.

6.2 - EDAVCOS Brite Euram research (Alenia Naples, Agusta)

This primary objective of EDAVCOS (Efficient Design And Verification of Composite Structures) programme was to determine a cost efficient route to certification for composite aircraft primary structures. The targets were 50% reduction of total costs for verification and 60% time scale reduction, by means of the development (and validation within this programme) of analytical and numerical tools.

The main partners were: SAAB (Project Leader), Aerospatiale, Agusta, Alenia, BAe, CASA, CIRA, DERA, DLR, FFA, INTA, ISTRAM, NLR, ONERA, SABCA.

Alenia objective was the validation of the damage tolerance capability of stiffened panels working in post buckling conditions by means of the Energy Release Rate approach, while the attention of Agusta was focused on the use of the same approach for the assessment of damage tolerance characteristics of sandwich structures.

The research activity was successfully completed on January 2001.

6.3 - ADMIRE Brite Euram research (Alenia Naples)

The ADMIRE (Advanced Design concepts and Maintenance by Integrated Risk Evaluation for aerostructures) programme will develop and validate advanced design tools for the simulation of the structural behaviour in the presence of manufacturing damage. The overall objective of ADMIRE may be stated as "to develop a probabilistic foundation for the application of damage tolerant design of metallic aircraft structures taking into account the innovative investigations on the initial flaw concept, crack growth evaluation improvements and residual strength in complex geometry's".

These new design tools will enable the fatigue design offices to compute, on the basis of a probabilistic approach, the in-service failure risk associated with the component. Main partners are: University of Pisa, Naples and Queen Mary Institute, DASA, BAe, CASA, Aerospatiale Matra and INASCO industries and NLR and ISTRAM Research Institutes.

A flow chart of the main research activity is shown in Figure 23.

6.4 - TANGO Brite Euram technology platform (Alenia Naples)

The continued growth in air transport has placed an increasing demand on the aerospace industry to manufacture aircraft at lower cost, whilst ensuring the products are efficient to operate, friendly to the environment and ensure that the safety requirements are met.

In order to achieve the required levels of operating efficiency, specific industrial objectives for the next generation of products have been set:

- 20% weight reduction in comparison to current structures,
- 20% cost reduction in comparison to both current manufacturing processes and state of the art design.

TANGO (Technology Application to the Near-term business Goals and Objectives of the aerospace industry) represents an integrated approach to the validation of these technologies through the construction of the following main airframe components (see Figure 24):

- composite lateral wing box and metal-to-composite joint,
- composite centre wing box,
- composite fuselage section,
- advanced metallic fuselage section.

In the production of these structures, the partners will use new design and test methodologies as well as a series of new materials and manufacturing and assembly processes. These include:

- ❑ Design processes: multi-disciplinary optimisation, advanced simulation techniques, design oriented to new materials, design for manufacturing assembly,
- ❑ Manufacturing processes: friction stir and laser beam welding of aluminium alloys, resin transfer moulding, resin film infusion, adhesive bonding and automated lay-up,
- ❑ Materials: Aluminium-Lithium alloys, Aluminium-Magnesium-Scandium alloys, fibre-metal laminates (e.g. Glare), innovative carbon fibre reinforcements.
- ❑ Integration: best practice management techniques (including data exchange) will be applied by the lead aircraft companies and throughout the supply chain in a manner that is representative to the design and manufacture of a future European aircraft.

The main partners are: Airbus Industries, BAe, DASA, Aerospatiale, CASA, SAAB, GKN Westland, FIAT and Fokker. The following Research Centres are involved: CEAT, CIRA, DERA and NLR.

Alenia main activities are related to the design, manufacturing and testing of metallic and composite fuselage panels, and of composite upper wing panel and ribs.

6.5 – NASGRO development consortium (Agusta)

The NASGRO development consortium was formed to improve the software, keeping into account small cracks behaviour, new materials data, load interaction, ageing problems. In general, it is expected a wider use of the code, with improved analytical capabilities in fracture mechanics. Agusta is taking part in the consortium.

7. COMPONENT AND FULL-SCALE TESTING

7.1 - EF TYPHOON (Alenia Turin)

After the Major Airframe Fatigue Test (MAFT) performed on a prototype, a production structure is in preparation for being submitted to a fatigue test (PMAFT).

The fatigue test on the wing tip DASS pod is ongoing in ALENIA Turin. The spectrum includes manoeuvres with associated buffet conditions and gust loads; the test reached 12000 Test Hours, the target simulated life being 18000 Test Hours.

7.2 - TORNADO (Alenia Turin)

The test article of the TORNADO IDS MAFT (Major Airframe Fatigue Test), after the end of the test, was maintained for some limited studies that are now on going.

The AD-MAFT (Air Defence Variant Major Airframe Fatigue Test) has reached 14500 simulated flight hours. An accelerated fatigue test on the ADV wing was performed to verify the effectiveness of a retrofit action to improve the fatigue performance under the ADV spectrum (more severe than the IDS one).

7.3 - AM-X (Alenia Turin)

The second Whole Aircraft Fatigue Test, called WAFT2, was programmed, in order to qualify the main modification of fuselage Main Frames in the wing-to-fuselage attachment area and to complete (up to 4000 EFH) the qualification of the main components partially “cleared” during the WAFT.

The test set-up is similar to that defined for the WAFT and the loading sequence is the same.

WAFT2 successfully reached 16,000 SFH on August 5th 2000.

7.4 - DASSAULT FALCON 900 and 2000 (Alenia Turin)

After theoretical crack propagation calculations and damage tolerance test on the Falcon 900 engine mount system, the analysis of the results was completed, so allowing the tuning of the theoretical method by means of the comparison between calculations and test results.

The programmes are now completed from the design and verifications point of view, while the sustaining to the production phase is maintained.

7.5 - Helicopter EH101 (Agusta)

For the Civil variant – 510 of the helicopter, the Type Certificate of 1998 was improved with several kits and extended usage:

1) Rescue Hoist 600 lb, including compliance to the latest issue of JAR 29.65 and NPA 29-17 with the fatigue evaluation of the rescue hoist and the cable. Extensive tests were carried out for the evaluation of the cable, considering a loading spectrum derived from a vibration survey of the hoist plus additional loading cases, derived analytically. The critical loading cases are the overloads that may occur during the winch engagement and during the passengers recovery operations. Damage tolerance demonstration was provided, supporting the inspection criteria specified in the Maintenance Manual.
2) Cargo Hook at 7000 lb, further improvement to 10.000 lb is envisaged within a short time.
3) Extension of flight envelope at 15000 ft altitude.
4) High field operations at 9000 ft (hovering conditions and take off and landings), demonstrated by means of a load survey carried out at Mammoth Lake (USA) in summer 2000.

5) T = -26°C cold weather, demonstrated by means of a load survey at Fairbanks, Alaska (USA) in winter 1999-2000. Recorded loads did not show any significant increment due to the increased Mach number and change in stiffness on the elastomeric bearings.
6) Ramp Open in flight.

For the CSH version for Canada – 511, a SAR variant developed with the Utility configuration, the fatigue lives were calculated according to the usage spectrum based on customer's data.

As far as the Navy variants (for Royal Navy – 111 and MMI – 110) are concerned, the fatigue lives for both RN and MMI usage were calculated according to the customers' usage spectra.
The most relevant activity for both testing and analysis was the evaluation of the main rotor blade and tail unit folding and spreading cycles, including deck parking conditions, and rotor run up and shut down with blade sailing loads. An extensive load survey was carried out:

'HMS Grafton' (Frigate Type 23): 500 folding and spreading cycles, 50 loading parameters recorded during each cycle, wind conditions from 0 up to 65 Kts and sea state up to 9/10;

'RFA Argus': 90 rotors run up and shut down, 225 approach and deck landings, 25 loading parameters recorded (rotors only) with wind speed up to 40 kts.

7.6 - ATR 72 Full Scale fatigue test - Tear down inspection (Alenia Naples)

As already outlined in the last National review, after completion of fatigue loading, the scheduled tear down inspection (including non destructive and destructive checks) has been carried out. The tear down inspection results substantially confirmed the damage scenario detected during fatigue testing; some small differences were discovered after the disassembly of main components and can be attributed to the better access condition.

The "Lessons Learned" have been formalised in a dedicated test report, which will constitute the basis for the ATR-72 Ageing Programme development. This programme will be implemented on the ATR-72 fleet over the Economic Repair Life of 70.000 Flights, in order to comply with Continued Airworthiness Requirements as per JAR 25.1529.

8. FATIGUE SUBSTANTIATION OF NEW DESIGN AIRCRAFT

8.1 - Rotorcraft fatigue substantiation - Harmonization working group (Agusta)

The Rotorcraft fatigue substantiation - Harmonization working group was made by AECMA and AIA on request by FAA and JAA to revise current advisory material on safe life and to provide detailed comments for a new Advisory Circular document. This new AC should address more detailed guidelines toward a consistent safe life approach for all the helicopter manufacturers. Agusta took part to this project with BHTI, Sikorsky, Eurocopter, Kaman and Boeing Mesa.

The main topics of improvements are:

- ❑ guidelines for safety factors on S-N curves, typical range of values
- ❑ analytical evaluations, rational methods
- ❑ operational conditions to be investigated in flight load survey
- ❑ usage spectra and multiple type of operations

The final revised AC was issued by the group for publication on March 2001.

8.2 - New rule JAR/FAR 29.571 - ARAC working group

A new Working Group was formed in 2000, with the objective to revise the existing rule 29.571 on fatigue for Large Helicopters considering both the inputs of TOGAA comments and the White Paper issued by the manufacturers. According to the process, the group has to issue even a new Advisory Circular specific for the proposed new rule.

In conjunction with this rulemaking activity, the WG was encharged to revise the current AC on the existing rule, AC 29-2C MG11, to provide a clearer and harmonized understanding of the methods of compliance for the applicants, due to the major discussion occurred in these years on the applicable criteria (TOGAA comments, White Paper meetings, RTO-AVT Corfu meeting, Cranfield Workshop).

8.3 - C 27-J JAR 25 Civil Certification (Alenia Naples)

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 Certification basis is JAR 25, change 14 for new major components, and FAR 25 amendment 35 for unmodified components.

The Civil Certification for Structural Integrity is mainly based on the substantiation of:
Design objectives:
_ Economic Repair Life = 25.000 Flight Hours, 15.000 Full Stop Landings
_ Crack Free Life = 12.500 Flight Hours
_ Inspection Threshold = 6.000 Flight Hours
Weights
_ Max Take-Off Weight = 30.500 Kg
_ Max Landing Weight = 27.500 Kg
Mission Profiles:
_ Training Mission (25%)
_ Tactical Mission A (8%)
_ Tactical Mission B (12%)
_ Airdrop Mission (5%)
_ Short Range Logistic Mission (45%)
_ Long Range Logistic Mission (5%)

The Structural Certification Path, according to JAR/FAR Requirements, is:
For new Engine Nacelles:
❑ . Fatigue and Damage Tolerance Analysis
❑ . Full Scale Fatigue and Damage Tolerance Test
❑ . Maintenance Plan based on MSG-3 Approach
For new Landing Gears:
❑ . Fatigue Analysis
❑ . Full Scale Fatigue Test
❑ . Maintenance Plan based on MSG-3 Approach
For unmodified structure (Wing, fuselage, empennage, etc.):
❑ . Demonstration of G 222/C27J Fatigue Spectra Equivalence
❑ . Assessment of Fatigue Capability based on G 222 Full Scale Fatigue Test results
❑ . Damage Tolerance Theoretical Analyses
❑ . Maintenance Plan based on MSG-3 Approach

The Type Certificate is expected for June 2001.

8.4 - ATR 42 Maritime Patrol - Damage Tolerance assessment (Alenia Naples)

The ATR 42-400 MP aircraft is the Maritime Patrol version of the ATR 42-400 aircraft, which has been modified to meet the MP stringent system-level requirements as determined primarily by customer needs. The Certification basis is JAR 25, change 14.

The main structural modifications, with respect to the basic ATR 42-400, are:

- Installation of two pods on the fuselage, fitted by two proper pylons:
  - The Search Pod
  - The Baggage Pod
- Installation of a Bubble Window on the rear fuselage for Patrol Mission
- Installation of a Parachutist Door on the rear fuselage
- Installation of several cut-outs on fuselage for new antennas

The Civil Certification for Structural Integrity was mainly based on the substantiation of:
Design objectives:

- Economic Repair Life = 35.000 Flight Hours, 6.500 Full Stop Landings, 25 Years
- Crack Free Life = 17.500 Flight Hours
- Inspection Threshold = 6.000 Flight Hours

Weights:
- Max Take-Off Weight = 18.200 Kg
- Max Landing Weight = 17.900 Kg

Mission Profiles:
- Maritime Patrol,
- Personnel Transport,
- Military Troop Transport,
- Paratroops Transport,
- Medical Evacuation (Medevac),
- Cargo Transport.

