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 2005 - March 2007

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 2005 – March 2007. The main topics covered are: load monitoring, fatigue of metallic structures, fibre metal laminates, full scale testing.

30th ICAF Conference, Naples, Italy, 14-15 May 2007

CONTENTS

1. INTRODUCTION

This paper summarises aeronautical fatigue investigations which have been carried out in Italy during the period April 2005 to March 2007. The different contributions have been arranged according to the topics, which are loading analysis, fatigue and fracture mechanics of metallic materials, fatigue behaviour of composites, joints and full scale component testing. A list of references, related to the various items, is presented at the end of the document.

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

2. MEASUREMENT AND ANALYSIS OF OPERATIONAL LOADS

2.1 - AM-X life monitoring (Alenia Turin)

The life monitoring program for the AM-X aircraft is an activity that has been in progress for a long time and regularly information has been given in the various National Reviews; it is based on g-meter readings, together with configuration/mass analysis and mission profiles. With respect to the situation described in the last Review, where the data base included 130,600 flight hours, corresponding to 108,800 flights, the flight activity has made progresses, reaching 158,000 flight hours corresponding to 132,000 flights. The usage severity is measured by means of the Load Severity Index (L.S.I.), that is the ratio between the damage cumulated in a flight hour and the damage of an average hour of the reference spectrum. The analysis of the data, reported in fig. 1, is an update of the similar analysis carried out two years ago, and shows that the average utilisation is very close to the design spectrum (LSI equal 1, fig. 2) with about 33% of the Italian Air Force fleet flying with LSI grater than 1, i.e. the flown spectrum is more severe than the design one. Another comment to the data is that there are significant variations in fatigue consumption rate of various airplanes, but with a trend to reduce the differences.

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

This aircraft is in service since 1980. Alenia continues the fatigue management of the Italian fleet 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, 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, using a PC. From the beginning of the monitoring activity, 226,400 flight hours were processed, corresponding to 159,500 flights. The analysis of the data of this large statistical basis produced a good knowledge of the fatigue consumption of the fleet. The average fatigue consumption rate is quite low in comparison with the design one, and also rather constant during time, with an average LSI that is steadily around a value of about 0.2 (see fig. 3). However, looking into more details, significant differences can be observed in the years among individual aircraft, fig. 4.

The general trend shows that the life of the Tornado aircraft can be extended over the original design assumption of 4000 flight hours and, on the other hand, that the individual tracking must be maintained. On this basis, a long term work, aimed at the re-assessment of the fatigue status of the aircraft, is on going, in order to guarantee airworthiness during future operational life which is expected to be extended to at least 6000 flight hours.

In co-operation with other PANAVIA Partners the reorganisation of qualification data cumulated during the past years took place, identifying for each significant item all modifications applied; the job is now continuing with the identification of all the tests and analyses performed to sustain the qualification of each item. A re-assessment of the fatigue life of the entire structure was performed for the Italian Air Force. The study was oriented to identify maintenance activities needed to extend the Italian aircraft life at least to 6000 FH. Moreover, a great importance has been given to the evaluation of the fatigue consumption of items that are not specifically monitored.

The status of qualification of several structural areas of the wing, that is under Alenia responsibility, was analysed and, where necessary, precautionary maintenance activities were identified in order to cover the lack of knowledge between actual service and assumptions originally used in the design phase. Other possible outcome of these analyses were recommendations for OLM activity and requirements for further investigations.

2.3 - EF Typhoon (Alenia Turin)

In February 2003 the first series aircraft was delivered to the Italian Air Force, and so far 21 aircraft (13 single seater and 8 twin seater aircraft) have been delivered to the IAF. Service activities started in April 2004, and since December

2005 the Typhoon was declared operational in the role of patrol and interception. At the date of December 2006, the Italian fleet had performed 2667 flights, for a total of 3024 F.H.

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

In the last Review, some indications were given about the Structural Health Monitoring system (SHM), developed by BaeSystems in collaboration with other Eurofighter companies. In the period of the present Review, Alenia Aeronautica provided support to the Italian Air Force for the initial operations of such SHM, to facilitate the reading of the results and the correct interpretation of “event monitor” messages. Alenia Aeronautica signed a contract with IAF for the Typhoon fleet fatigue and usage support for the 2007-2008 period. The contract will include the analysis of the SHM data and the fatigue monitoring.

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

In the last Review, detailed information was given about the definition of an I.A.T.P. (*Individual Aircraft Tracking Program*) for the C 27-J aircraft, the control points and the routines that allow to define the severity of the actual usage, which is evaluated in terms of the potential crack growth.

The IATP activity has started, and the IATP Data Processing is in progress for the Hellenic Air Force and for the Italian Air Force. Alenia is involved in the activity related to the evaluation of preliminary results and of software improvement on the basis of some customer specific requests.

2.5 - MB-339 Aircraft (Alenia Aermacchi)

The MB-339 aircraft is in service in nine different nations. The Italian Air Force operates it with a secondary close support role. A customised version is operated by the Italian Air Force aerobatic team, the "Frecce Tricolori". The MB-339 advanced trainer covers the entire advanced training syllabus, up to and including lead-in fighter training.

The main activity on MB-339 thus consists in fatigue life consumption monitoring of the fleets all over the world.

In the graph in Fig. 5, an example of the results of the monitoring activity on different fleets is presented; in total, 423,513 flight hours have been monitored, for the various versions of this aircraft. Depending on the version, different monitoring systems (i.e. based on different principles) are used.

3. METALS

3.1 - Fatigue behaviour of notched and un-notched materials

3.1.1 - Fatigue tests of repairs in metallic fuselage structures (Uni. Pisa)

Within the framework of the IARCAS research project, funded by the EU within the 6FP and focused on the development of advanced repair solutions for metallic fuselage skins, a collaboration took place between the Department of Aerospace Engineering of Pisa and Airbus Deutschland. The objective of this collaboration was the performance of about 10 fatigue tests on large 2024-T3 panels, 1.8 mm thick, containing a repair at the centre; various solutions were defined and the study was to assess their ranking as well as the fatigue damage development. Fig. 6 shows a sketch of the repair solutions evaluated; all the tests were performed under the same load conditions, i.e. sinusoidal loading, with a Smax = 100 MPa and R=0.1. Fig. 7 shows a picture of the test set-up, a 500 KN servohydraulic fatigue machine, capable of accommodating a very large test article (width: 1.3 m, height: 3.0 m). The tests were monitored visually and, at prescribed number of cycles, with eddy current inspections. The results, in terms of number of cycles to first crack detection, are reported in table I; in the second column, the first letter indicates the configuration (with reference to fig. 6), while FP, when present, indicates the application of the Flap Peening process. A bonded configuration was also tested.

A paper in the Symposium will present in detail the results of this very articulated and complex research activity.

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

A large research activity has been developed at the Department of Aerospace Engineering of the University of Pisa in order to correctly evaluate fatigue life enhancement of “cold worked” holes in aerospace aluminium alloys.

The detailed experimental activity comprised focused fatigue tests, crack propagation tests, crack surface analyses and "Sachs" measurements of residual stress fields of holes processed by different "cold working" technologies.

In simple "open hole" specimens in 7075-T73 aluminium alloy, thickness 2.3 mm, a remarkable increment of fatigue life due to the "Split Sleeve Cold Expansion^{TM}" process was observed. Even greater improvements were observed by applying the cold expansion twice on the same hole or by the "StressWave^{TM}" method. All the experimental results obtained are presented in [1].

In order to evaluate the effect of "cold working" on more realistic structures, an extra activity on cold worked rivet joints was also performed, in cooperation with Agusta Westland. The results are reported in [2].

If the "cold working" technique is to be included in damage tolerance structural design, a predictive methodology for the evaluation of the fatigue behaviour of cold worked holes must be developed.

The first step toward fatigue life estimation is a correct quantitative assessments of the compressive residual stress fields present around cold worked holes.

First evaluations, performed by 3-D ABAQUS Finite Element models, highlighted important differences between stress fields at the mandrel 'entry' and 'exit' faces of "split sleeve" cold worked holes and instead a more regular field in "stresswave" specimens.

The numerically evaluated stress fields were experimentally confirmed by the destructive "Sachs" method and several peculiar effects of the process, experimentally observed, were clearly confirmed by FEM analyses. So numerical results were qualitatively in good agreement with experimental data, but thus far, predicted crack nucleation and propagation in cold-worked holes by AFGROW software mismatched with experimental evidence, [3].

The problem of the quantitative assessment of the complex three-dimensional compressive residual stress field was consequently faced by means of highly non-linear ANSYS Finite Element Analyses performed in cooperation with EnginSoft S.p.A., Florence. Particularly, more attention was focused on modelling the real plastic material behaviour; Fig. 8 shows experimental results, obtained by means of various load histories. In fact, a general kinematic hardening material behaviour was not able to describe the strong Bauschinger effect exhibited by the aluminium alloy 7075-T73 during the unloading phase, giving rise to a non conservative compressive residual stress field around the hole, inconsistent with experimental fatigue test results. The "Chaboche" plastic material model, implemented in the Ansys code, has been selected for performing Ansys FEM analyses with the multi-objective design optimization tool, modeFRONTIER, Fig. 9. The model is obtained by superimposition of five kinematic hardening models, tuned with static tests data obtained on the base material subjected to a stress-strain history similar to the one experienced by the material at the cold worked hole edge, Fig. 8. The "Split Sleeve Cold Expansion^{TM}" was so simulated by modelling a complete mandrel drawing across the hole with an interposed sleeve. A more realistic description of the stress fields during the process phases was so achieved, [4-5].

3.1.3 - Evaluation of the effect of retained austenite on carburising steel (Agusta Westland)

The presence of retained austenite in gear steels is a consequence of the high alloying elements content as well as the high Carbon in the hardened case. Retained austenite is not tolerated beyond a well defined low limit because it is in a metastable state and its transformation during or after final machining may lead to tolerance problems as well as to unpredicted residual stresses.

This is the reason why most of the heat treatment cycles for high quality gears contain a deep freeze phase, aimed at the transformation to the stable martensitic structure.

In presence of demanding performance requirements, an X-Rays diffraction inspection is required to evaluate the final percentage of retained austenite.

Contradictory literature data on the fatigue effect of an high level of R.A. are usually reported.

Recently the need to build up data on the effect of this austenitic phase on the fatigue behaviour, in order to justify the applied specification value, led to the performance of a small test program on un-notched specimens, where two typical R.A. conditions of 8 % and 15% were compared. From the results, plotted in Figure 10, it was possible to conclude that the effect on fatigue is clearly not present.

3.1.4 - Evaluation of the effect of super finishing on carburising steel (Agusta Westland)

Super-finishing processes are often selected to obtain a very high degree of performances in high quality gears. Several studies have been devoted to this subject and an almost unanimous conclusion was that usually the super-finishing gives place to a parallel increment in the pure fatigue performances.

Most of these processes are based on a chemical and a mechanical effect, that are applied in sequence on the metallic surface in order to obtain the desired effect. The present study was aimed at two purposes. One was to evaluate the fatigue effect of the complete process, the second was to find the possible detrimental effect of the unique chemical effect. It is in fact clear that some geometric features may restrain the accessibility to the mechanical shots to certain areas.

Figure 11 shows the cut section of a super-finished carburised steel coupon. Figure 12 shows the fatigue diagrams of base material, superfinished material and material subjected only to the chemical effect.

The conclusion was a quantification of the fatigue enhancing effect and the suggestion to mask all the areas where the shots cannot arrive freely, but on the other hand, even if there was a certain decay with respect to the base material curve, the effect was still not too much detrimental.

3.1.5 - Fatigue of gears (Agusta Westland)

A collaboration is in progress between Politecnico di Milano – Dip. di Meccanica and AW Fatigue and Transmissions Dpts. on the subject of 'Fatigue of Gears'. A mechanical resonant machine is used to test case hardened steel gears, differing for material, geometry and grinding process. An initial phase was done in the range up to 10 million cycles and now a second testing phase is being completed, covering root bending fatigue behaviour in the gigacycle fatigue range up to 100 million cycles.

The test methodology was optimized to achieve a very efficient procedure, allowing megacycle fatigue tests with reduced efforts. The total plan for case hardened gears will be close to 10^9 fatigue loading cycles. Experimental data are supplemented by detailed stress analysis and failure analysis to optimize the methodologies for gear fatigue design and verification. Examples of a fatigue failure and of FEM analysis are shown in Figs. 13 and 14.