The Structural Certification Path, according to JAR25.571 Requirements, was:
For modified and unmodified structural components:
- Demonstration of ATR 42 Basic/ ATR 42 MP Fatigue Spectra Equivalence
- Assessment of Fatigue Capability based on ATR 42 Full Scale Fatigue Test results
- Fatigue and Damage Tolerance Analysis
- Maintenance Plan based on MSG-3 Approach

The Supplementary Type Certificate was achieved at the end of July 1999.

8.5 - Helicopter AB139 (Agusta)

This is a new helicopter of 6000 kg gross weight, twin-turbine, multirole capability.

Civil Certification will be carried out according to JAR 29 Rules and therefore the fatigue assessment will require the Flaw Tolerance evaluation. The Dept. of Aerospace Engineering of the University of Pisa and the Dept. of Mechanical Engineering of the Milan Polytechnic are supporting Agusta in the Flaw Tolerance evaluations for AB139, having identified specific areas of interest which are respectively: the complete metal fuselage for Pisa and the rotor parts for Milan.

The first run of TDH (Tied Down Helicopter) occurred on the 22nd December 2000, while the first flight of A/C 1 (Aircraft 1) took place in February 2001

More than 50 full size fatigue tests were carried out for flight clearance in about 1 year.

Three main documents issued for fatigue assessment:

1) AB139 Fatigue and Flaw Tolerance Substantiation Criteria
Addressing the criteria to comply with the JAR 29.571, including flaw tolerance.

2) AB139 Monitoring Limits
Addressing the monitoring limits used to manage flight trials. About 800 loading parameters are recorded during flight, about 20 are maintained in real time monitoring during preliminary flights and to achieve a complete load survey of the flight envelope.

3) AB139 Fatigue lives for TDH
Based on the load survey carried out for the TDH, preliminary fatigue lives are established to manage the prototype.

8.6 - Tiltrotor BA609 (Agusta)

The relevant test activities on primary structures designed by Bell have already required the design of dedicated rigs by the Laboratorio Prove Strutturali.

The most relevant rigs that for the Wing, the Prop Rotor Mast and the Swashplate Drivers.

The rig for the wing fatigue test has required a major improvement in the laboratory capability, having 48 channels used for load monitoring and 256 channels used for load acquisition in continuous during the test.

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

9.1 – Fatigue crack propagation resistance of 2219-T851 sheets after high velocity impact (Uni. Pisa)

Large spacecraft and manned pressurised structures are susceptible to high velocity impacts from meteoroids and pieces of orbital debris. An experimental programme for the assessment of fracture mechanics properties of high velocity (6.29 Km/sec) impact damaged 2219-T851 aluminium plates was carried out at the Department of Aerospace Engineering of the University of Pisa, within the framework of a co-operation with Alenia, Space Group. The material is commonly used for the manufacturing of pressurised modules. The purpose of the programme was to obtain information about three main topics: distribution of the residual stresses in the plates, static resistance of the plates in the presence of a through crack and fatigue crack propagation rate. In the following, some information will be given about the crack growth characterization; the other topics are discussed in [11], where also more details about crack propagation can be found.

Rectangular plates 400x600 mm, thickness 4.8 mm, were tested. High velocity impacts were produced by the Light Gas Gun equipment at the Ernest Mach Institute in Friburg. The energy of the impacts was the ballistic limit, i.e. higher energies produce the perforation of the pressure vessel.

Fig. 25 shows the detail of the impact damaged area in one specimen. A bump formed in the plates as a consequence of the high velocity impact; bumps were circular, with a diameter approximately of 130 mm and depth in the 8-12 mm range.

Crack propagation tests were carried out on specimens with a start through notch in the centre of the bump; this location was the most consistent with a defect produced as a consequence of the impact. The crack propagation rate of this defect was very low when compared with the same quantity measured in standard flat specimens tested under the same asymptotic load conditions, Fig. 26. Besides, during the tests, a number of cracks nucleated naturally in the boundary area of the bump. A finite element model clearly explained the experimental results, showing that important bending stresses act in the bump area and its neighbourhood. The maximum combined stress near the bump boundary was about 2.6 times higher than the asymptotic applied stress, while the distribution of the membrane stress was at a minimum in the centre of the bump, where it reduced to about 25% of the asymptotic value.

By taking the actual stress distribution into account in the evaluation of the stress intensity factor, a good interpretation of the crack propagation test results was obtained, Fig. 27.

9.2 – Fatigue behaviour of AISI 301 spot welded joints (Uni. Pisa)

Stainless steels are imposing more and more over carbon steels in the construction of bodies for the transport industries, such as buses and trains, due to unquestionable advantages from the corrosion point of view. Besides, the higher cost of the raw materials is partially compensated for by the elimination of the costs connected to painting and maintenance of the painted structures.

There is a current tendency in the transport industry towards the increase in the efficiency of the structures, also by greater attention, in comparison with the past, to their weight. The reduction of weight has an immediate positive consequence on energy consumption, but has obviously a negative impact on the stress levels, which, combined with the fluctuating characteristic of the applied loads, makes these structures often more sensitive to fatigue problems.

Actually, fatigue resistance is probably the main problem of spot welded joints; this resistance is low when compared with that of other joining systems, but none of these systems is competitive with spot welding as far as cost is concerned.

A research programme has started at the Department of Aerospace Engineering of the University of Pisa on the fatigue resistance of stainless steel spot welded joints. The activity was performed in the framework of a cooperation with Breda – Railway Construction (Pistoia). The aims of the research were manifold; among others, no information was available about the effects of the technological parameters on fatigue resistance. For this reason, tests were carried out on specimens welded with different values of the welding current, of the force applied to the electrodes, and of the welding time parameters. Besides, the effects of a different surface preparation before welding and of the presence of a sealant on the matched surfaces were investigated from the fatigue point of view. Finally, some fatigue tests were carried out in a corrosive environment.

The tests were carried out on single spot weld specimens, Fig. 28, and on panels containing five spot welds. Fig. 29 shows the fatigue results obtained from the specimens welded in accordance with the parameters suggested by the American Welding Society. Fig. 30 shows the results of the fatigue tests carried out in corrosive environment, at different frequencies of the applied load, compared with the best fit curve of the fatigue results obtained in air.

A more detailed description of the results of this research is given in [12].

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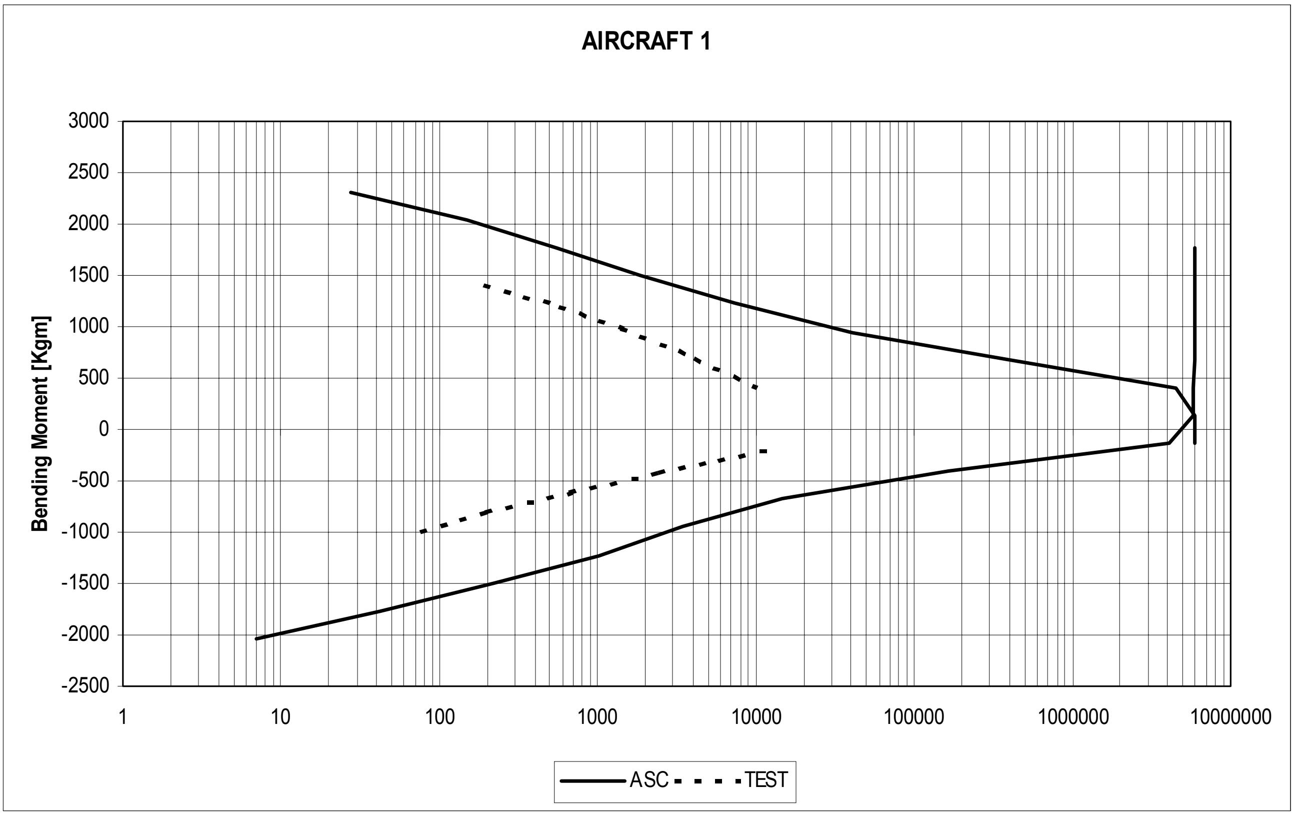

Figure 1 – Example of fin root bending moment spectra for MB-339CD aircraft.

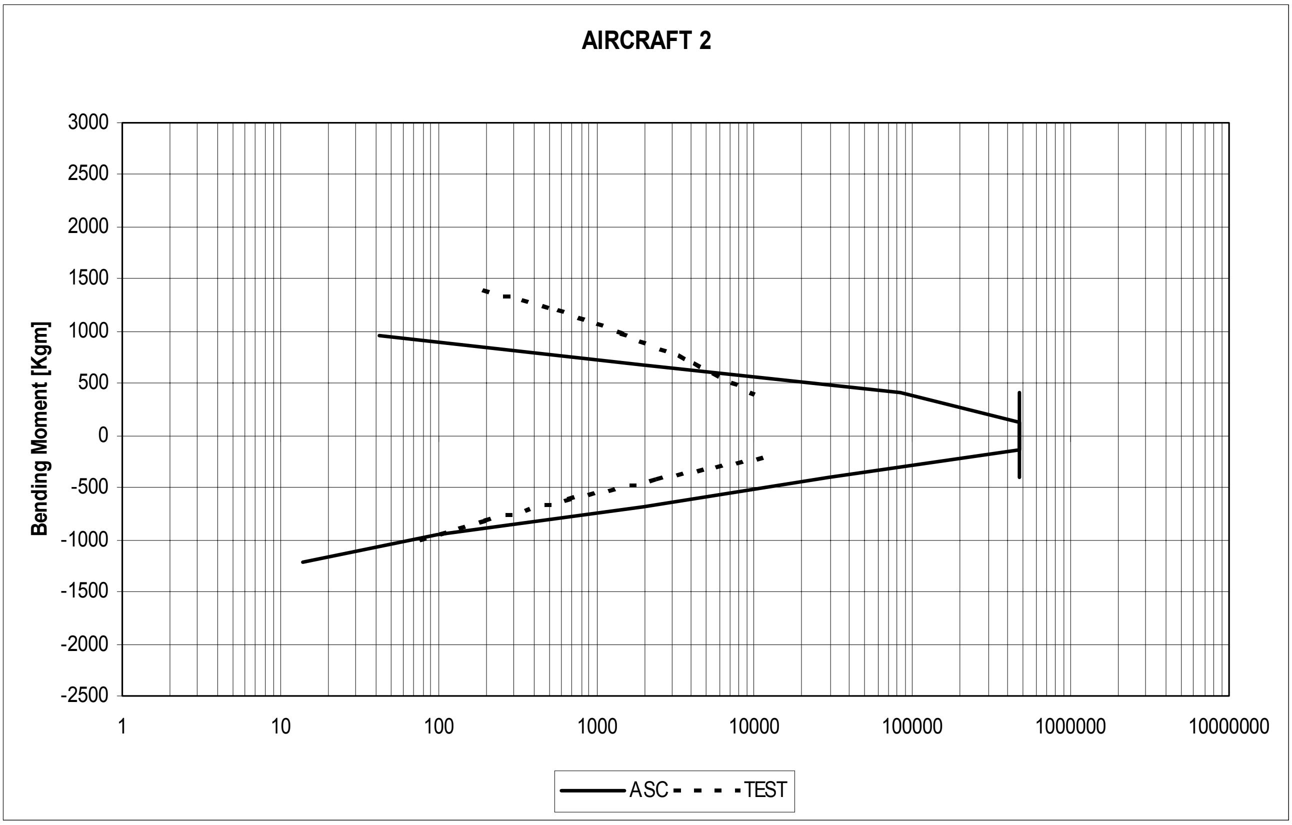

Figure 2 – Example of fin root bending moment spectra for MB-339CD aircraft.