3.1.6 - Material characterization for participation in civil programs (Alenia Aermacchi)

Alenia Aermacchi is involved in the A380 program, for what concerns the Thrust Reverser and Fixed Fun Duct beams of the nacelles, as well as in other civil programs (e.g. CF 34), always with interest focused on the nacelles. The participation to such programs, with responsibility for the design and the certification, has required the performance of an extensive test campaign for the characterization of the materials utilized.
The test campaign has been focused as hereafter presented:

a) 7175-T73 Hand Forging
Axial fatigue and fracture toughness tests have been performed, in various material orientation, under different stress ratios and stress concentrations Kt values. Just to give an idea of the effort, for this material 355 fatigue tests have been carried out, and 41 fracture toughness tests, on CT specimens.

b) 7175-T7352 Hand Forging
Axial fatigue tests have been performed on this hybrid material (hand forging and T7352 treatment) to assess consequences of a material change. 90 tests have been performed.

c) 7010-T7452 Hand Forging & Die Forging
Other 90 axial fatigue tests have been performed, all in the S-T orientation, from different thickness plates.

d) 7175-T7352 Die Forging
This is another extensive campaign for material characterization. All the 330 fatigue tests have been carried out on CAA treated specimens. Also fracture toughness will be assessed (36 CT specimens).

e) 2219-T62
This material is used in the CF34 and in other nacelles programs. Axial fatigue tests have been performed to evaluate the behaviour of various protection systems. Therefore, tests have been performed on untreated specimens, on CAA and SAA specimens (at RT) and on SAA specimens at 150 °C. A total of 216 fatigue tests have been performed.

All the results of this large test campaign are proprietary data, and are not fully available. Nevertheless, some information can be deduced from Figs. 15 and 16.

3.2 - Crack propagation and fracture mechanics

3.2.1 - Damage Tolerance analysis of unitized structures (Uni. Pisa)

Within the framework of the 6FP of the EU, a research project on the study of Damage Tolerance analysis methodologies applicable to "new" unitized structures (such as high speed machined integral stiffened panels, laser beam welded panels and friction stir welded panels) has started, under the coordination of the Technical University of Braunschweig (Germany). Major partners are NLR, DLR, FOI, IAI, EADS Innovative Works, Universities of Brno, Porto, Sheffield, Patras and Pisa. An articulated test program has been defined with three different materials (2024-T3 and 6056, a weldable alloy provided to the consortium by Alcan in the T4 temper, which gives rise to two options: heat treat to T6 and then weld, or weld and then heat treat to T6) and four different configurations / processes. The test activity is in progress.

A preliminary Work Package was dedicated to the analysis of crack growth methods, with particular interest, in the first phases of the project, for integral structures. Most of the partners have performed finite element analysis (of various complexity and sophistication level) for the definition of the stress intensity factor, keeping also the interaction with crack in the stringer (when present) into consideration. It was also quite evident the importance of the secondary bending, that changes during the test due to the progressive reduction of the residual section, which modifies the position of its center of gravity.

Fig. 17 shows a comparison of predictions, obtained by using a standard code, like AFGROW, with appropriate modifications, with test results from a High Speed machined 7-stringers integral panel (test results were provided by Airbus Deutschland).

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

The series version of the M346 military trainer aircraft is currently under construction at Alenia AerMacchi (Venegono Superiore, Italy). The design target life of the aircraft, which will be certified for Damage Tolerance, is 12,000 flight hours (FH), with the possible extension to 16,000 FH after specific inspections. Fatigue tests were performed on critical elements at the Department of Aerospace Engineering of the University of Pisa in order to verify crack propagation calculations.

The wing to fuselage connection is one of the most interesting elements from the fatigue point of view. Spars and frames, both integrally machined, are connected by two lug-fork joints; the base material is aluminum alloy 7050-T7451 for both the elements. High interference bushings, ForceMate®, produced by FTI (Fatigue Technology Inc., Seattle, WA) were used in the lug/fork connections.

An experimental activity was carried out on two different types of specimens. The first one, a Compact Tension specimen, was tested under constant amplitude loading to verify the fatigue crack growth rate data contained in NASGRO 4, the software used for Damage Tolerance evaluations. Experimental results were fully comparable with the NASGRO 4 material database. Additional variable amplitude loading tests were carried out with a sequence simulating the loads acting in the lower wing skin near the wing root. The sequence was composed of 178 different flights; the results obtained from these tests were useful to calibrate the crack growth prediction models used in the analyses.

The second type of specimen was a lug-fork joint designed as the actual joints present on the aircraft. Both constant and variable amplitude loading fatigue tests were carried out. The results obtained clearly indicated the strong beneficial effect of ForceMate bushings: the design life of the connection was largely reached and overcome, also when large defects, such as corner cracks up to 6 mm in depth, were introduced, Fig. 18.

The whole process was realistically simulated by a complete ABAQUS Finite Element model, drawing the mandrel across the specimen hole with the interposed bushing, Fig. 19. The beneficial effect of interference fit mounting on fatigue resistance is well known but, in this case, it results also in a cold working of the work piece, with an additional beneficial effect. The residual stress numerically obtained were confirmed by continuous strain gauge measurements obtained during bushing installation. Besides, three comparative crack propagation tests on lug specimens demonstrated that in ForceMate bushing installation, the hole cold working effect prevails over the bushing interference effect; indeed the beneficial effect persists even if bushing is removed, Fig. 20.

The fatigue life estimation was strongly complicated by the anomalous crack shapes observed during crack propagation tests in all the specimens: particularly, cracks grow faster in "c" direction (surface) instead of the "a" direction (depth), as predicted by NASGRO 4, Fig. 21a.

Different potential factors were investigated such as pin elasticity, friction coefficient between pin and hole and clearance between pin and hole by means of complete 3D FEM models: no significant differences were obtained in the extreme load conditions to justify the observed behavior.

Microscope analyses finally showed that the specimens’ material had a strong anisotropy with a stratified structure in the Short Transverse direction, Fig. 21b, which considerably slows down the crack propagation rate in the thickness direction. The main results obtained during all the activity are fully reported in [6].

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

Fatigue certification according to the JAR 29 Rules require compliance with the Flaw Tolerance requirements.

The evaluation of Damage Tolerance properties is based on:

• ‘no growth’ concept for most of mechanical parts, with reference to an initial 0.38 mm crack
• inspection plan defined in accordance with crack growth analysis for the airframe.

Agusta preferred method for compliance with Flaw Tolerance requirements for dynamic components is the adoption of the “no damage growth” concept.

The typical flaw size assumed is a corner or a semi-circular crack of radius r = 0.38 mm, for parts exposed to accidental damage in flight, and a smaller flaw of radius r = 0.25 mm for parts protected in flight, after maintenance inspections. As far as the no-growth concept is concerned, it is applied through the use of the Kitagawa-Takahashi diagram.

The FTDB is now part of the Agusta Westland Damage Tolerance design methodology. This was initially developed for the AW139 Helicopter within the framework of a research program with Politecnico di Milano – Dip. di Meccanica. The FTDB proved to be a valuable tool for design and verification and was extensively used in compliance demonstration to airworthiness requirements for the AW139 and NH90 helicopters.

The FTDB was further extended, covering also Al castings (A357 and A356 Hipped and as cast, see an example in Fig. 22) and additional titanium alloys (Ti-6Al-4V beta solution and Ti 10-2-3) in addition to the materials for which Kitagawa diagrams were already obtained, i.e.:

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

At present high strength steel (32CDV13, 9310, EX53 and Pyrowear) for transmissions, shafts and gears, are tested within a program to improve Safe Life and Damage Tolerance design and evaluation of transmissions.

Most of the Fatigue and Flaw Tolerant methodologies developed in the latest years were successfully applied in the programs for the Civil Type Certificate of AB139 and the Military Qualification of NH90. More details and examples can be found in [7-9].

4. COMPOSITES AND FIBER METAL LAMINATES

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

Within the framework of the DIALFAST project, funded by the EU, an investigation on fatigue crack growth in Glare material was performed at the Department of Aerospace Engineering, University of Pisa in cooperation with Alenia Aeronautica. The behaviour of two standard Glare grades was investigated: Glare 3-3/2-0.3 (with 2024-T3 or 7475-T761 aluminium alloys) and Glare 4A-3/2-0.3 (only with 2024-T3).

The tests showed a better behaviour in Glare 3 with 2024-T3 than in the one with 7475-T761, thanks also to the lower yield strength, that corresponds to a larger plastic zone at the crack tip, and lower crack growth rates. Glare 4A shows even lower crack growth rates, because of the larger quantity of fibres in the load direction.

The specimens (flat panels with central crack, CCT) were fatigue tested under Constant Amplitude loading until the crack reached a fixed length (see table II). Then, the specimens were cut in strips, perpendicular to the crack length. These strips were subsequently buffed on one side and examined with an optical microscope, in order to measure the delamination length at the interface between the outside aluminium layers and the fibres layer (see Fig. 23).

The delamination area has larger dimensions in Glare 3 with 2024-T3 than in the case of 7475-T761; cyclic shear stresses at the interface are influenced by the lower yield strength of 2024-T3 (see Fig. 24). Glare 4 has the largest delamination area because it was tested with a higher σ_{max}.

These measurements were used to model flat panels with the FEM ABAQUS code; the analysis allowed to calculate ΔK at three different crack lengths. The calculated ΔK values resulted slightly higher than the experimental ones and the analyses are still in course to understand better the role of constituent stiffness on ΔK.

5. JOINTS

5.1 - Fatigue and static strength of Glare specimens containing internal splices (Uni. Pisa)

Within the framework of the DIALFAST project, an experimental activity has been carried out at the Department of Aerospace Engineering of the University of Pisa, for the assessment of the static and fatigue performance of a configuration of internal splice in Fibre Metal Laminates (FML). The specimens were designed and manufactured by Alenia Aeronautica; for the sake of simplicity, it was decided to select only two FMLs materials and one splice configuration, which is shown schematically in Fig. 25. It is based on the bonded lap-joint concept, which allows, in comparison to other solutions, a strong increase in the strength as well as in the resistance to environmental attacks, at the expenses of a small local increase in thickness, of the order of one metal layer.

Both fatigue and static tests were performed in normal laboratory conditions on unnotched dogbone specimens, complemented by an additional small number of static tests on the two basic material systems, in order to assess the joint efficiency.

Two materials systems were used to manufacture the specimens. The two FMLs systems, both belonging to the FML3-3/2-0.3 mm type, were:

a) 2024-T3 with pre-preg based on Cytec FM94 resin and 27% volume S2 glass fibres; in this case, the adhesive was AF-163 gr.5, curing at 125 °C (± 5 °C) for 80 minutes (± 10 minutes); for the sake of brevity, this material system will be called “A” in the following text, and in the relevant figures;

b) 7475-T761 with pre-preg based on Cytec FM906 resin and 27% volume S2 glass fibres, while in this case the adhesive was the one corresponding to the Boeing specification BMS 5-137 gr.5, curing at 175 °C (± 5 °C) for 90 minutes (± 10 minutes); this material system will be called “B” in the rest of the paragraph.

Static tests were performed on joints and on coupons obtained from the basic laminates, to assess the joint efficiency of the selected splice configuration.

Table III summarizes the obtained results, in terms of ultimate strength for specimen unit width (N/mm).

The static strength of the 2024 splice specimens is unexpectedly about 20% higher than the one of the 7475 specimens, but it must be kept in mind that this results depends also on the influence of the adhesive system (and of the pre-preg resin system). The high temperature curing system (used in conjunction with 7475 layers) is more brittle.

In the basic static tests, the elongation to failure of the “B” material is systematically higher, on average about 0.5%, and this gives a significant contribution to the higher strength shown by the “B” material system.

For the 2024 material system, the strength of the spliced specimen is 89% of the basic material strength, a quite high value, while in the case of 7475 material it drops to 64%.

Fatigue tests were carried out in order to assess also the fatigue strength of the two configurations. Two S-N curves were derived for a stress ratio of 0.1, at room temperature and in normal laboratory conditions. The width of the specimens in the critical area was 12.7 mm, i.e. rather small, so that the nucleation of an externally visible crack took place quite close (in terms of number of cycles) to the final failure. The results of the two groups of specimens are compared in Fig. 26, where it can be seen that the 2024 material system shows a clearly superior fatigue resistance with respect to the 7475: for the same life, about 30 % higher stresses can be withstood by the 2024 material.

This result could be expected, as the specimen life depends on the time required for the nucleation of a crack in one of the three bonded lap-joints, which were the fatigue critical details. Therefore, the splice specimen fatigue life is controlled by the resistance of the metal to a given stress concentration; in this respect, the behaviour of 2024 is superior to that of 7475.

Points H and C (see the sketch in Fig. 25) have been observed as more frequent crack initiation locations in the tests performed, irrespectively of the material.

5.2 - Fatigue and residual strength study of riveted joints in FML (Uni. Pisa)

When installing rivets to Fibre Metal Laminates (FML) materials, additional possibilities exist to strengthen the joint, through the inclusion of local reinforcements in the joining area during the FML material production. The present activity concerns the study of the fatigue behaviour and the residual strength degradation of various configurations of riveted joints. In all of them, the basic material was a Glare 3-3/2-0.3 laminate, i.e. a FML made of 3 layers of 2024-T3 aluminium alloy, thickness 0.3 mm, and two double layers (0/90) of pre-preg FM-94-27%-S2 fibreglass.

Seven different configurations of riveted joints, named LAP1-LAP7 and summarily described in tab. IV, were examined. The differences in the various configurations were the number of row rivets, the rolling direction of the aluminium laminae with respect to the load direction, the rivet (type, head, diameter and material), presence in the overlap area of an interlaminar metallic doubler and/or two additional glass fibre layers. Alenia Aeronautica manufactured and assembled the specimens, which had all similar characteristics (190 mm wide, seven rivets per row). All the tests have been performed at the Department of Aerospace Engineering of the University of Pisa, under Constant Amplitude load conditions, with a stress ratio equal to 0.1.

Figs. 27 and 28 show the main dimensions of LAP1 specimens, together with a photograph of a small strip in the overlap area of a specimen, after having removed the external aluminium layer. The unidirectional fibre glass layers are clearly visible; the small empty zones in correspondence with thickness variations were filled with AF-163 adhesive.

The LAP1 configuration was the first to be tested in the whole campaign. A preliminary fatigue test, Smax=140 MPa, R=Smin/Smax=0.1 was carried out on a LAP1 specimen with the aim of assessing the fatigue life and the failure modes. The test was suspended after 771,600. cycles due to specimen failure under the grips. Even if some fatigue cracks nucleated in the overlap area, serious fatigue damages nucleated in the laminates, far from the grips and the joining area. The same failure mode was observed in the subsequent fatigue tests carried out on these specimens.

Also the specimens of the other two 3 rivet rows configurations showed a very good fatigue resistance: LAP2 specimens were fatigue tested at the same stress level, in order to have an indication of the scatter in the results, while LAP6 specimens were tested at different stress levels, so obtaining an S-N curve.

Since the fatigue behaviour of the joint configurations with three rivet rows was better than the base material, the attention of the test program moved to the assessment of the fatigue behaviour of configurations with only two rivet rows. The joint configurations tested in the remaining part of the research were manufactured by Alenia Aeronautica on the basis of a 2 rivet rows design. Various solutions were experienced, assessing the influence of the fastener system, in conjunction or not with local reinforcement, as summarized in Table IV.

	Rolling Direct.	Rivet rows	Fastener type	Fastener	Interlaminar metallic doubler	Interlaminar double glass fibre layers
LAP1	T	3	Solid	BACR15FV7KE7; 7050-T73, D=5.55 mm	Aluminium 0.3 mm	YES
LAP2	L	3	Solid	NAS1097D7; 2017-T3, D=5.55 mm	Aluminium 0.3 mm	YES
LAP6	L	3	Solid	NAS1097D6-7; 2017-T3, D=4.8 mm	Titanium 0.1 mm	YES
LAP4	L	2	Solid	NAS1097D6-7; 2017-T3, D=4.8 mm	Titanium 0.1 mm	YES
LAP3	L	2	Solid	NAS1097D6-7; 2017-T3, D=4.8 mm	Titanium 0.1 mm	NO
LAP5	L	2	Lock-Bolt (protr. head)	ASNA2392-3-02, D=4.8 mm, Collar NAS 1080-06	NO	NO
LAP7	L	2	Hi-Lok (protr. head)	NTA1151-6K4/BACB30MY6K4; D=4.8 mm, Collar: NTA 11752-6	Aluminium 0.3 mm	YES

Table IV - The seven different riveted lap joint configurations.

All the test results are reported in Figs. 29 and 30, where the behaviour of the various configurations examined is compared. In Fig. 27, reference fatigue results relevant to standard aluminium lap joints, from [10], are also reported: they are relevant to 2024-T42, thickness 1.2 mm and the lap joint contained two rows of seven rivets made of 2017-T3 aluminium alloy, diameter 4 mm. It is evident, once again, the better behaviour of FML specimens, when compared with standard monolithic aluminium specimens.

Fig. 30 shows the residual strength decay of joint specimens, that were statically tested after having been subjected to a specific number of fatigue load cycles (the maximum stress is indicated in the legenda of the figure, while the stress ratio was always 0.1).

Fig. 31 shows the evolution of this phenomenon during the fatigue test of a specimen tested at Smax=135 MPa, failed after 227100 cycles. Looking at the enlargement of the central rivet in the critical row, small cracks in the pre-formed rivet head can be observed even after only 32000 cycles. Part of the rivet head detached at 83200 cycles. A fatigue crack on the external surface is evident at 143300 cycles. Additional parts of the rivet head detached at the same time. The test concluded with the pull-through of the pre-formed rivet heads.

The conclusions of this activity is that FMLs are a class of material with an excellent fatigue behaviour; if seen with an adequate magnification glass, it is possible to state that the resistance to crack nucleation is small (due to a redistribution of stresses within aluminium and fibre layers, that penalizes the aluminium layers) while the crack propagation resistance is excellent. The result is a very good durability and riveted joints in FMLs can further improve their fatigue life by means of a local reinforcement in the joint area, at the expenses of a small cost and weight penalty.

6. INTERNATIONAL AND NATIONAL RESEARCH PROGRAMS

6.1 – WELAIR Brite Euram Research (Piaggio Aero Industries)

Within the WELAIR project, funded by the EU, Piaggio Aero Industries has performed two research activities, aimed at studying the application of the Friction Stir Welding technology to fuselage structures, that are described in the following paragraphs.

6.1.1. Fatigue behaviour of a FSW stiffened panel

A small technology development program was performed for the evaluation of the FSW process to manufacture stiffened panels in 2024-T3 aluminium alloy. A number of small panels, stiffened by two FS welded Z-shaped stringers, were produced.

Two types of welded stiffened panels have been considered (see Figs. 32 and 33):

1. Continuous Welding;
2. Step Welding

The fatigue behaviour of the panels was assessed by means of pressurization fatigue tests, carried out with a specifically designed pressure box: the panel was fixed along the four sides by rivets.

The test results were compared with those relevant to classical joining technique (riveted stringers), which were tested first within the test campaign. The test aimed at the attainment of 60,000 cycles, with a pressurization cycle from 0 to 0.9 bars (13psi); the panels were visually inspected every 3000 cycles.

The riveted panel, without the introduction of any defect, confirmed the prediction of the numerical analysis, reaching 60,000 cycles without any failure. The test of the first Type 1 welded panel, on the contrary, was suspended after 19,899 cycles for the presence of a crack, located under the welding line, close to the edge of the panel; the crack did not affect the stiffener, but the skin only.

The other type 1 welded panels showed the same fatigue life (around 20,000 -23,000 cycles).

The type 2 welded panel subjected to a pressurization fatigue test has demonstrated a remarkably longer fatigue duration compared to the continuous welded stiffened panels, under the same load conditions.

The same type 2 panel configuration has been analyzed and tested to evaluate the crack propagation, starting from an artificial defect introduced in the centre of the bay (a hole with two crack starters).

Different types of analysis have been performed and compared for the evaluation of K, i.e. numerical analysis with the Poe approach and with Fem analysis. The AFGROW code has been used to perform crack growth predictions.

The results of all numerical analyses show that the FSW defines pattern and shape of the SIF suitable to act as crack retarders. This is anyhow a preliminary conclusion, because the effect of residual stresses has been completely ignored.

Crack growth test of FSW stiffened panels have been performed under CA load, R=0.1, Smax = 69 MPa. The experimental results are shown in Fig. 34.

6.1.2. Test of a FSW barrel

The same test procedure used for the panel will be applied to a barrel test, performed on a stringer-less solution with FSW welded frames. Circumferential joints (in correspondence with frames) and longitudinal joints (in correspondence with four intercostals) are all butt joints.

Only part of the analysis has been reported for brevity of exposition; the test results are not yet available, being the tests still in progress.

A FEM model has been prepared, where each welding line was supposed to be 12.5 mm wide; it has been assumed that the elastic modulus of the nugget is 70% of the basic material modulus.

A barrel has been manufactured: the material of the skin and stiffeners was Al 2024-T42, while steel closures were applied (see Figs. 35 and 36). The test is in progress and uses a pure pressurization load condition.

The test article will be inspected in various points, considered potentially critical, such as welding run in/run out, intercostal joints, butt joint close to run-in, high stress concentration points (as identified by the FEM analysis).

6.2 - ALCAS Research (Alenia Naples)

ADVANCED **L**OW **C**OST **A**IRCRAFT **S**TRUCTURES

The specific objective of this program is to reduce the operating costs of relevant European aerospace products by 15%, through the cost effective application of carbon fibre composites to aircraft primary structures. In the Alcas project, two aircraft typologies are considered: Airliner and Business Jet, for each one, two platforms are defined.

Alenia Aeronautica is involved in the design, analysis and manufacturing of a Business Jet configuration.

Main partners (for the Business Jet) are: Dassault (Project Leader), EADS CASA-MTA, Fokker, NLR, Ceat, Saab.

6.3 - AHMOS-2 military research (Alenia Naples)

Aircraft **H**ealth **MO**nitoring **S**ystem

The objective of this program, funded by the Italian Air Force, is to develop an integrated Health Management System in order to enable the I.A.F. to perform the Maintenance on Demand through an Health Monitoring Equipment.

This equipment is based on Fiber Optics (Bragg sensors) embedded in Composite Layers (for Carbon/Epoxy components) or bonded on the surface (for metallic components).

Alenia approach is essentially based on Fiber Optic Bragg Grating (FOBG) sensors and an Health Monitoring Equipment (HME) based on Acousto-Optical Tunable Filter (AOTF).

The main Italian partners and their field of competences are: CNR-IMM (Optical), MARS (Integration, s/w, electronics), AEROSTUDI (Models/Strain Counting), ALENIA MARCONI (AOTF), CIRA (Active monitoring for UCAV. Acoustic Sensors), Potenza Univ. (Miniaturization).

Two flying applications have been made: on Eurofighter 2000 in the Outer Wing Structure (Fig. 37) and on Airbus A340 inside the Rear Fuselage Structure (Fig. 38).

7. COMPONENT AND FULL-SCALE TESTING

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

In the last Review, information was given on the preparation of the set up of the fatigue test of a LH prototype wing structure of the M346 aircraft. A picture of the test rig is shown in Fig. 39.

The aim of the test is to validate the analytical calculations on fatigue strength and crack propagation behaviour of the structure, to verify the evaluations about the location of the critical areas and to highlight any other unpredicted criticality (hot spots).

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

The development test has reached about 10,000 simulated Flight Hours up to now. The severity index range of the test spectrum ranges from 1 to more than 2, according to the location, and thus some of the critical areas already reached the design fatigue life.

7.2 - EF Typhoon (Alenia Turin)

The PMAFT (Production Major Aircraft Fatigue Test), in progress at BaeSystems plant in Brough (UK) on the production aircraft, reached 3000 simulated FH, so clearing 1000 FH utilization with a scatter factor of 3. Alenia is involved in this full scale test for the components under its responsibility and for the definition of buffet load spectra. During the 3000 SFH applied to the test article, manoeuvres, ground, gust loads and the fin buffet dynamic loads were simulated. Buffet loads are treated separately for the fin and for the wing. The fin buffet loads are simulated by means of a shaker applied to the fin leading edge. During this phase of the test, the test article is modified in the rig, installing dummy engines (to simulate the engine inertia characteristics) and disconnecting the load actuators in the wing. The fin buffet loading is planned to be applied every 3000 SFH, simulating the effects of aircraft high angle of attack and high speed airbrake opening, responsible of the buffet installation. On the contrary, the wing buffet will be simulated every 6000 SFH in a quasi static manner, with a loading spectrum defined on the basis of the equivalent fatigue cumulative damage. A paper presented in the poster session of the Symposium will be dedicated to describe in detail the methodology followed by Alenia in defining the fatigue damage associated to buffet conditions.