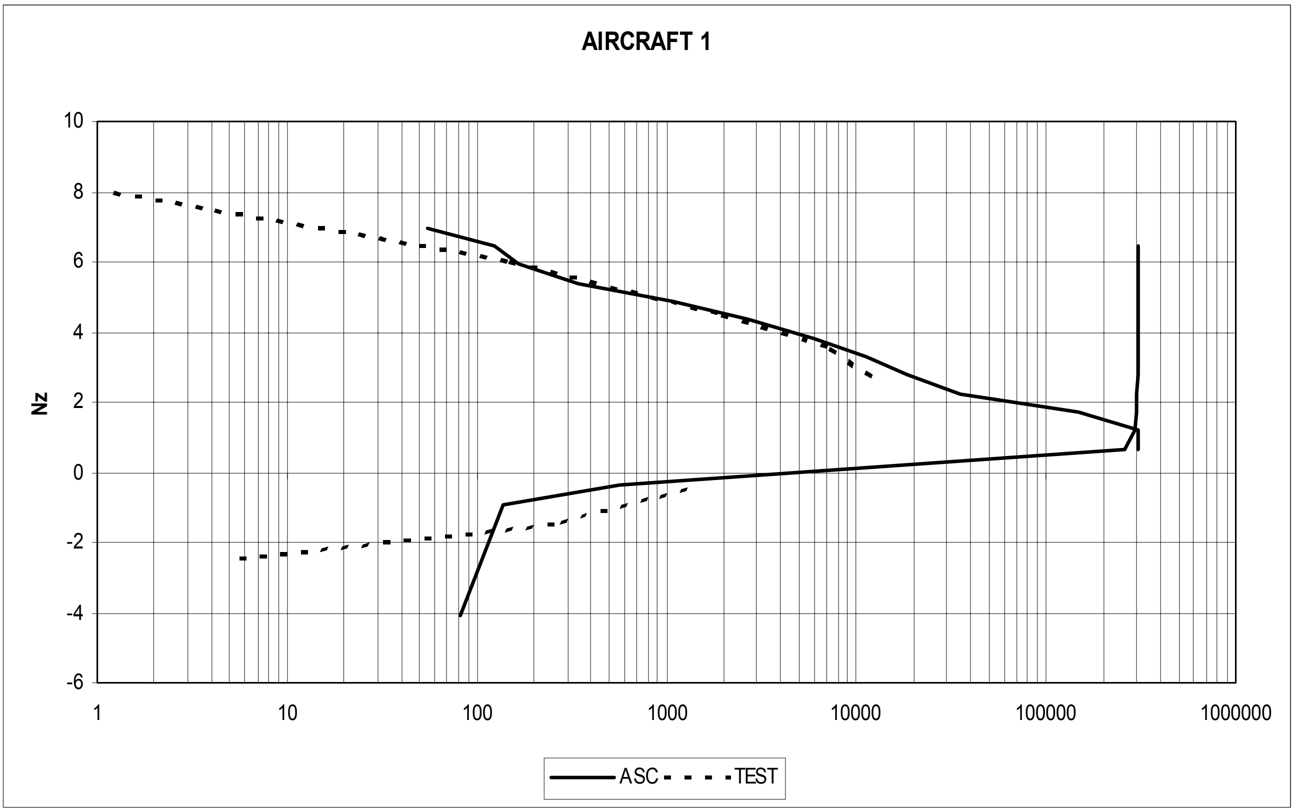

Figure 3 – Vertical load factor (N_Z) spectrum for MB-339CD aircraft.

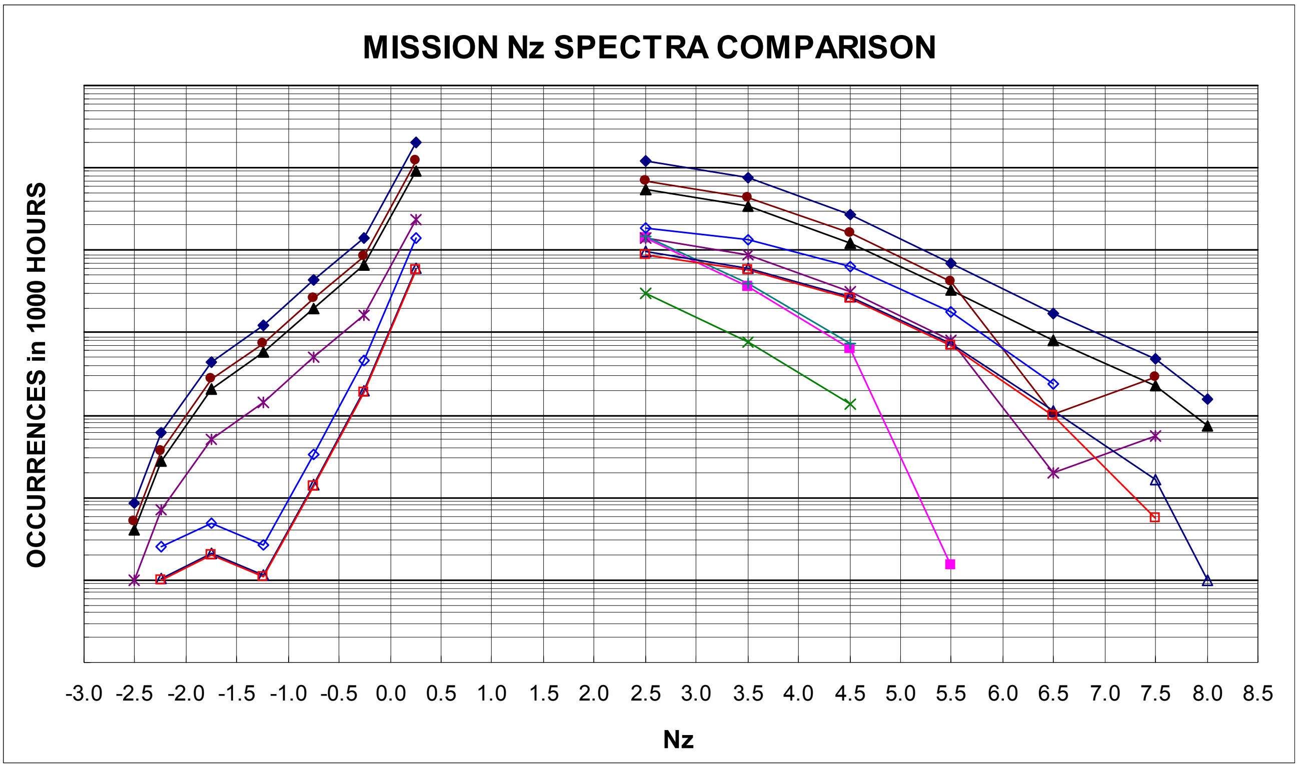

Figure 4 – Nz spectra developed for different M-346 aircraft missions.

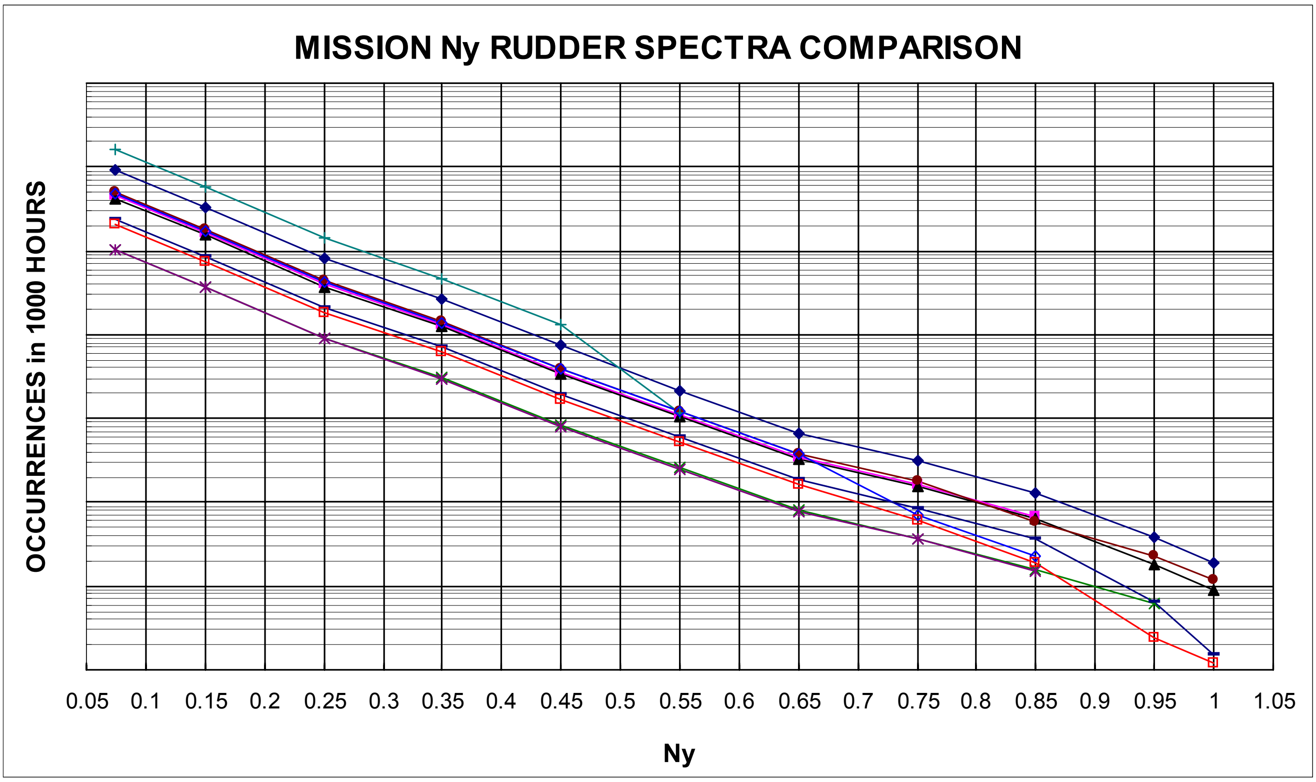

Figure 5 – Ny spectra developed for different M-346 aircraft missions.

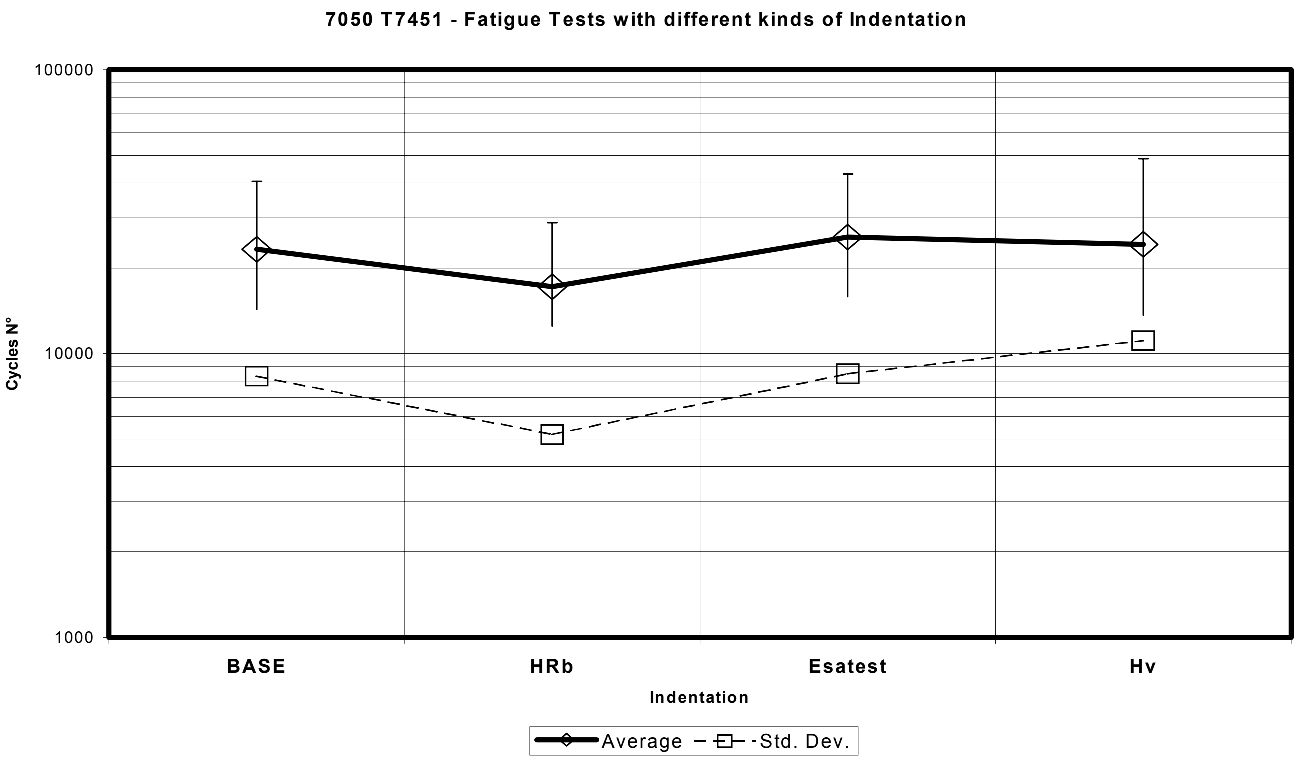

Fig. 6 – Fatigue results of smooth and indented specimens in 7050 alloy (R=0.1).

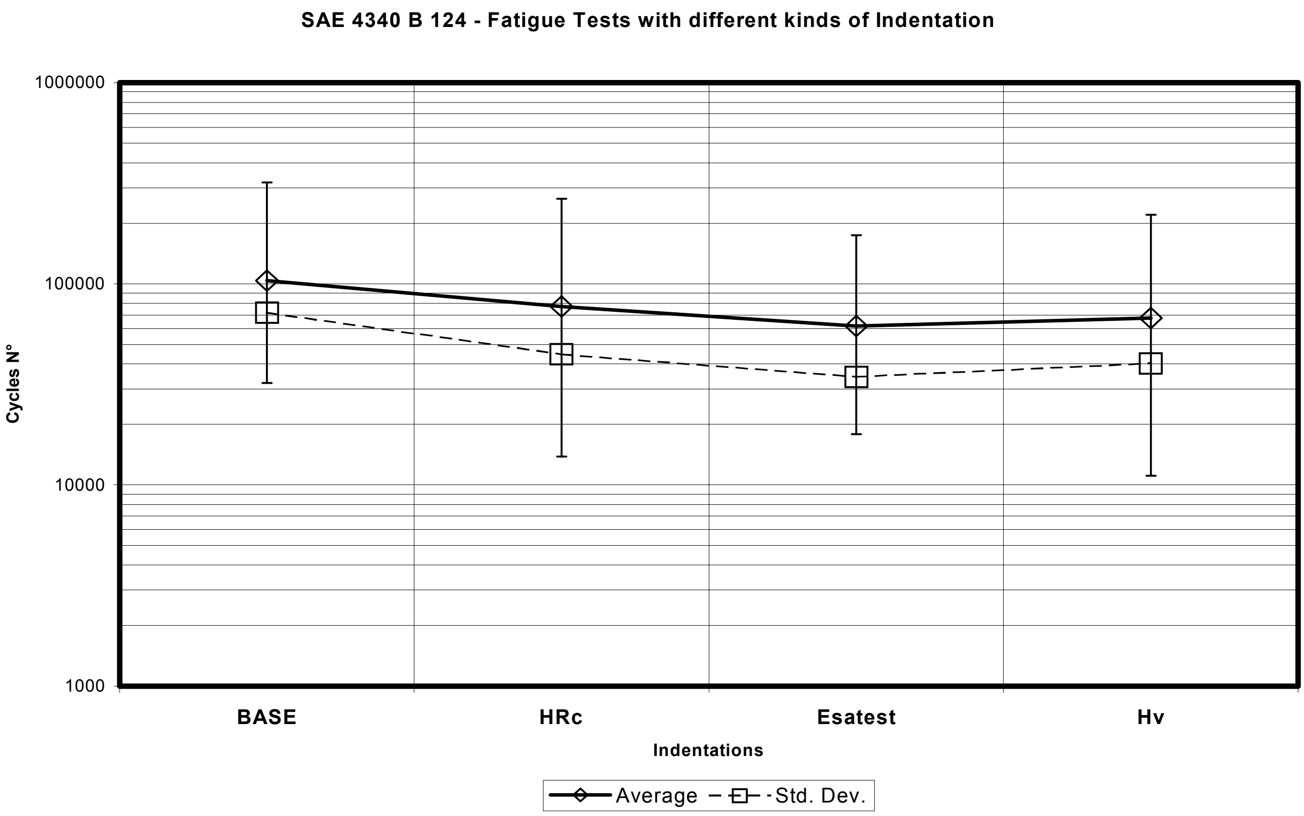

Fig. 7 - Fatigue results of smooth and indented specimens in 4340 steel (R=0.1).

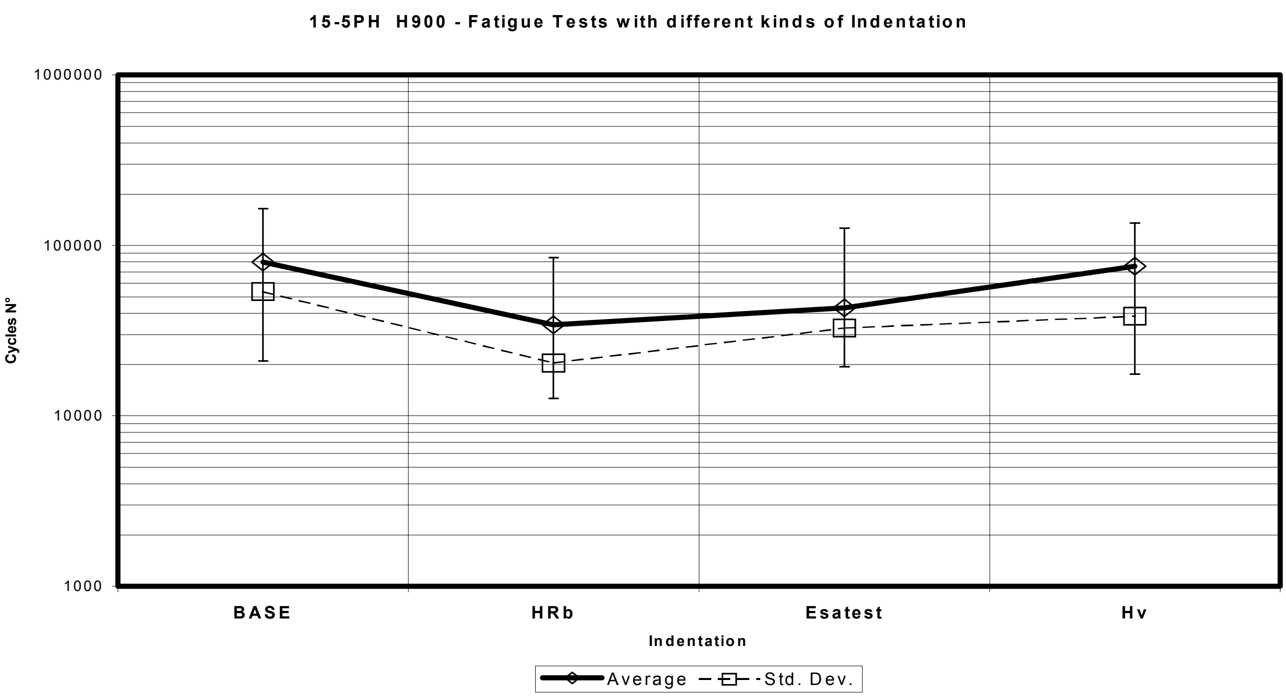

Fig. 8 - Fatigue results of smooth and indented specimens in 15-5 PH stainless steel (R=0.1).

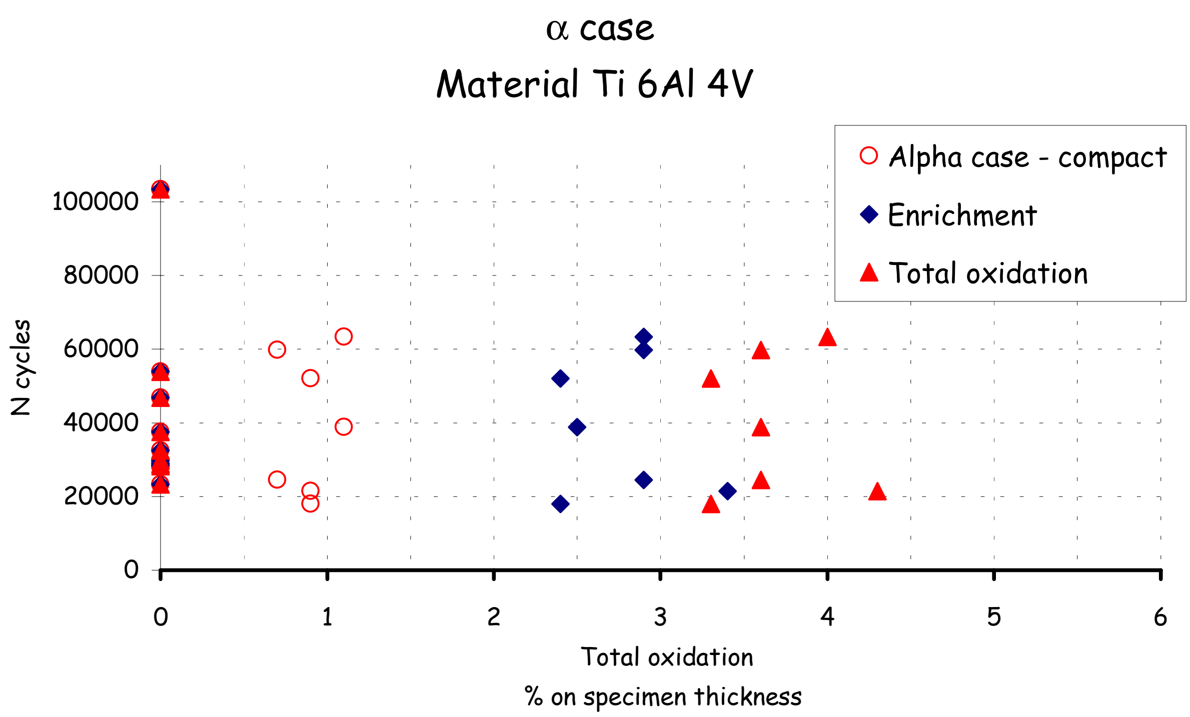

Fig. 9 – Fatigue test results of coupons with different alpha phase presence, SPF Ti-6Al-4V.

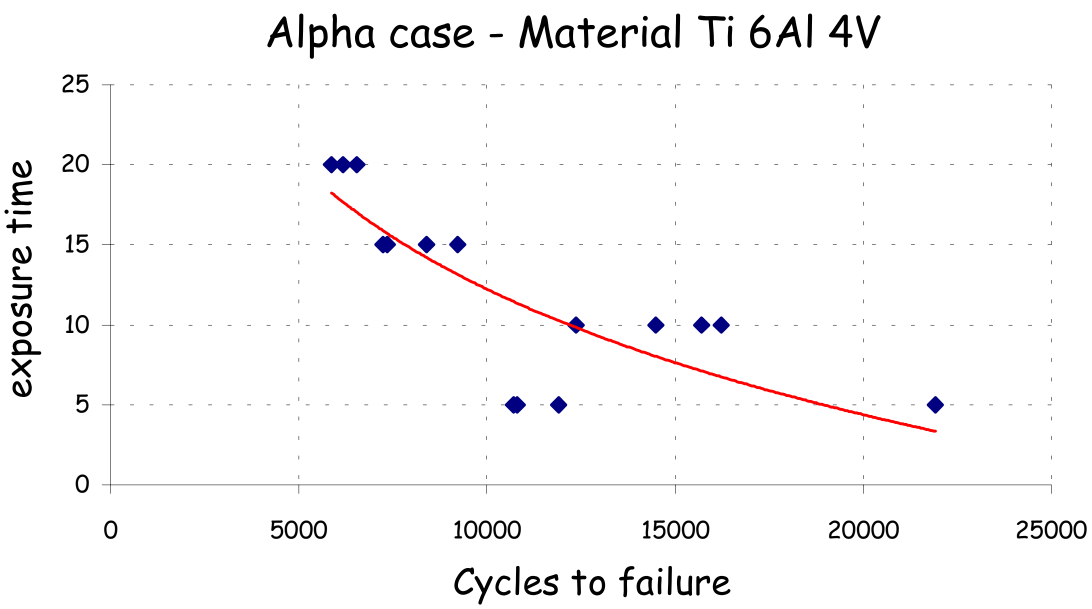

Fig. 10 – Fatigue test results of SPF Ti-6Al-4V coupons, with different exposition times at high temperature.