A test on the wing inboard pylon, already introduced in the last Review, was completed in the Pomigliano d'Arco plants, reaching successfully 18000 Test Hours. The spectrum was calculated to verify that the pylon had fatigue capabilities in excess to the original fatigue requirements of the aircraft. The spectrum included loads due to manoeuvres, gusts, and buffet, as well as those originated from heavy stores and their release. At the end of the fatigue loading, a residual static strength test was successfully performed up to 100% of ultimate load.

8. AIRCRAFT FATIGUE SUBSTANTIATION

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

The C 27-J aircraft is a derivative of the Alenia G222/C27A aircraft; 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,..).
Anyhow, a number of tests is still in progress on specific structural elements, such as engine nacelles and landing gears; the major comments are reported below.

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

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

- Two Lifetimes (50.000 SFH) for the Durability assessment of Nacelle Metallic Structure, based on C 27-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 (artificial flaw introduction, Fail Safe demonstration, etc.);
- One additional Lifetime (25.000 SFH) for the Durability and Damage Tolerance assessment of the Nacelle Composite Structure (C/Epoxy Lower Cowl); based on C 27-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. At the beginning of 2007, all the Tests have been completed and no cracks were found after NDI inspections. The Damage Tolerance test (Single and Multi Load Path approach) is also completed.

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

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

- Five Lifetimes (73530 FSLs) for the Fatigue assessment of both NLG and MLG Structure, based on C 27-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 2003 and to date has reached the 100% of the scheduled test life. No fatigue damages have been discovered after NDI inspections.

The MLG Full Scale Fatigue Test started on 2002 and to date has reached the 65% of the scheduled test life.

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

The aim of these activities is to insure the airworthiness of the older aircraft structures and, also, to increase the Design Service Goal of the ATR Models by 50%.

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

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

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

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

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

- Corrosion Prevention & Control Program (CPCP)
  A CPCP program has been defined, according to the in-service experience (corrosion findings). This activity has been completed and new CPCP Tasks have been embodied in the Maintenance Manuals.

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

  Composite Structures
  In detail, for the life extension of ATR composite components, the following three SRM repaired Carbon/Epoxy parts are under analysis:
  • ATR 42-500/72-500 CFRP (Carbon Fibre Reinforced Plastic) solid laminate vertical fin stiffened panels
  • ATR 42-500/72-500 horizontal tail multi-spar box
  • ATR 72-500 carbon outer wing box

  The repair assessment will be performed by means of fatigue and residual strength test.
  The test article (Fig. 40) already used for horizontal and vertical tail repairs test (at the time of the baseline Certification Process) will be further aged, in a way to reach the required humidity content (95%).
  The purpose of these tests is to substantiate the typical repairs (through a fatigue test) for an additional half-life (35000 flights), paying particular attention to the following structural details: skin, skin/stringer, skin/spar and skin edge.

  At the end of the Fatigue Test a Residual Strength Test is planned up to Ultimate Load.

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

- Widespread Fatigue Damage Evaluation
  This program aimed at confirming that Widespread Fatigue Damage (WFD) or Multi Element Damage (MED) will not affect the Fatigue or Damage Tolerance capability for the remaining aircraft life (Life Extension Time). This activity has been based on the results of the Full Scale fatigue test, with particular reference to the final tear-down inspection, and on service experience.
  The activity has been concluded for the fuselage structure where the assessment against WFD and MSD up to 105.000 flights has been provided to the Airworthiness Authorities.

A paper will be presented at the Symposium , focused on the detailed description of these activities.

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

As already outlined in the last Italian National Review, Alenia was in charge of the Design, Analysis and Manufacturing of the Airbus A 380 Centre Fuselage Upper Part.
For the passengers version, Alenia developed the full design of Fuselage Section 15 crown segment, including all the Analyses for Static, Durability and Damage Tolerance Justification. The MSG-3 Analysis, devoted to the development of the Structural Maintenance Plan, is also completed.
At the beginning of the year 2005, Alenia started the activities related to the Design and Analysis of the Airbus A 380 Cargo Version. Such activity is in progress.

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

At the beginning of 2004, the activities related to the design, analysis and manufacturing of the Boeing B 787 fuselage sections 44-46 and the Horizontal Tail started in Alenia. The fuselage sections 44 and 46 are conceived completely in composite materials, as well as the Horizontal Tail, which will be produced adopting the “One Shot” cocuring process.
Together with the design, Alenia is in charge of the Damage Tolerance analysis and of the test definition for the Structure Configuration development, manufacturing processes tuning and certification.

The Horizontal Tail is a Multi Spar Box realized through a “one Shot” process in autoclave. The structure is obtained starting from pre-preg carbon epoxy material, using as tooling internal and external bags: the internal ones for the cohesion of the spars, the external for the cohesion of the skins.

Currently, the test article for the performance of the full scale fatigue test of the Horizontal Tail has been manufactured and instrumented with about 500 Strain Gauges (1200 channels). The preparation of the test set-up is in progress and the test activity is scheduled to start in October 2007.

A dedicated technique was used to install internal strain gauges after that the test article was cured in autoclave (fig. 41). The strain gauges are positioned and bonded on a glass fibre strip together with their flat cables. The adhesive to bond the strip to the box internal surfaces is applied on the opposite side of the instrumented glass fibre strip is applied. Each strip is positioned on the internal tubular bags and inserted again into the structure for the new processing phase in autoclave (in controlled vacuum and temperature conditions).

8.5 - Agusta A109 helicopter family (Agusta Westland)

The A109 'Grand' is the latest variant with extended AUW (3175 Kg), improved composite rotors, MR blades with anti-nodal masses for better dynamic response, winglet tailplane and extended fuselage for better cabin arrangements. This helicopter has received full civil certification with the kits of rescue hoist and cargo hook.

8.6 - AW 139 Helicopter (Agusta Westland)

The AW139 was certified at 6400 kg All Up Weight with the kits of rescue hoist and cargo hook, and an increase of the payload from the initial Type Certificate at 6000 kg.

This is the first helicopter that Agusta fully designed and certified according to the “Flaw Tolerance” requirements, specified in the latest FAR / JAR regulations. Damage Tolerance covers all dynamic parts, fuselage and transmission, i.e. fuselage, main rotor assembly, tail rotor assembly, transmission casings (Main case, Intermediate and Tail Gear Box), tail rotor drive shaft and couplings, transmission support, engine installation, tailplane and servoactuators. The only exceptions are gears and MR and TR shafts

The evaluation of Damage Tolerance properties is based on:

- ‘no growth’ concept for most of mechanical parts, with reference to an initial 0.38 mm crack
- inspection plan defined in according with crack growth analysis for the airframe.

Structural components made of composites are evaluated according to flaw tolerant safe life concept. Additional fatigue tests allowed the increase of the retirement life and of inspection intervals for Damage Tolerant parts. Fuselage improvements and small modifications are carried out to increase durability.

As far as the no-growth concept is concerned, it was applied through the use of the Kitagawa-Takahashi diagram, as explained in parag. 3.2.3 of this same Review. The “no growth” concept was proved by comparing proprietary material data with validated stress analysis for the relevant loading cases. In a few cases, smaller flaw sizes were assumed based on threat assessment. If application of the “no growth” concept was impractical, other approaches were considered, like fail safety by dual loading path.

Full scale tests of flawed components were carried out to validate the analysis in the cases when low safety margins were reported.

Crack propagation analyses were mainly performed in relation to airframe structures. Elements and subcomponent tests were carried out supporting the initial evaluation. Two full scale tests (a tail beam and an upper deck) are in progress, supporting the improved design of the airframe for durability.

The following table collects a list of components, their substantiation method and the methodology used for showing compliance with FAR requirements.

Part	Substantiation method	Analysis/Testing
M/R Blade	Flaw Tolerant Safe-Life	Testing with manufacturing defects + impacts at both BVID and CVID level
M/R Hub	No crack growth Fail-safe	Analysis Testing
M/R Elastomeric Bearing	No crack growth for metal Crack propagation for elastomer	Analysis + Testing Testing
M/R Pitch Control Lever	No crack growth	Analysis
M/R Tension Link	Flaw Tolerant Safe-Life	Testing with manufacturing defects + impacts at both BVID and CVID level
T/R Blade	Flaw Tolerant Safe-Life	Testing with manufacturing defects + impacts at both BVID and CVID level
T/R Hub	No crack growth	Analysis

T/R Elastomeric Bearing	No crack growth for metal Crack propagation for elastomer	Analysis + Testing Testing
T/R Blade Damper Attachment	No crack growth	Analysis + Testing
T/R Hub Damper Attachment	No crack growth	Analysis
T/R Elastomeric Damper	No crack growth + crack growth for metal Crack growth	Analysis Testing
Transmission cases	Flaw Tolerant Safe-Life	Testing
T/R Drive Shafts	No crack growth + Flaw Tolerant Safe-Life	Analysis
Main Gearbox Fittings + backup structure	No crack growth	Analysis
Main Gearbox Mounting Rods	No crack growth	Analysis
Anti-torque beam + backup structure	No crack growth	Analysis
T/R Gearbox Fitting	No crack growth	Analysis
Fin	No crack growth + crack growth	Analysis
Tail Cone	No crack growth + crack growth	Analysis
Tail/Rear Fuselage Attachments + backup structure	No crack growth + crack growth	Analysis
Engine Attachments + backup structure	No crack growth + crack growth	Analysis
Tailplane	Flaw Tolerant Safe-Life	Testing
Tailplane Attachment Fittings	No crack growth	Analysis

8.7 - EH101 and derivatives (Agusta Westland)

A new articulated tail rotor was developed improving durability, damage tolerance and performance. This will be certified as fully damage tolerant. The first flight was in December 2006 and the flight spectrum was already open for all relevant conditions of the civil usage.

As far as the VH71 helicopter is concerned, which is the EH101 derivative for the US President, a very demanding review of the Fatigue, Damage Tolerance, Flaw Tolerance and Fail Safe requirements and of the compliance methodologies followed by Agusta Westland was done with NAVAIR specialists for about 18 months, achieving recently a common agreement.
A preliminary fatigue life evaluation was done for the initial variant, which will fly this year.

8.8 - NH90 (Agusta Westland)

NH90 delivered production aircrafts for Troop Transport Helicopter variant.
Fatigue and damage tolerance evaluation were carried out for the transmission system for both General Electric and Rolls Royce engine variants, including extended All-Up-Weight at 11 tons and high cabin for Nordic variants. Fracture mechanics analysis was used for damage tolerance evaluation of the transmission assembly, except gears.
In most cases, no growth was proved for the standard crack size of 0.38 mm, according to flaw tolerant safe life.
Basic fatigue evaluation was issued for the Navy configuration Navy Frigate Helicopter.

8.9 - M-346 trainer (Alenia Aermacchi)

The M-346 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 has been designed according to damage tolerance principles, keeping also durability requirements into consideration during the fatigue design process.
In the last two years, durability and damage tolerance activities have covered the following issues:

1. Wing structure development fatigue test
2. Structural characterisation of a new design solution for the fin
3. Certification analysis activity: critical parts criteria identification, fatigue and DT substantiation, parts management

4. FCS actuators qualification

In addition, basic activities have just started to develop some of the processes that will be applied in the manufacturing of the M-346 series aircraft; those with grater impact on the fatigue behaviour are shot-peening and surface treatments, alternative to chromium and cadmium plating, since their application is being progressively reduced, due to environmental and health safety issues. In the following some information will be given about the points 2-4, while point 1 is treated in another chapter of the National Review.

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

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

The “building block approach test campaign” for this unconventional design reached its “stage III”.

Constant amplitude fatigue tests have been performed on single lap and scarf joint specimens (Figure 42 and Figure 43), with the objective of assessing both the fatigue life and the influence of damage (specific specimens containing 20%, 40% and 60% debonding were tested) on the fatigue strength.

Ageing effects due to exposure to an adverse environment (mainly hot/wet, salt fog) will also be evaluated.

The last (and more complex) tests of this activity will be a fin box rear fitting test (under a block spectrum, simulating also the aggressive environment effect) and the full scale fatigue and damage tolerance test of the complete fin. In this case the load spectrum will be a flight-by-flight spectrum, where also the dynamic loads will be included.

The fin box rear fitting test is going to start as soon as the conditioning treatment (in progress) of one of the 2 specimens will be completed. The test will be configured as a comparative investigation, with the aim to evaluate the fatigue and damage tolerance characteristics of the unconventional structure (metal to metal primary bonded joints and honeycomb full-depth) and the influence of an aggressive environment on its fatigue performance.

The experimental activity will terminate with the full scale fatigue test of the entire aircraft. During this test, also the fin structure will be certified.

8.9.2 – Structural certification analyses activity

The design spectrum is now being updated, on the basis of the results of the load survey activity performed by prototypes 1 and 2. The verification of the airframe will be iterated with the current data and the full scale fatigue test will be designed in order to verify the structure capability versus such new spectra. Fatigue and Damage Tolerance criteria are applied following the military international regulations.

8.9.3 – Systems qualification

The activity to qualify the fatigue sensitive parts of the systems has reached a considerable development phase.

The Nose Landing Gear nearly completed the safe life qualification (both numerical and experimental) while the Main Landing Gear will rapidly start the fatigue test.

Also the series Flight Control System primary and secondary actuators completed the analysis assessment and are going to be submitted to the test campaign. Some preliminary information on this activity was already included in the last National Review.

8.10 - M-311 program (Alenia Aermacchi)

The M-311 is a new derivative of the previous S-211 and features a revised aerodynamic configuration, strengthened structure, more powerful engine and a completely new avionics suite. The aerodynamic configuration has new wing tips and fences and fuselage ventral fins. Strengthened structures and landing gear will allow fatigue life extension to 15,000 flight hours and the maximum manoeuvre load factors are now in the range of +7g / -3.5 g at a clean take-off weight of 3,100 kg.

M-311 nearly completed the preliminary design definition; fatigue critical areas have been identified, that will be subjected to durability and damage tolerance evaluation, and the design fatigue spectra have been outlined (Fig. 44).

8.11 – SF-260 program (Alenia Aermacchi)

The SF-260 is the world's most successful modern screener and primary trainer. Some 27 different military customers have already bought 880 SF-260 in all variants. Recently, the Italian Air Force ordered its fourth batch of thirty SF-260EA, with an avionics configuration tailored to its specifications. The worldwide SF-260 fleet has accumulated over 1,800,000 flight hours.

Main fatigue activities for this program have been related to the fatigue life qualification of SF-260EA.

(a) Assessment of Cold Working influence

A test campaign has been conducted to evaluate the influence of cold working on the life of the main spar of the aircraft. The joint between the lower cap and the corresponding plate has been tested with different levels of cold working and mean life curve have been extracted, that are reported in fig. 45.

The material of the two jointed parts is 2024, in different thickness (and heat treatment); within the present activity, two expansion levels have been assessed: 2.5 and 3.3 %.

(b) Wing attachment fatigue test

In order to qualify the fatigue life of the wing in the area between y=-500 and y=500 (i.e. internal to the fuselage), a subcomponent fatigue test has been performed (Figure 46). The design test spectrum has been applied in the form of a random time history.

8.12 - Tornado ageing structure activities (Alenia Turin)

In a previous paragraph of this Review, information has been given with respect to the extension of the operative life of the Tornado aircraft. In such conditions, corrosion becomes a very important issue, as well as its implications or interactions with fatigue phenomena. In Alenia Turin, two research activities started to assess the behaviour of some Tornado critical areas with respect to such issues:

a) behaviour of structures corroded and repaired;

An activity focused on modelling corroded structures has started; some preliminary results are available, showing:

- An example analysis on the stress distribution in a corroded area has shown a stress increase of about 18% compared to a stress increase of 25% calculated simply on the basis of the thickness reduction; this is a consequence of the stress redistribution in a multiple load path structure;
- Adopting the stress increase of 18%, instead of the 25%, the severity of the fatigue penalties decrease of about 26%

Next steps will be

- FEM analysis validation by means of local stress measurements in static tests
- Definition of fatigue methods tuned for different geometries, spectra and stress levels

b) change of fatigue properties of items with un-removed corrosion

The investigated area is the so-called diffusion member, in the wing attachment area. FEM modelling started, including also the simulation of the corrosion effects (from the point of view of geometrical changes and material property changes). Next steps will be:

- Perform comparative tests between corroded and un corroded coupons to identify fatigue performances degradations in presence of corrosion
- Calculation of stress levels for different locations with corroded and un corroded material
- Calculation of spectra for different selected locations
- Fatigue calculations for corroded material
- Identification of allowable corrosion levels
- Identification of a standard inspection procedure to determine corrosion extension and depth

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

9.1 - Thermal Stress Analysis (TSA) applied to composite materials (Agusta Westland)

Thermal stress analysis (TSA) is now a consolidated tool, commonly applied during Full Scale laboratory tests especially on complex components to obtain information on particular areas difficult to instrument with more conventional systems. (A similar contribution was reported also in the last National Review).

TSA is based on the thermo elastic effect, according to which the material cools down or warms up like a gas as an effect of its volumetric changes. The technique became very attractive for fatigue research and experiments when the progress allowed to be associated with very high resolution infrared cameras and acquisition software able to lock in the acquisition to the specific point of the cyclic loading. Research activities are currently performed to try to extend the use of this technique to the composite materials (Figs. 47).

This activity was carried out at Agusta Westland, in cooperation with Milan Polytechnic, and came to the conclusion that the application to composite materials is feasible on one side, but needs a much more extended data base relevant to the thermo elastic constants at the specific frequency which is used.

10. REFERENCES

[1] L. Boni, A. Lanciotti, C. Polese "Fatigue and Crack propagation in Open Hole Specimens with Cold Worked Holes", 24th ICAF Symposium, 16-18 May 2007 Naples, Italy.

[2] A. Lanciotti, L.Boni, C. Polese: "Fatigue Resistance of Riveted Joints with Cold Worked Holes", Document of the Department of Aerospace Engineering DDIA 2006-14, June 2006.

[3] L. Boni, A. Lanciotti, C. Polese: "Numerical and experimental assessment of fatigue behaviour of "cold worked" open holes", Invited Lecture at the 17° Italian ABAQUS Users' Meeting, October 04-06 2006, Pisa – Italy.

[4] L. Boni, R. Gonella, F. Pietra, C. Polese: "Numerical simulations and experimental evaluations of some technological processes employed to improve the fatigue resistance of stressed holes", TCN-CAE 2005, International Conference on CAE and Computational Technologies for Industry, 5-8 October 2005, Lecce, Italy.

[5] F. Franchini, F. Pietra, C. Polese, S. Urso Sculco: "Chaboche Material Model Optimization for Evaluation of Residual Stress Field in Cold Worked Holes", International ModeFRONTIER Users' Meeting, 28-29 September 2006, Trieste, Italy.

[6] A. Lanciotti, F. Nigro, C. Polese "Damage Tolerance evaluation of the wing to fuselage connection of the new trainer aircraft M346". Fatigue and Fracture of Engineering Materials and Structures, vol. 29, pp 1000-1009, October 2006

[7] U. Mariani and M. Vicario: 'Flaw Tolerance Substantiation of Rotorcraft for Civil Certification', ICAF Symposium 2005.

[8] U. Mariani and M. Vicario: 'Application of Flaw Tolerance Methodologies to Rotorcraft Fatigue Qualification', European Rotorcraft Forum 2005.

[9] M. Giglio, S. Beretta, G. Ratti, U. Mariani, M. Ciprandi: 'Evaluation of Fatigue Threshold of Metallic Materials With Cracks', Aerospace Testing Expo 2006.

[10] M. Chiarelli, A. Lanciotti, L. Lazzeri: "Fatigue behaviour of metallic lap joints: a study on the effect of riveting and of specimen geometry", ICAF Symposium, Bellevue (USA), 1999

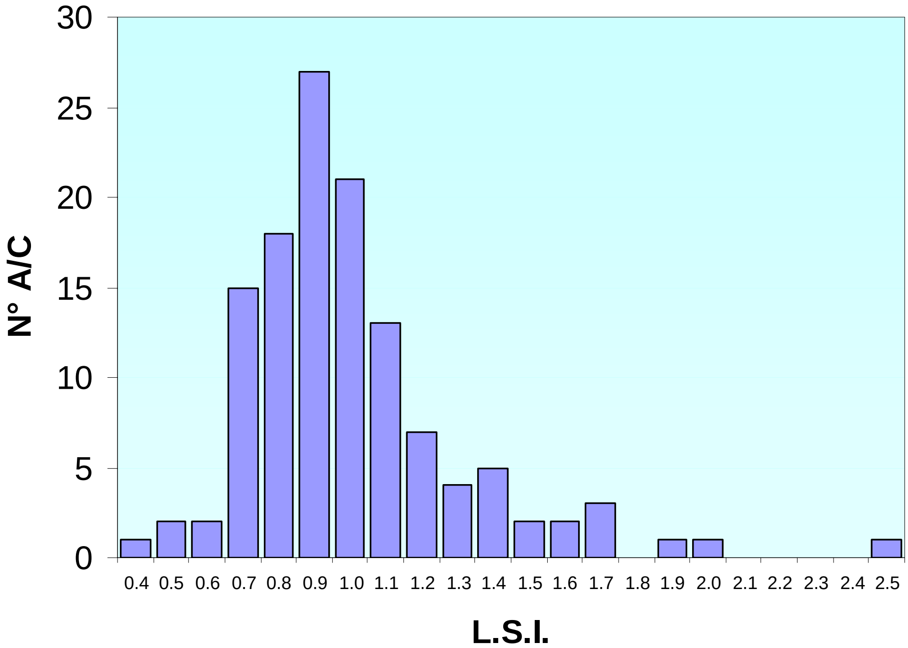

Fig. 1 – Load Severity Index distribution for the AM-X fleet.

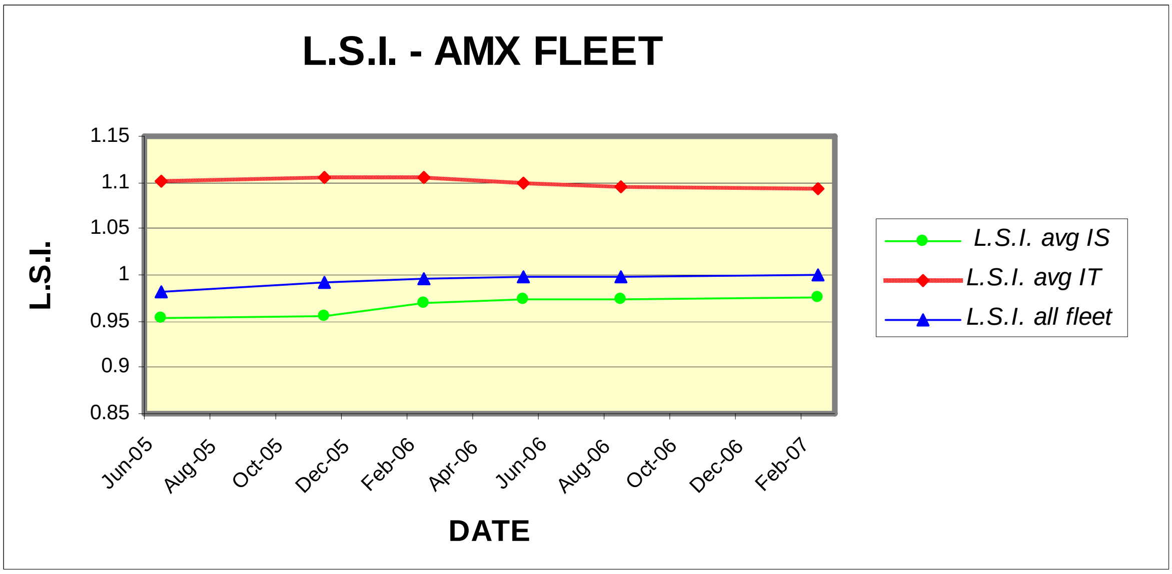

Fig. 2 – Trend of LSI relevant to the AM-X fleet

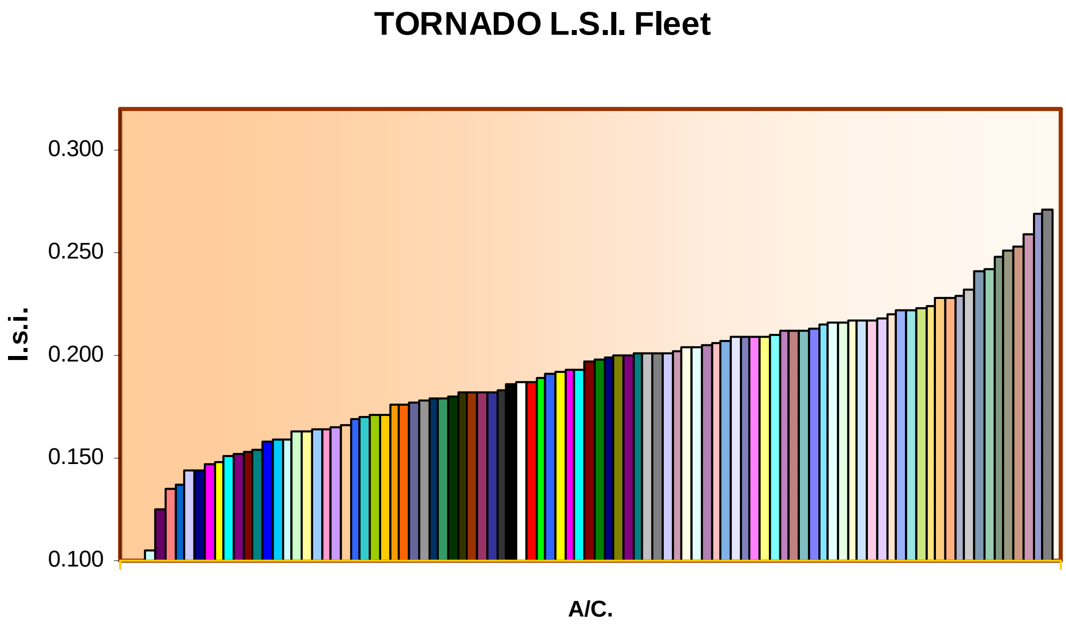

Fig. 3 - Load Severity Index distribution for the I.A.F. Tornado fleet.