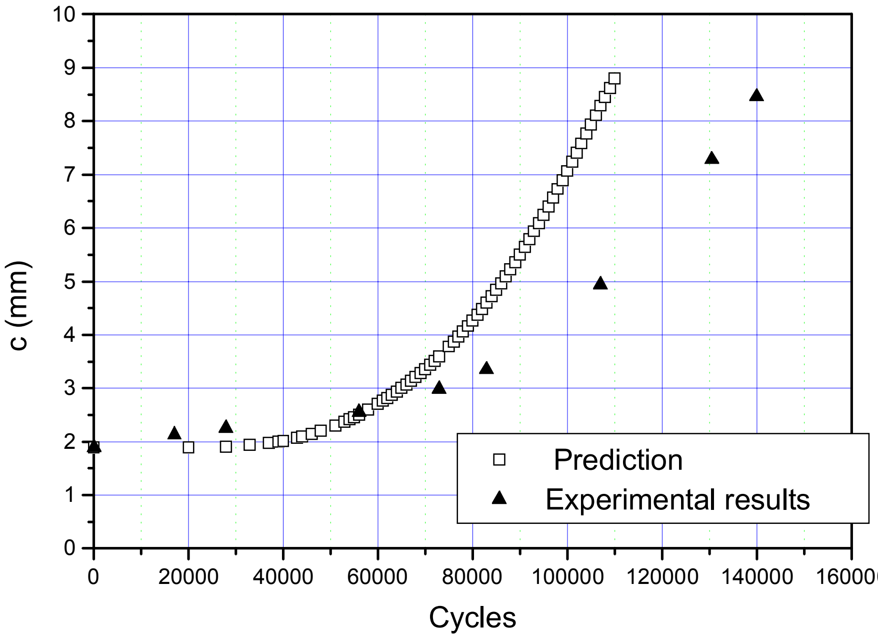

Fig. 11 – Comparison between AFGROW prediction and test data for fatigue crack growth under combined tension and bending loading.

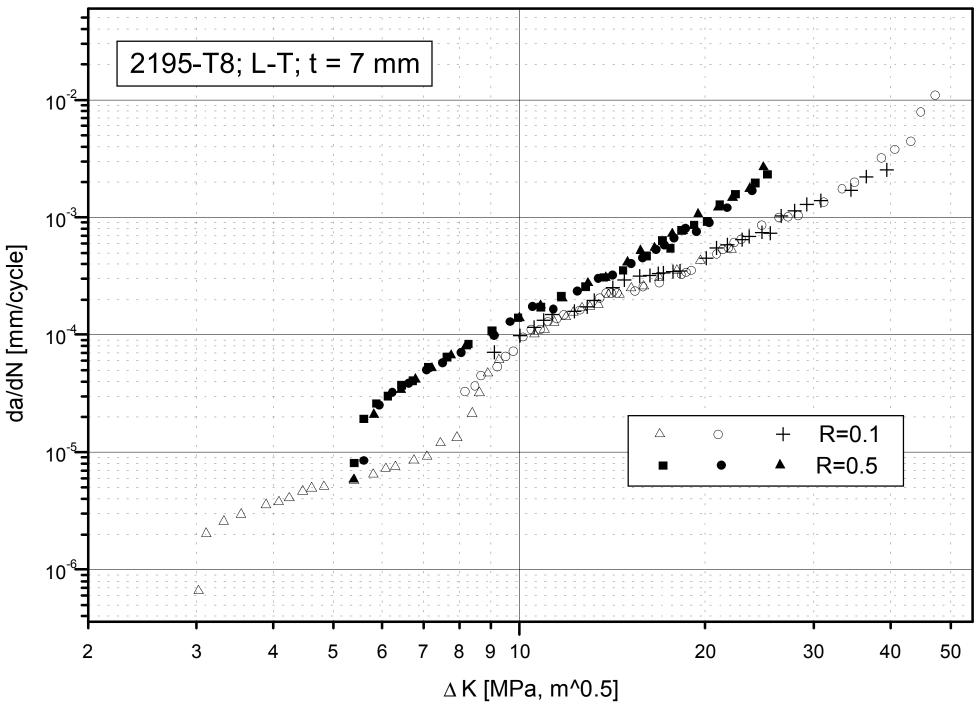

Fig. 12 – Fatigue crack propagation results in Al-Li 2195-T8 alloy.

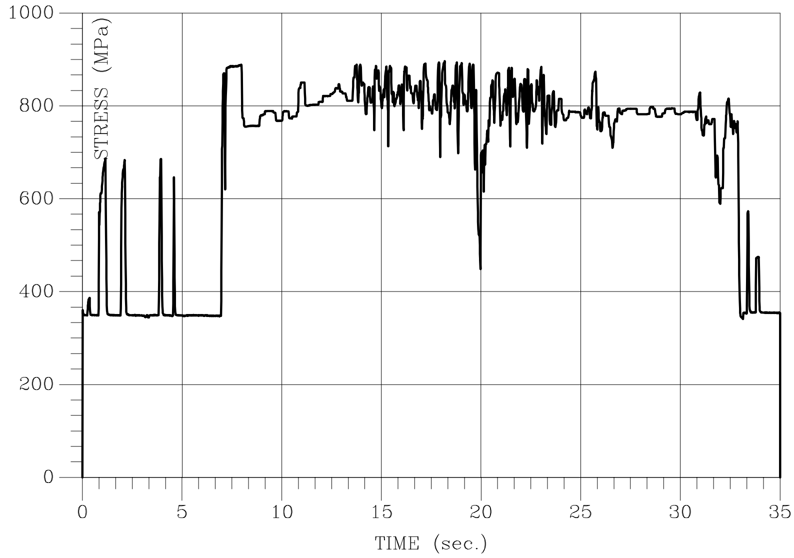

Fig. 13 - Part of the AMX turbine load spectrum.

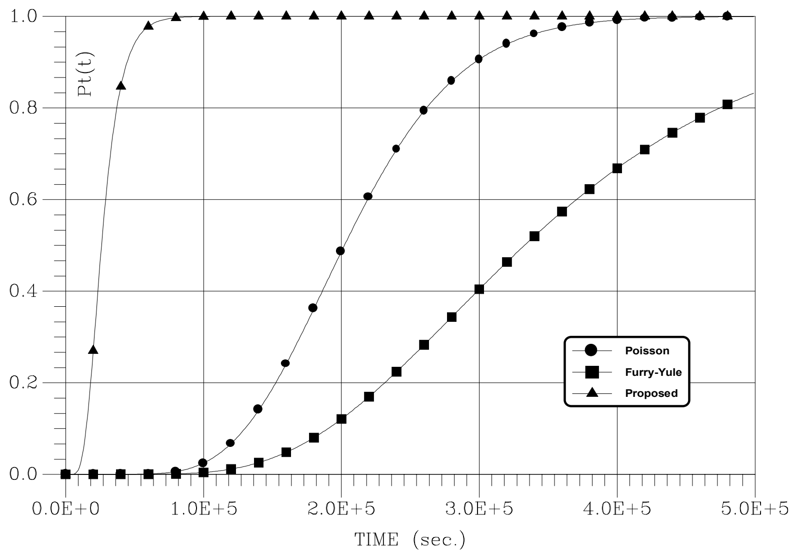

Fig. 14 - Life probability predictions.

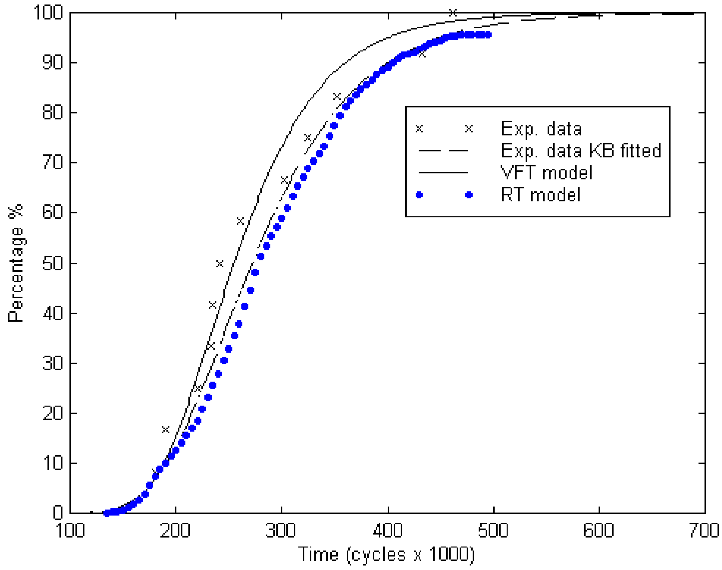

Fig. 15 - Crack length probability versus time.
Comparison among numerical results and experimental data.

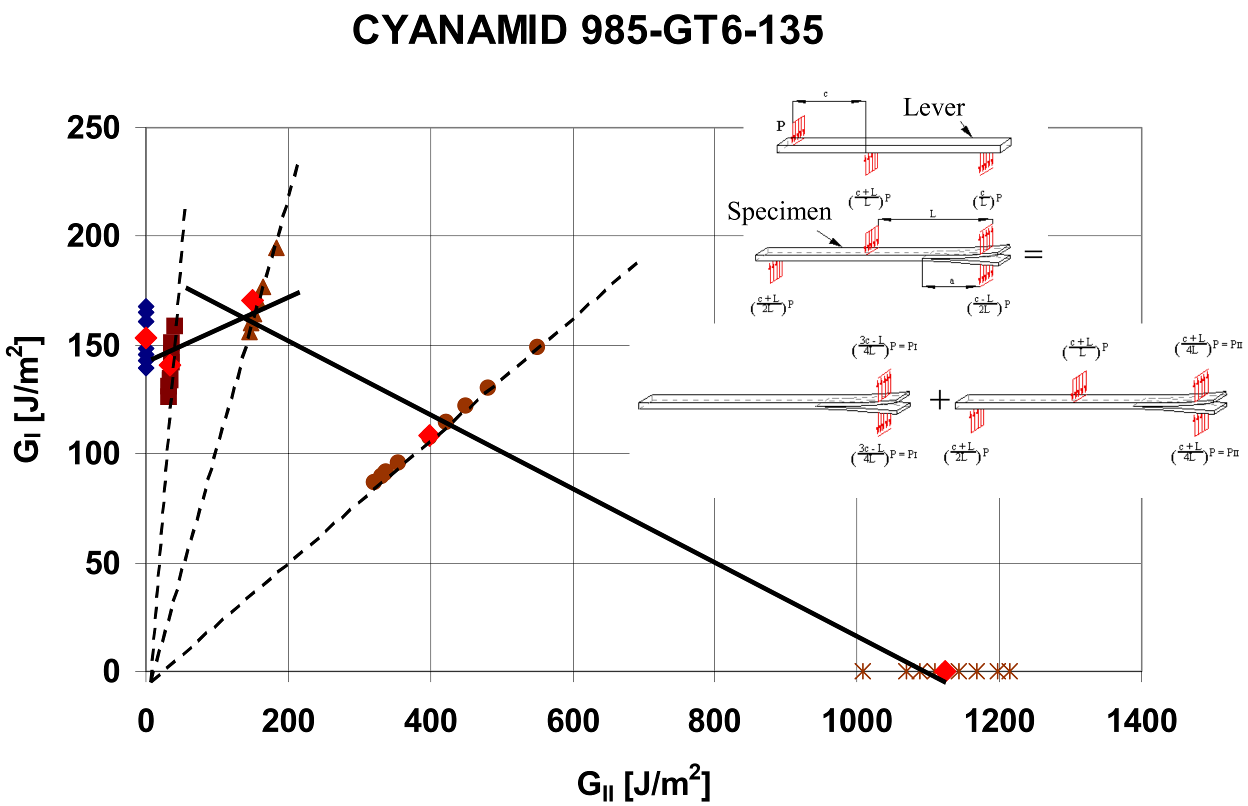

Fig. 16 – Results of mixed mode tests for interlaminar fracture toughness of Cyanamid 985-GT6-135.