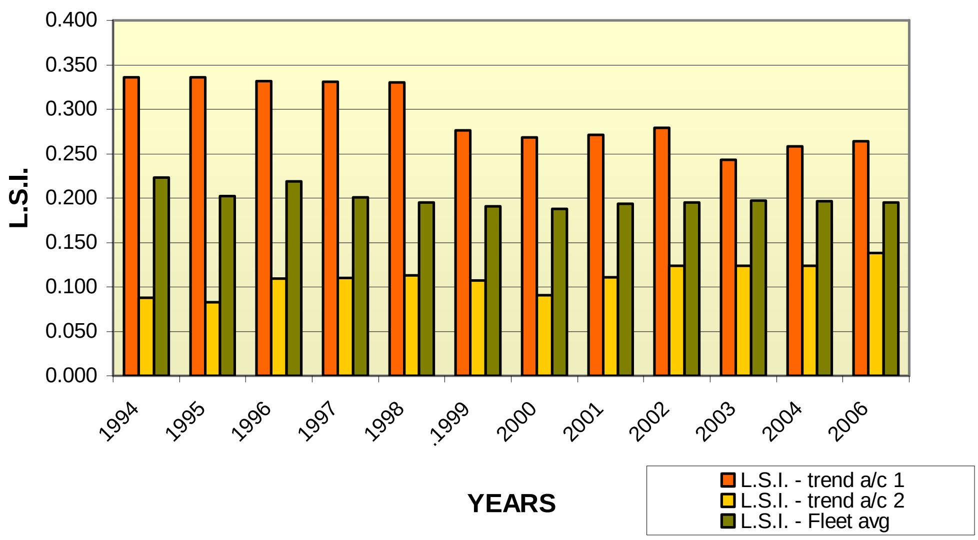

Fig. 4 - Examples of different fatigue consumption rates for individual Tornado aircraft.

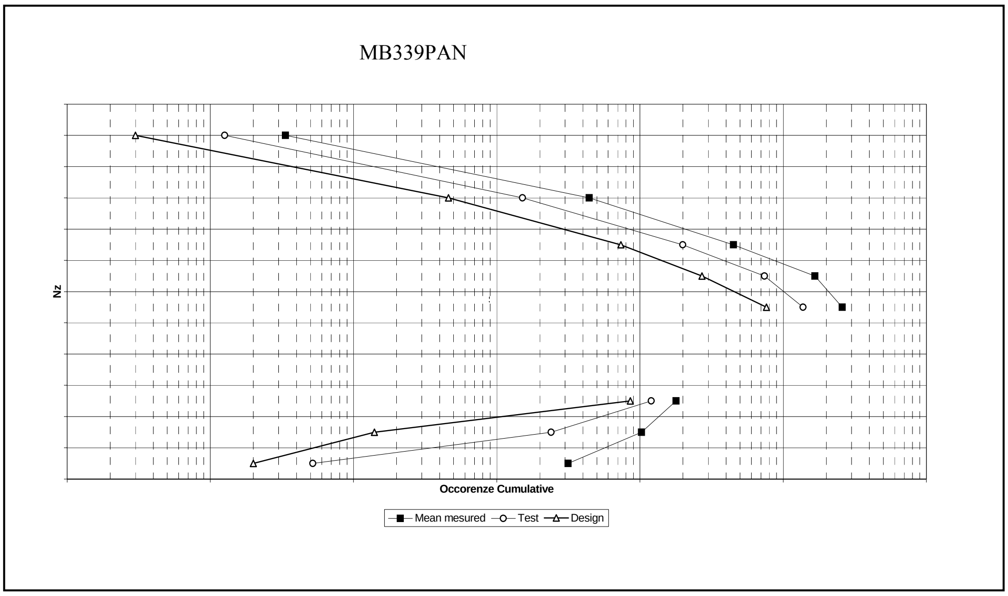

Fig. 5 - Spectrum of the MB339 operated by Italian Air Force aerobatic team.

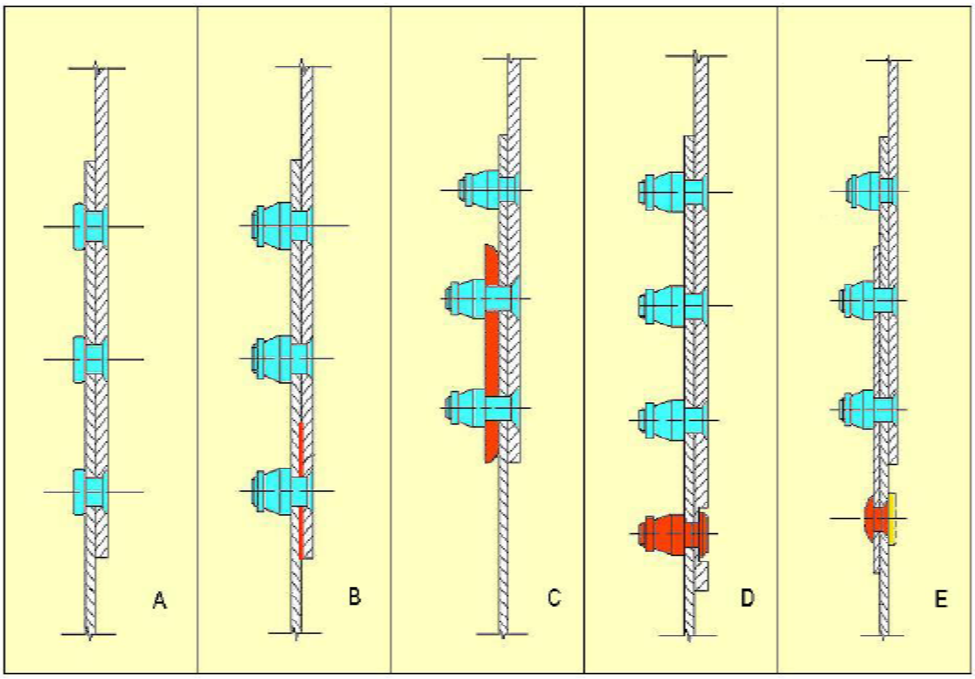

Fig. 6 - Sketch of the various riveted repair solutions evaluated.

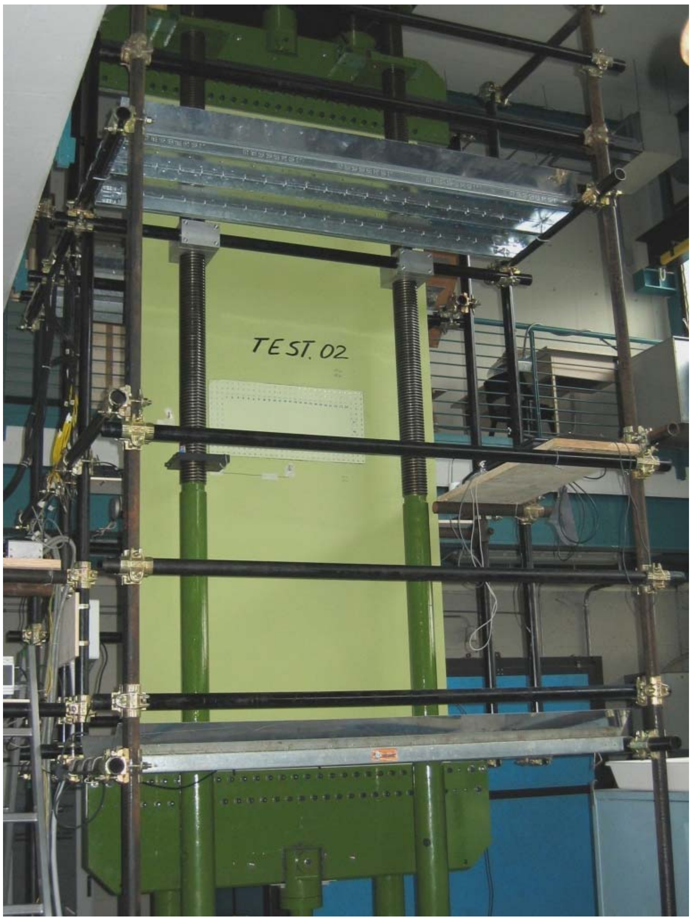

Fig. 7 - Test set-up for the fatigue test of IARCAS large flat panels.

Test Nr.	Solution	First crack
1	A, Base Line	110,000
5	A, Base Line	165,200
2	A, Base Line + FP	477,160
4	B, Hi-Loks + FP	350,000
8	B, Hi-Loks + FP	322,400
6	C, Support Doubler	59,300
3	C, Support Doubler	92,260
9	C, Support Doubler + FP	123,540
7	D, Counter Bore	95,030
10	E, Driven Rivet	452,410
11	E, Driven Rivet	470,870
12	Bonded	248,750

Table I – Results of the IARCAS Large Flat Panels fatigue tests

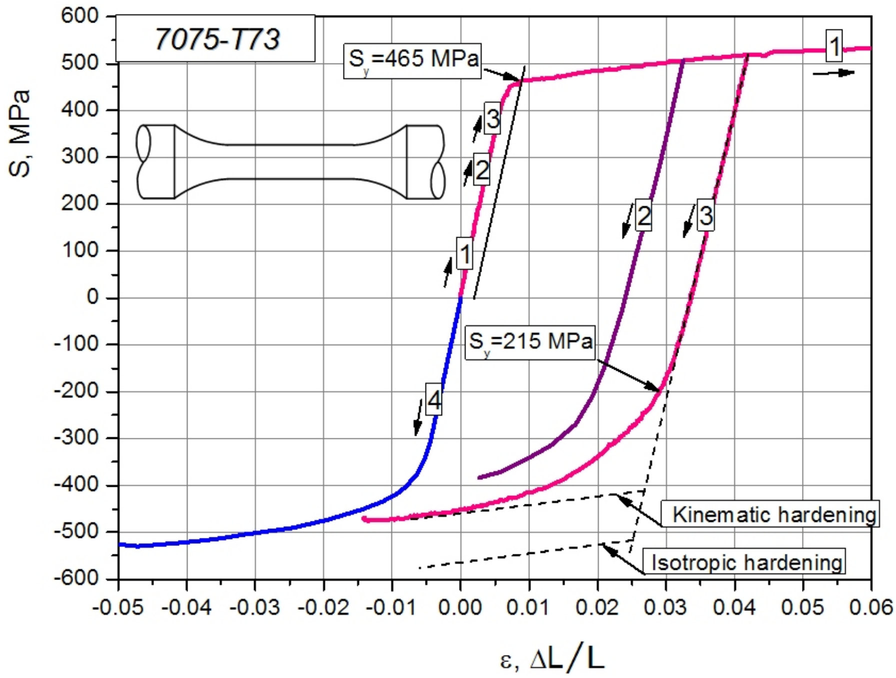

Fig. 8 – Experimental stress – strain curves of 7075-T73, obtained with four different histories, evidenced by the number. History 1 is monotonic tension, 4 is monotonic compression, 2 and 3 are tension-compression histories.

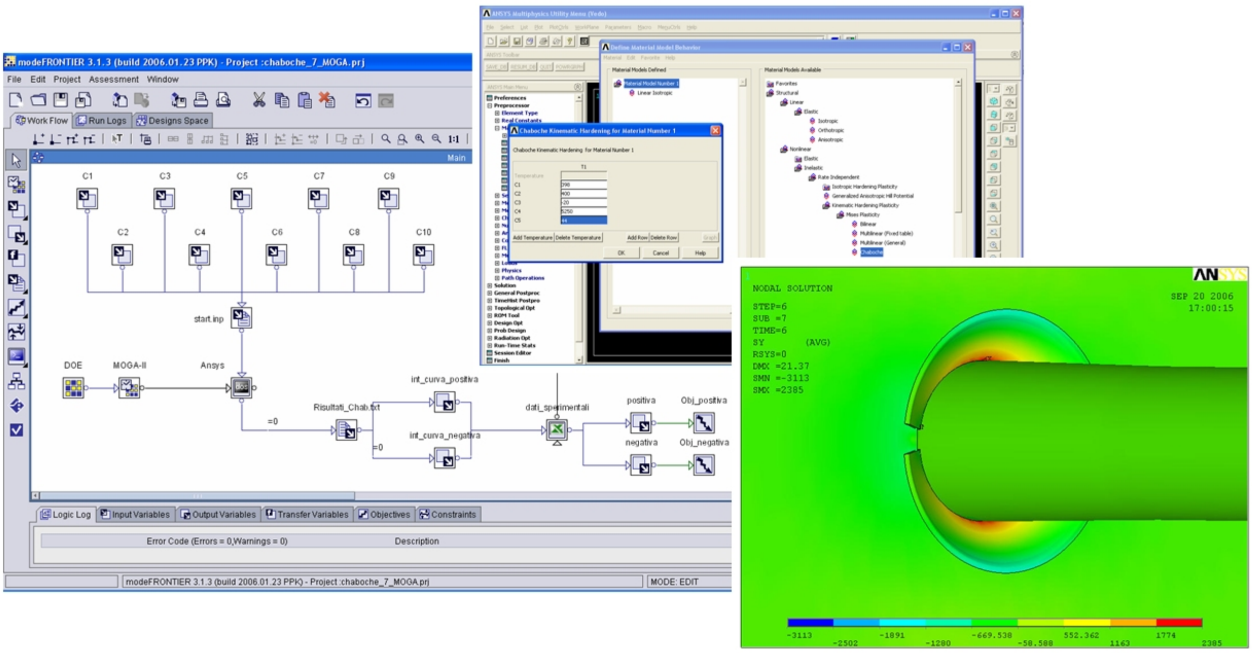

Fig. 9 – Mode Frontier optimized Chaboche Ansys model.

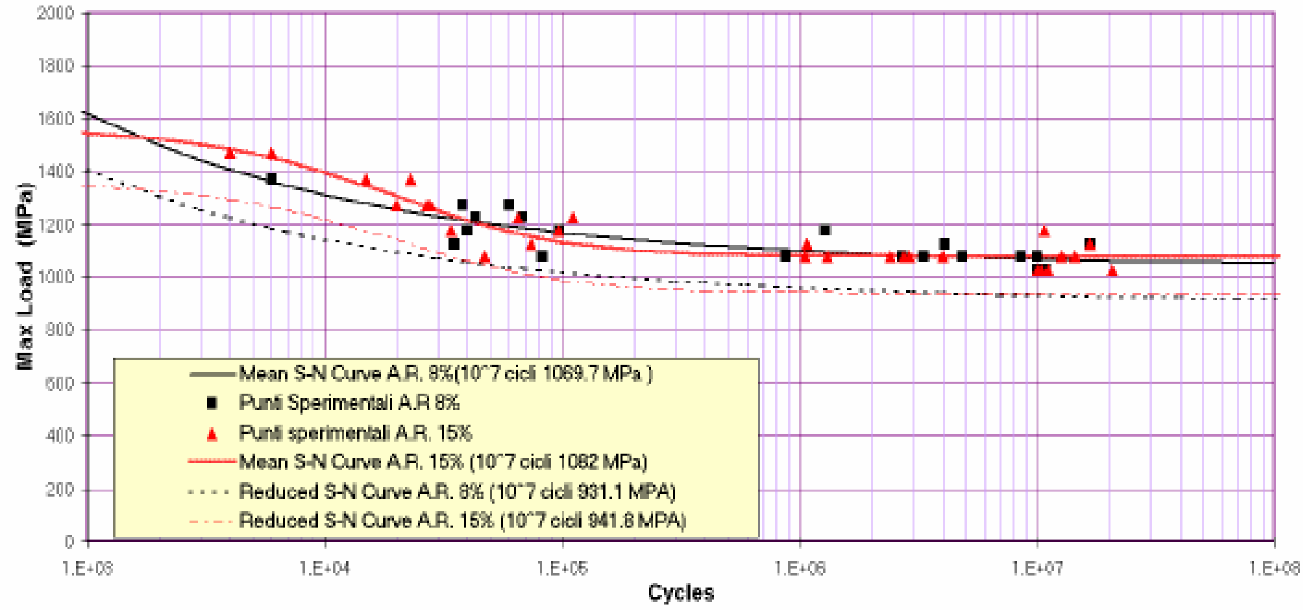

Fig. 10 - S-N curves of carburizing steel (AISI 9310 AMS6265-VIM+VAR) relevant to two different levels of Retained Austenite. Black squares represent specimens with 8% R.A. and red triangles represent specimens with 15% R.A. Tests were run in rotating bending with Kt=1 specimens.

Figure 11: High magnification metallographic cut section of a super finished surface. Steel AISI 9310 AMS6265-gas carburized

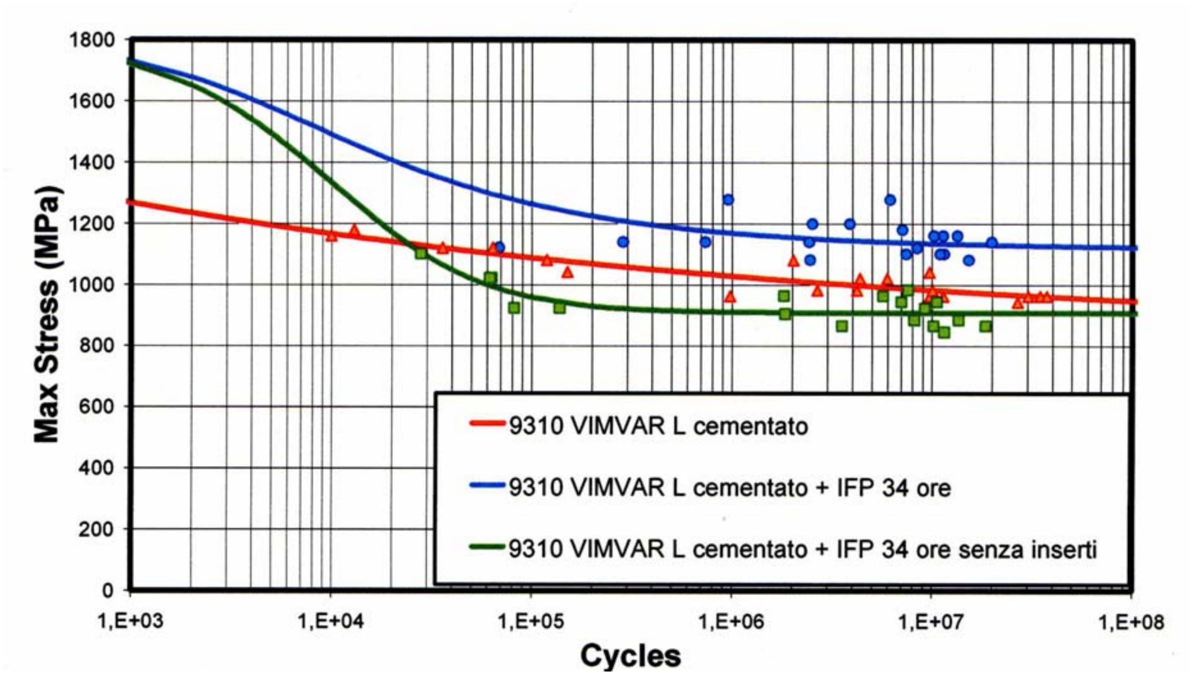

Fig. 12 - S-N curves of base carburized material (middle red curve), carburised and superfinished material (blue curve on top) and finally carburised and material subject to the chemical part only of the superfinishing process (bottom green line).

Fig. 13 - Failure in a gear tooth.