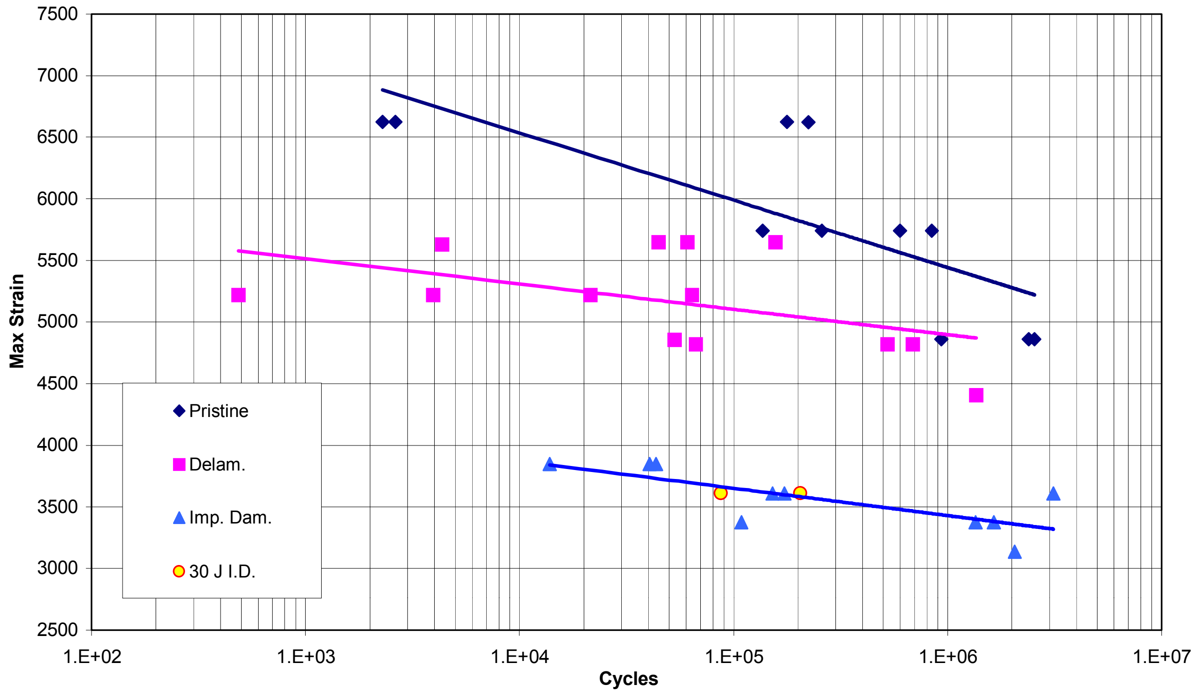

Fig. 17 – Results of fatigue tests of composite sandwich panels tested in FPB (R=5).

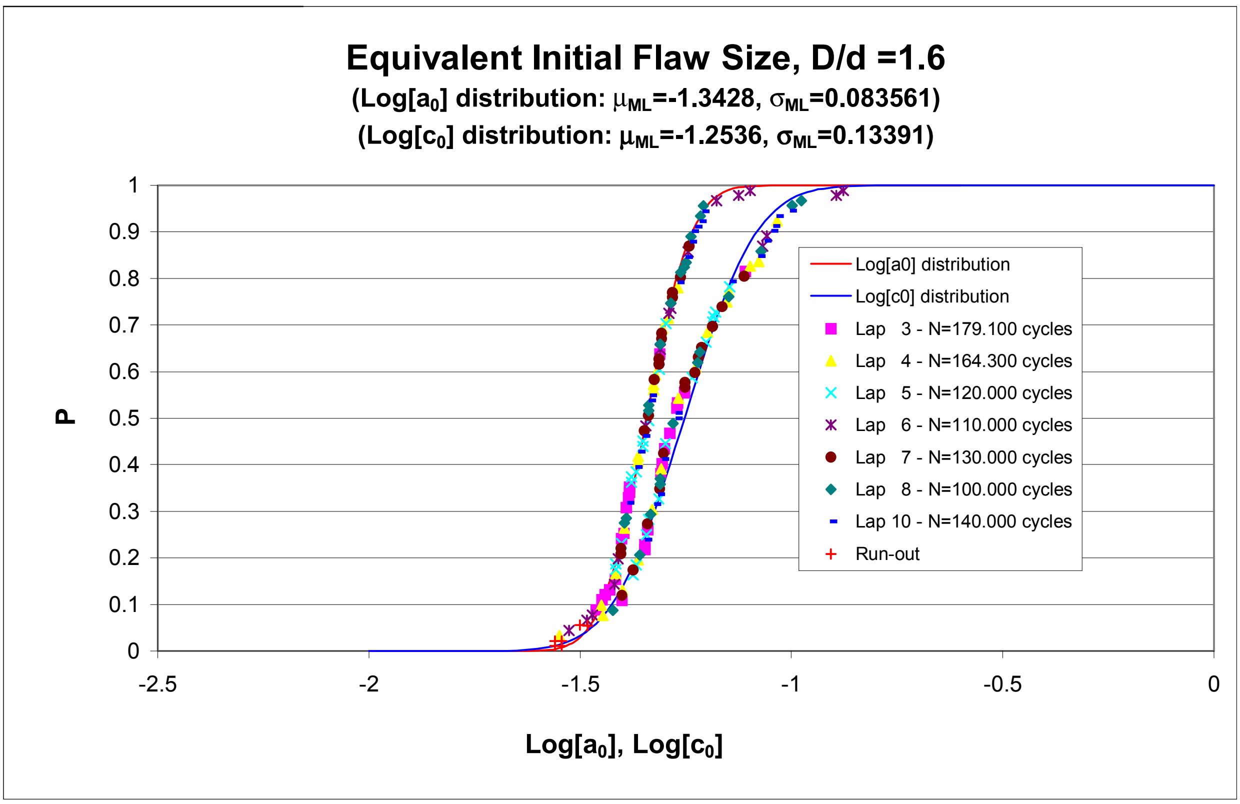

Fig. 20 – Equivalent Initial Flaw Size distribution from fractographic examination of lap joints fracture surfaces, (2024-T3, constant amplitude fatigue loading: Smax 100 Mpa, R=0.1).

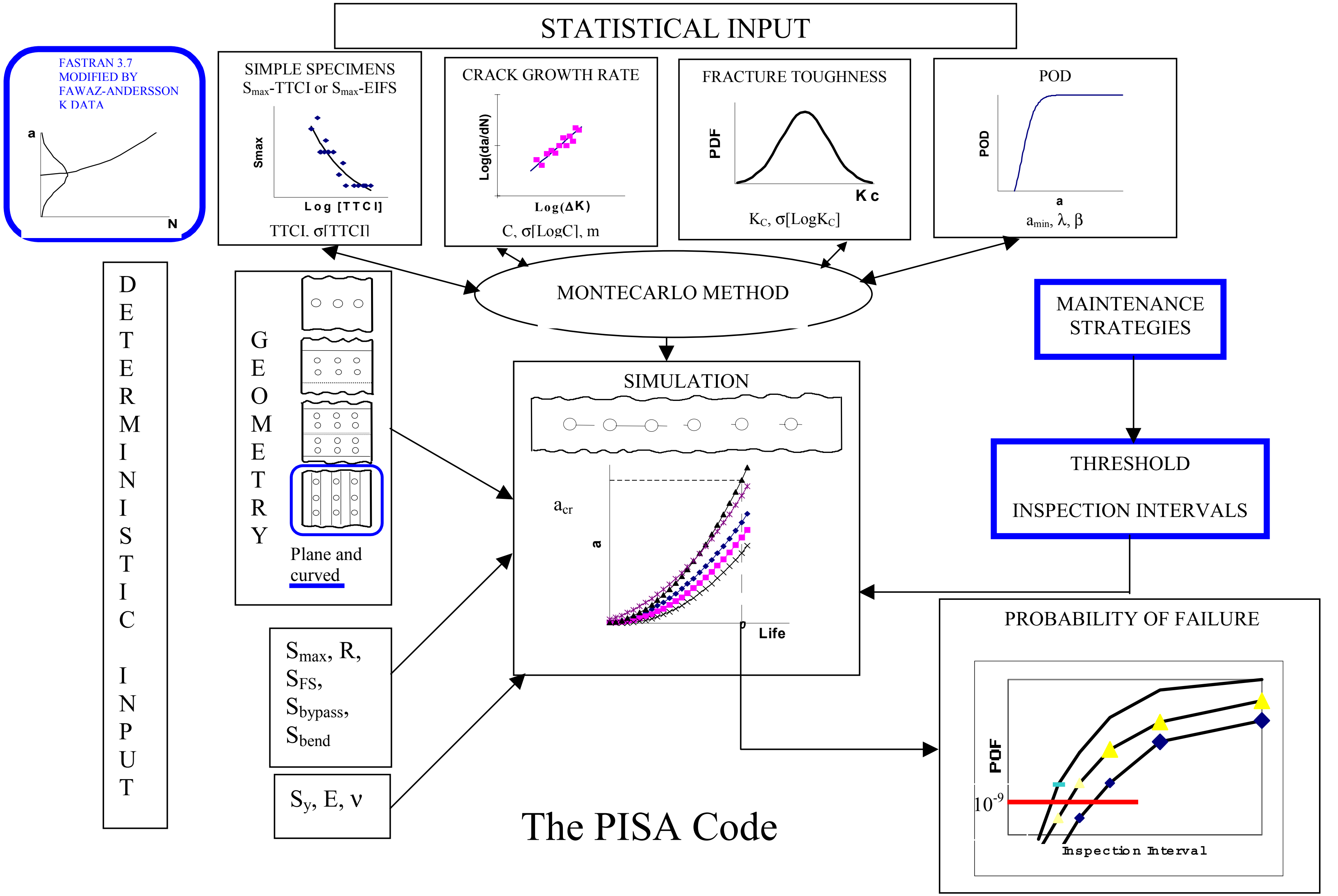

Fig. 18 – Organization of the PISA code.

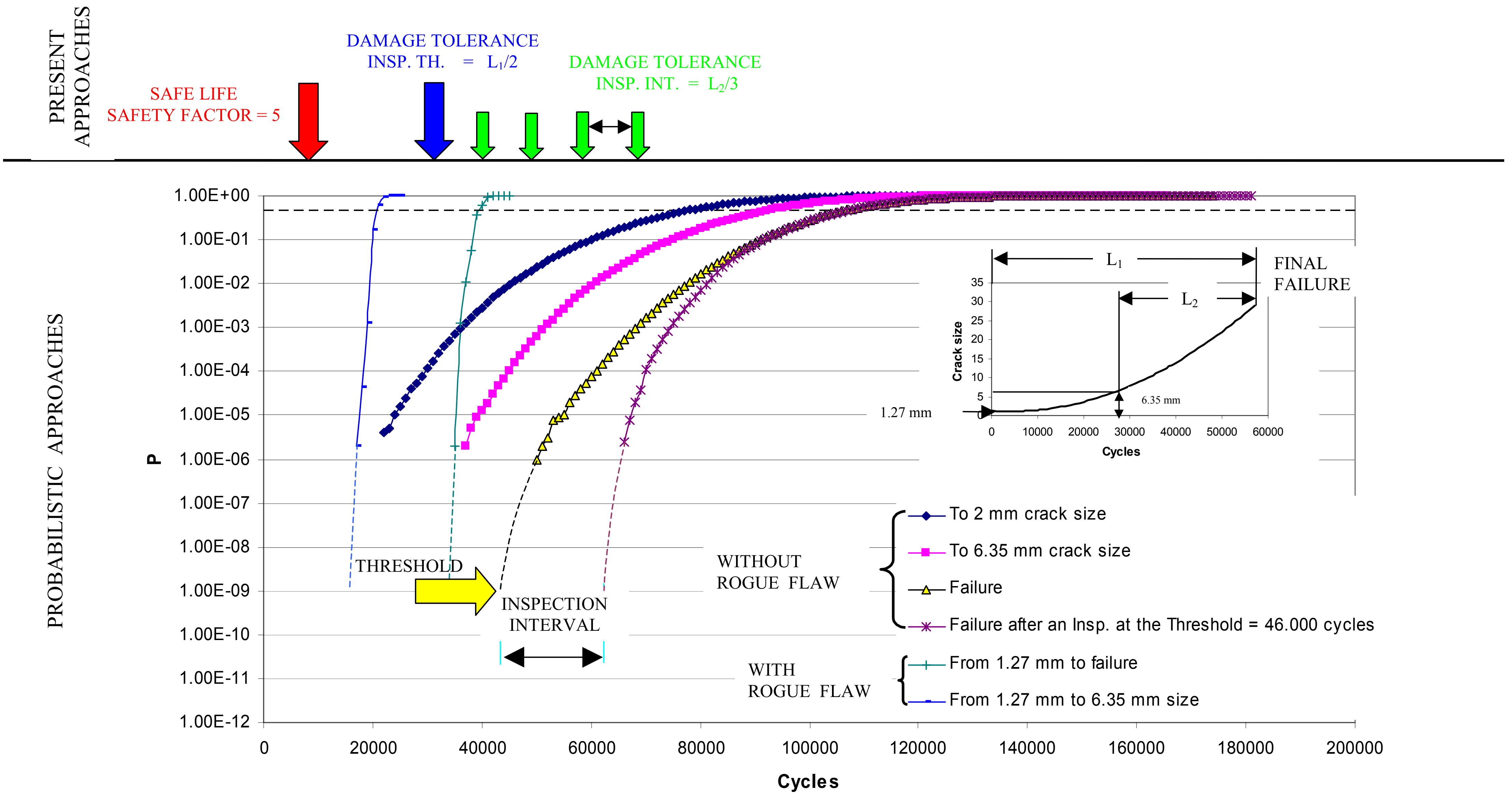

Fig. 19 – Strategy for definition of the threshold inspection

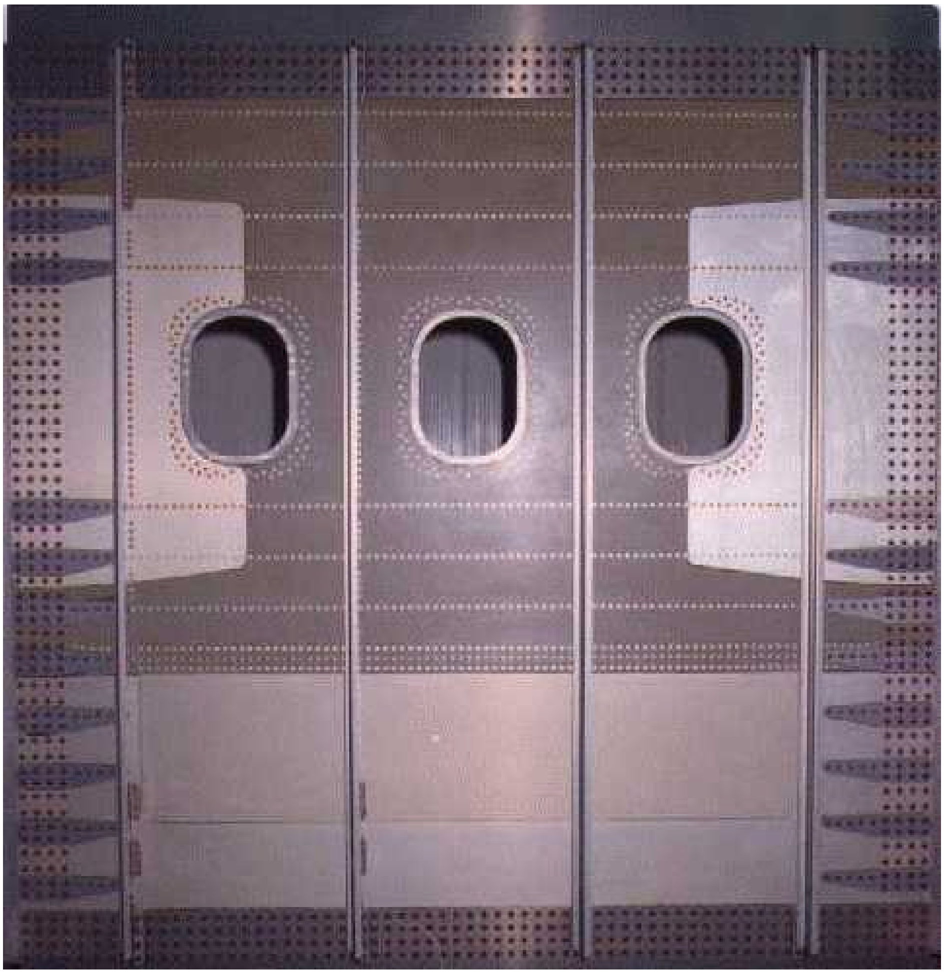

Fig. 21 – Fuselage side panel manufactured in Glare.

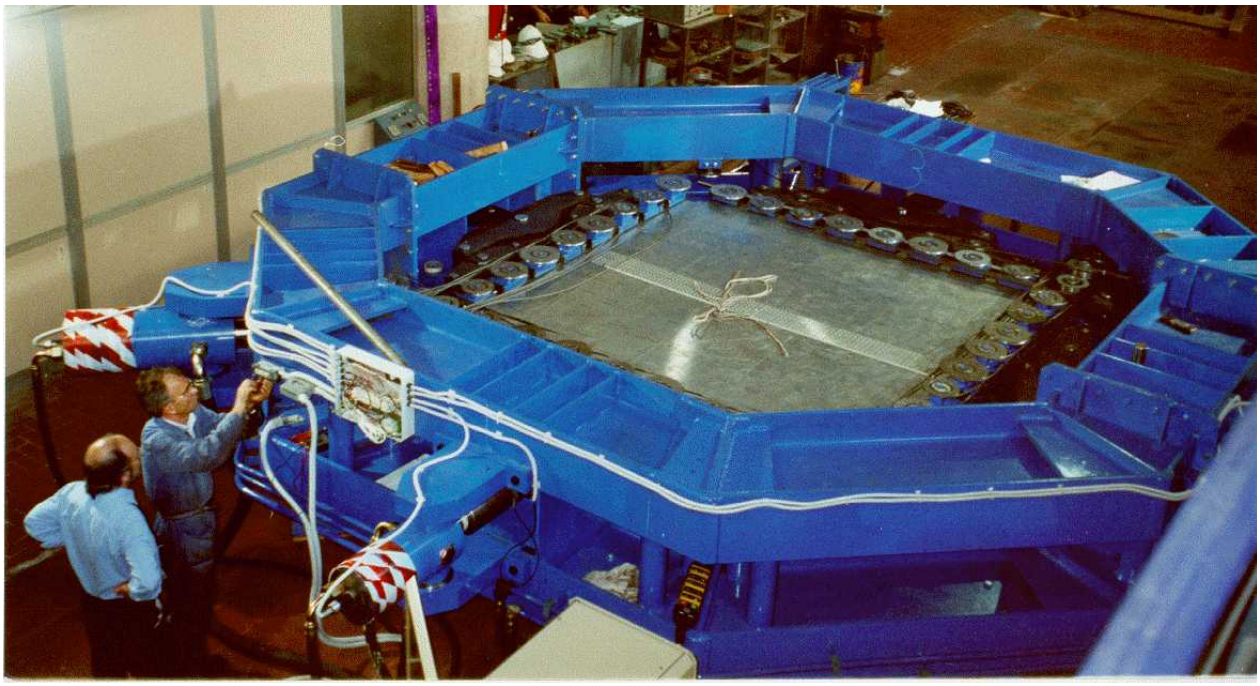

Fig. 22 – Tri-axial machine for testing flat Glare fuselage panel.

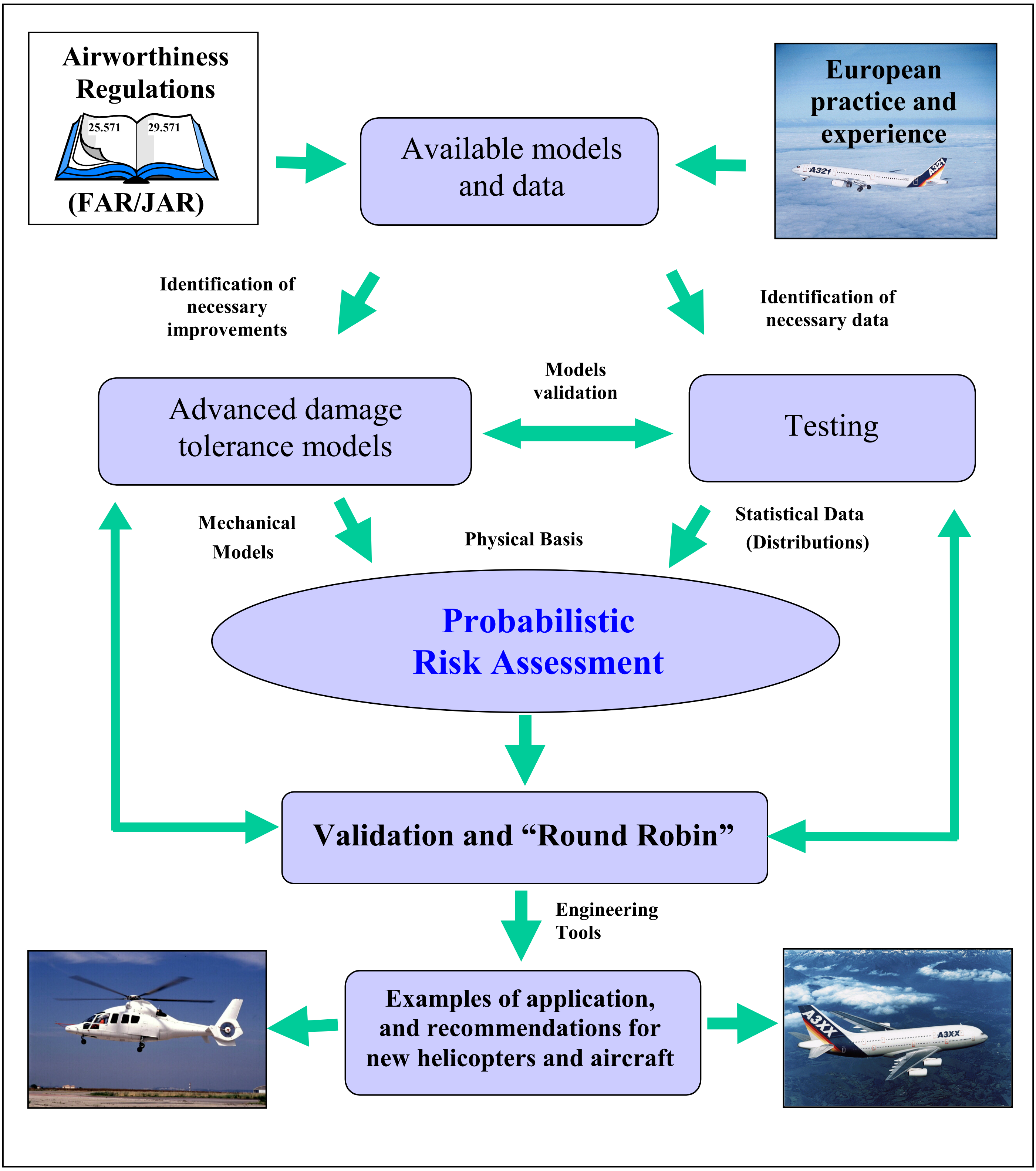

Fig. 23 – Flow chart of the activities planned within ADMIRE.

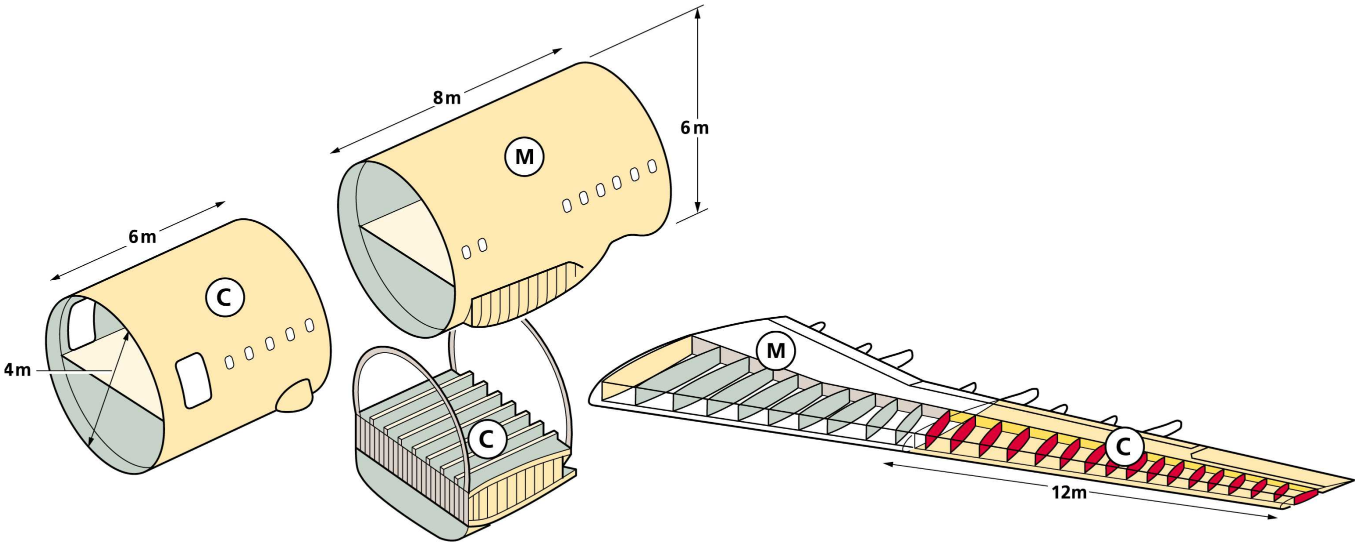

Fig. 24 – TANGO demonstrators.

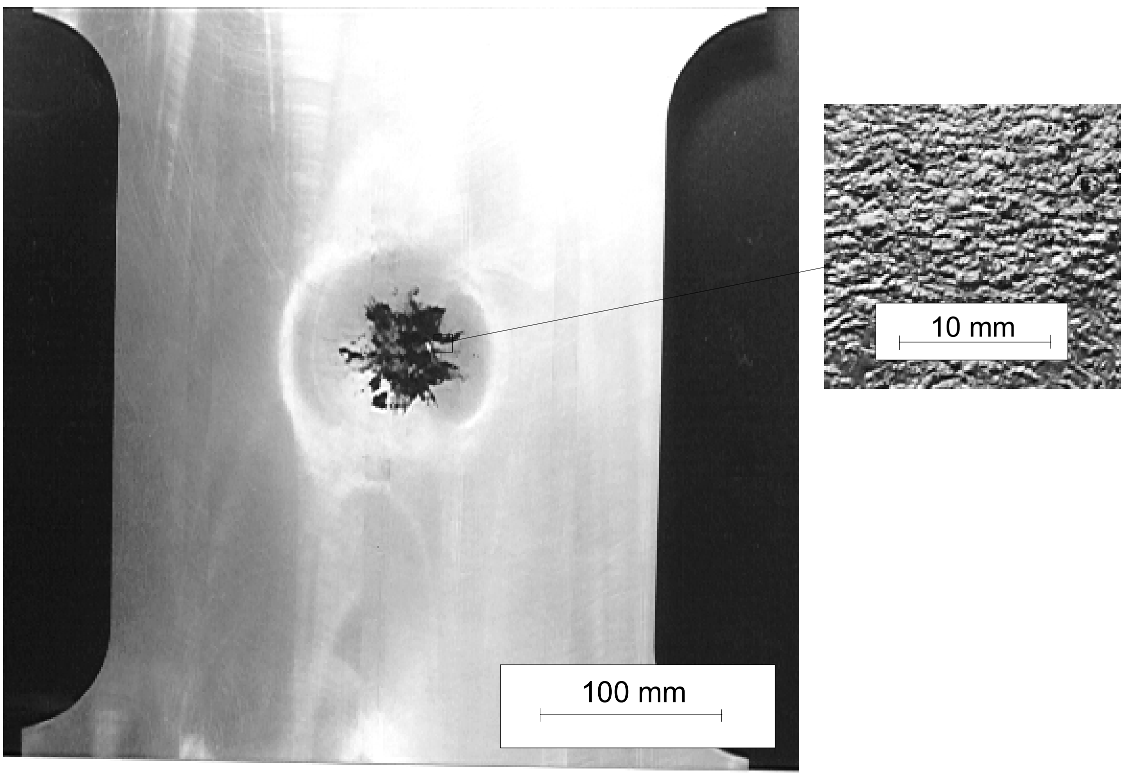

Fig. 25 – Panel in 2219-T851 after high velocity impact.

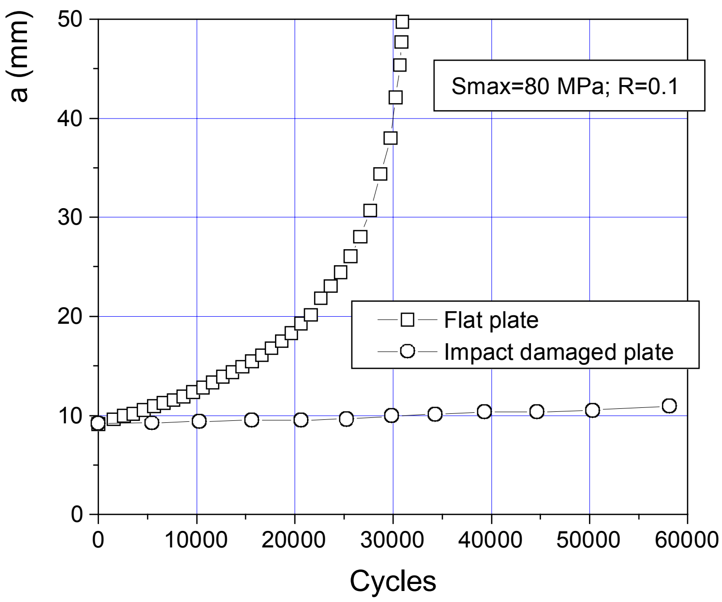

Fig. 26 – Fatigue crack growth results, for a defect at the centre of the bump.

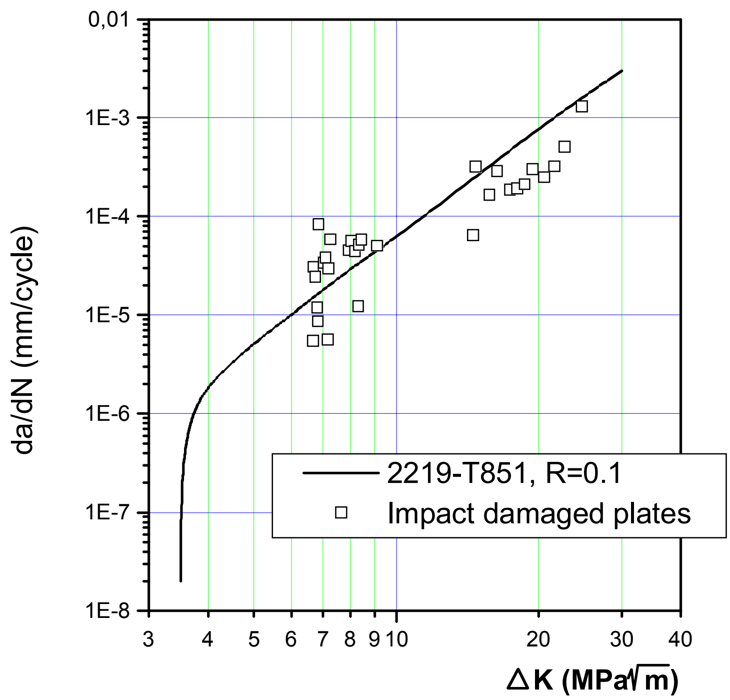

Fig. 27 – Comparison between base metal and impact damaged plates, keeping secondary bending into account in the K expression.

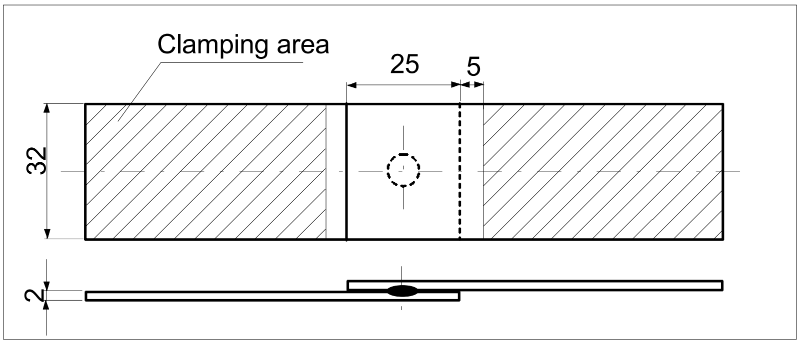

Fig. 28 – Spot-weld specimen.

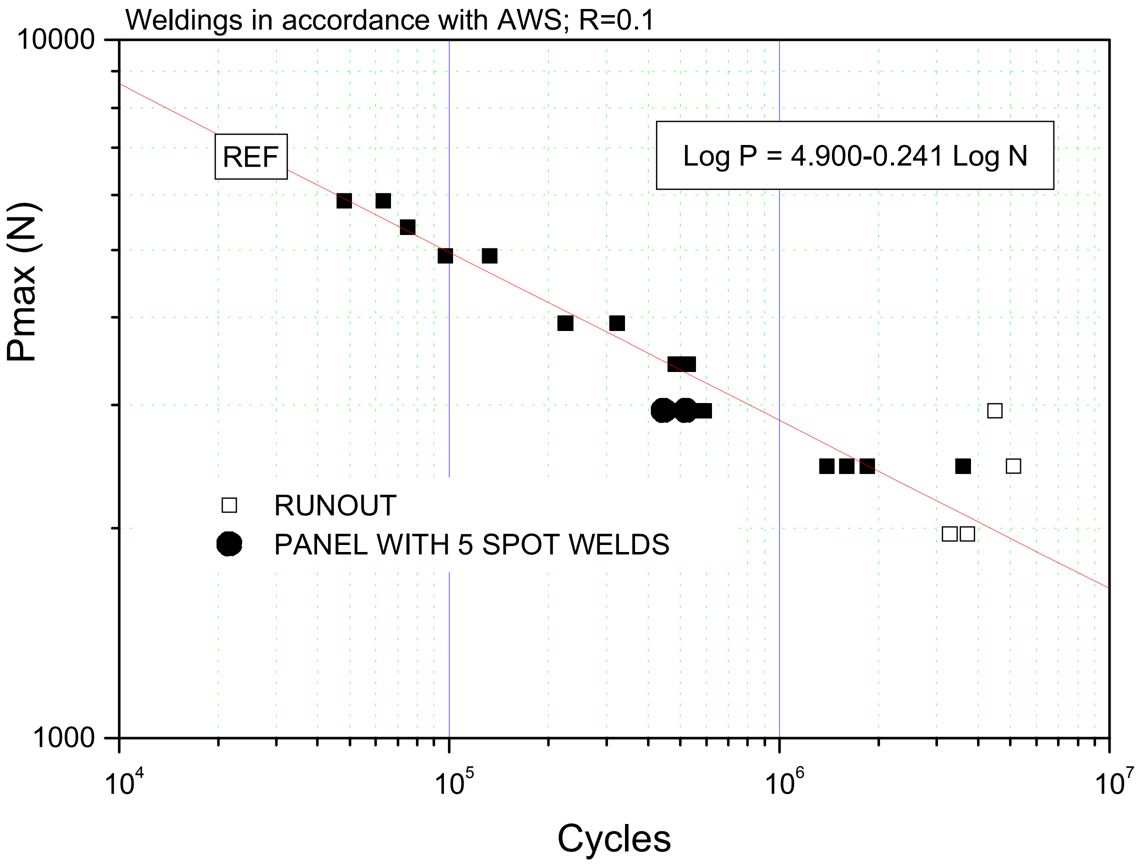

Fig. 29 – Fatigue test results on AISI 301 spot welded joints.

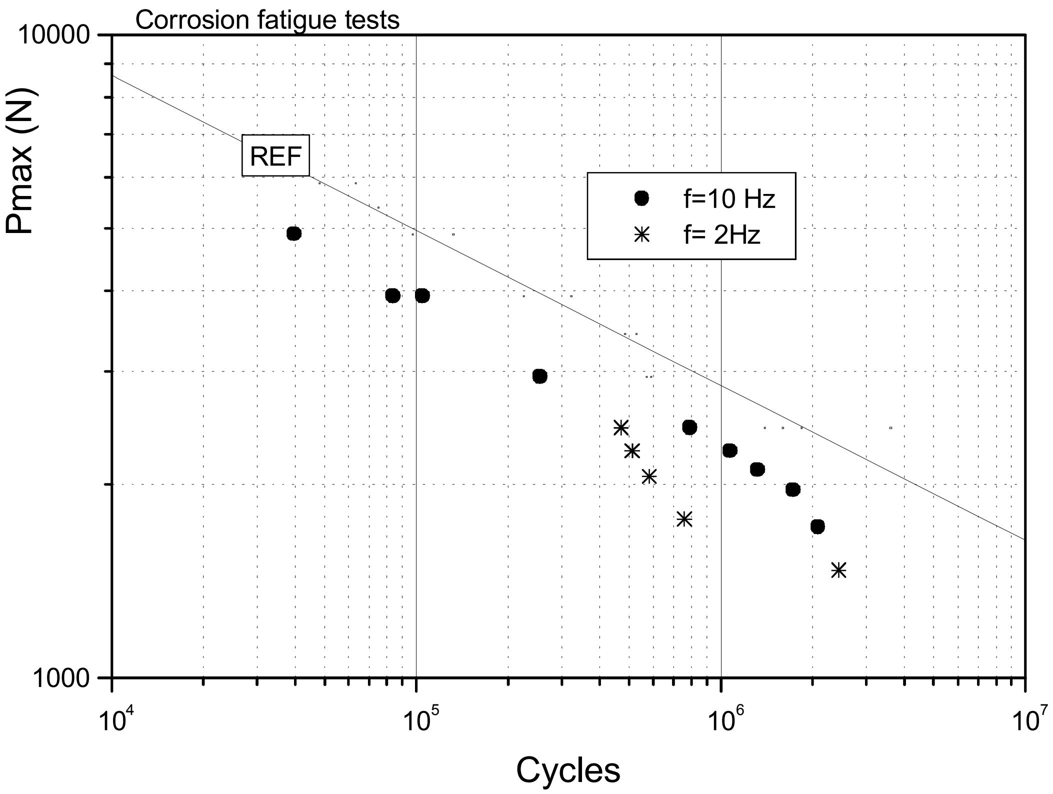

Fig. 30 – Influence of frequency on the fatigue test results in a corrosive environment.