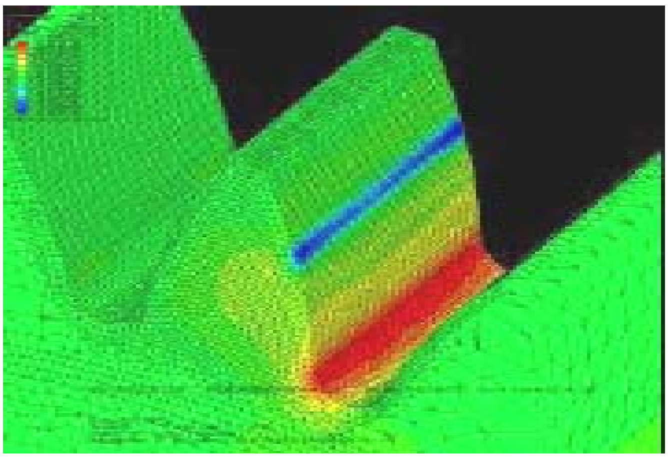

Fig. 14 - Finite Elements stress analysis of a gear tooth

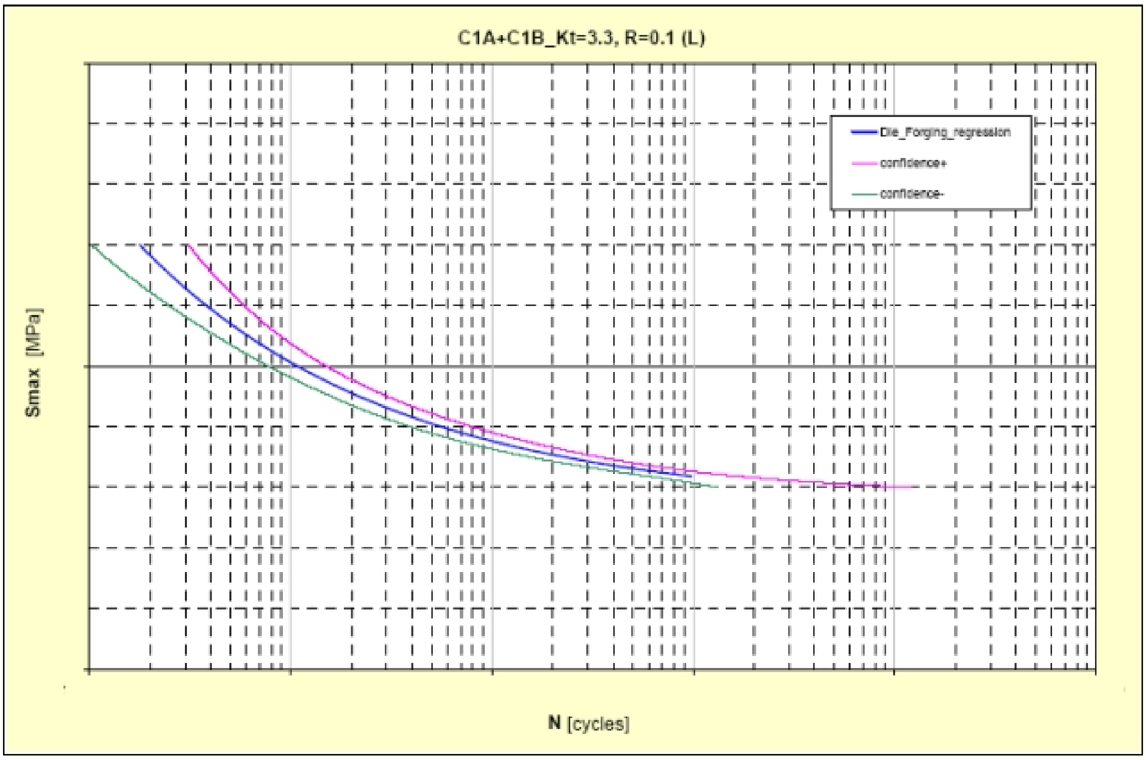

Fig. 15 - Fatigue test results from 7175 T7352 Die Forging

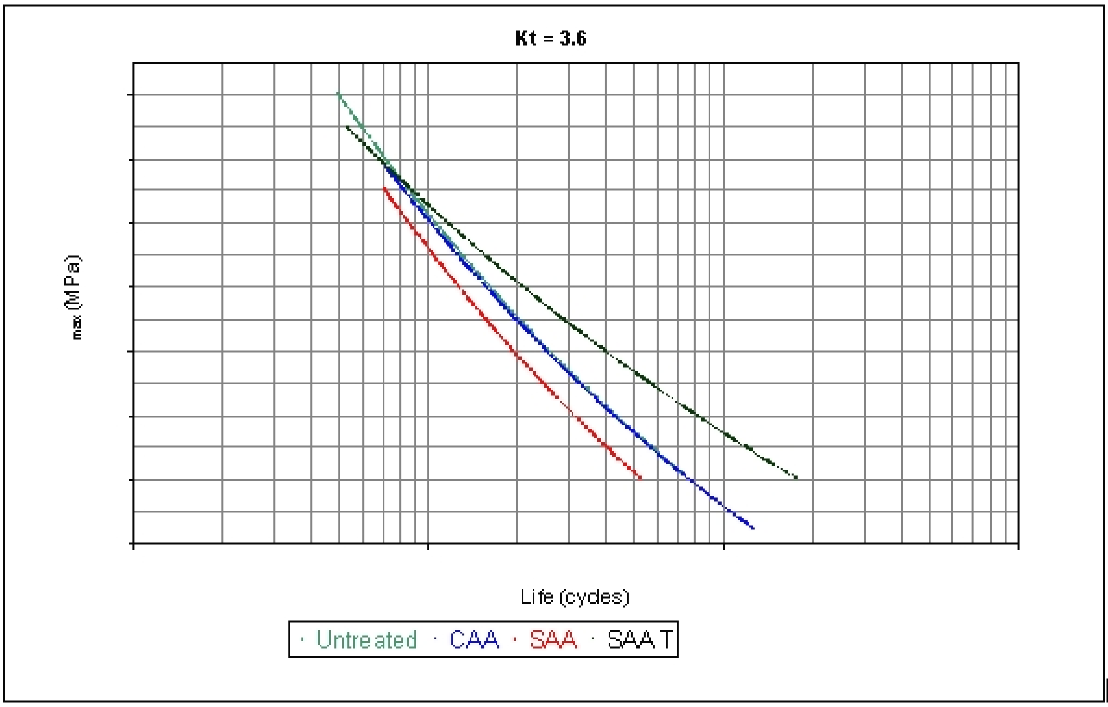

Fig. 16 - Comparison of various S-N curves relevant to 2219-T62 material

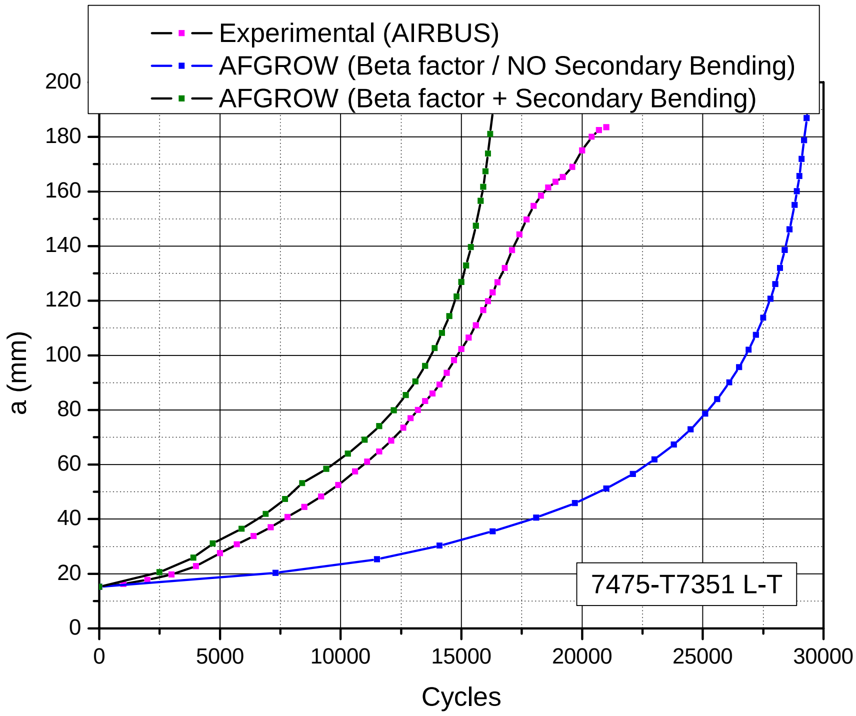

Fig. 17 – DaToN : comparison of predictions with test results for a 7-stringer HSM integral panel.

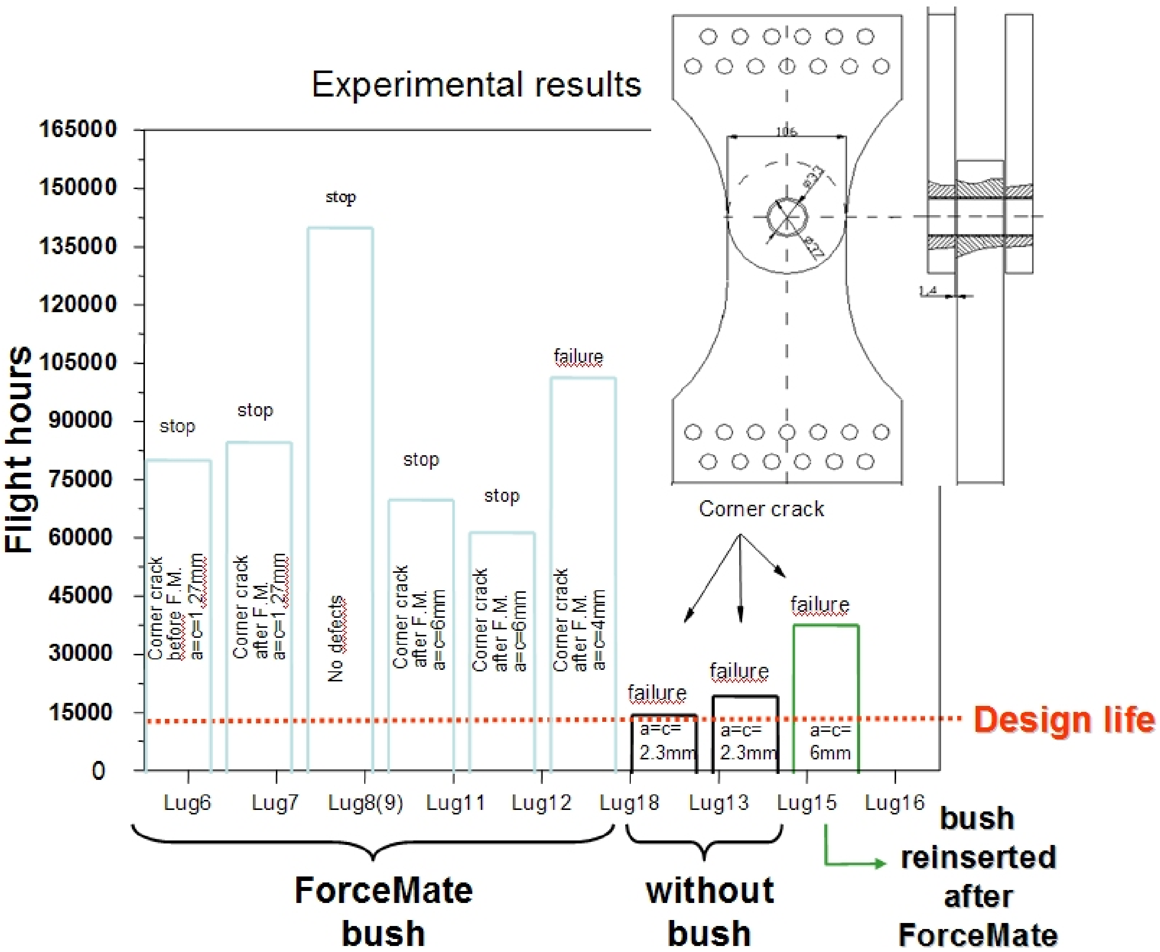

Fig. 18 - Results of variable amplitude loading tests carried out on lug specimens.

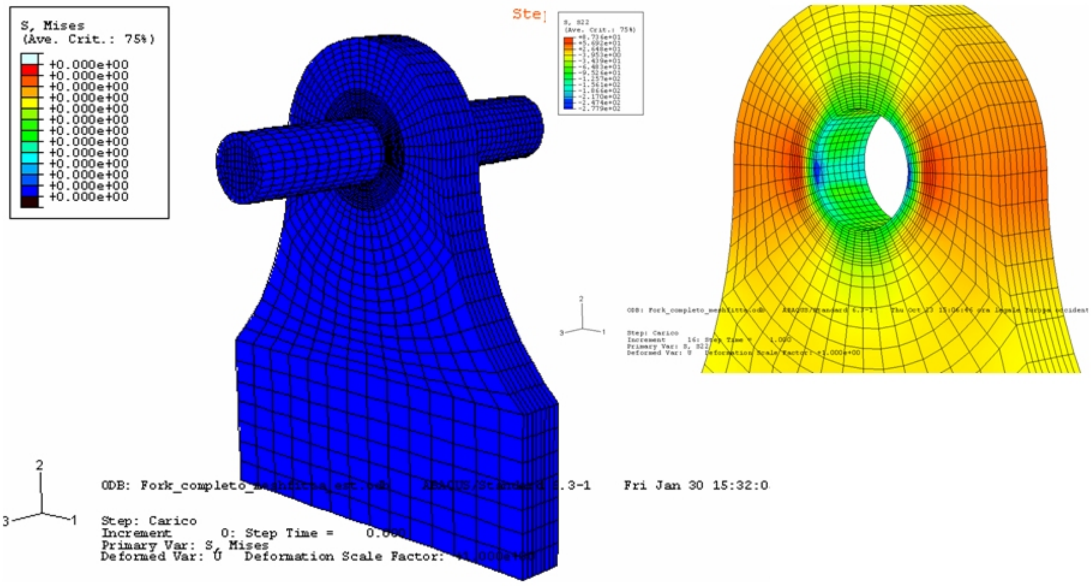

Fig. 19 - ABAQUS 3D FEM model of the ForceMate process.

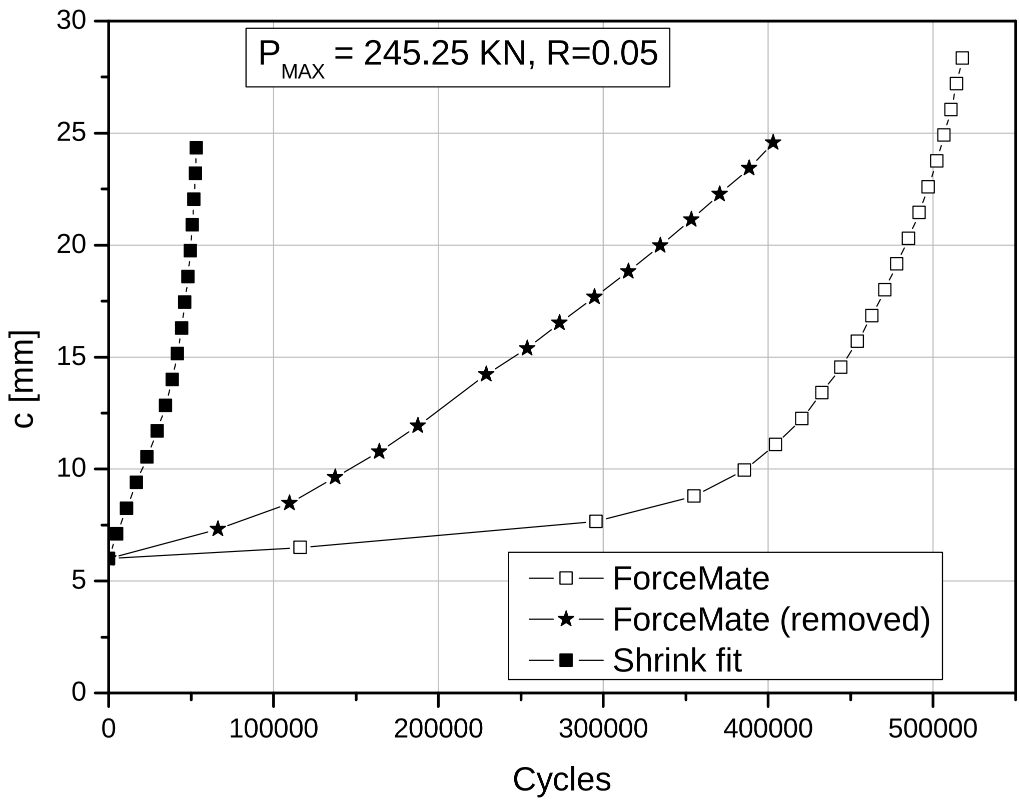

Fig. 20 - Crack propagation in lugs having shrink fit or ForceMate bushings.

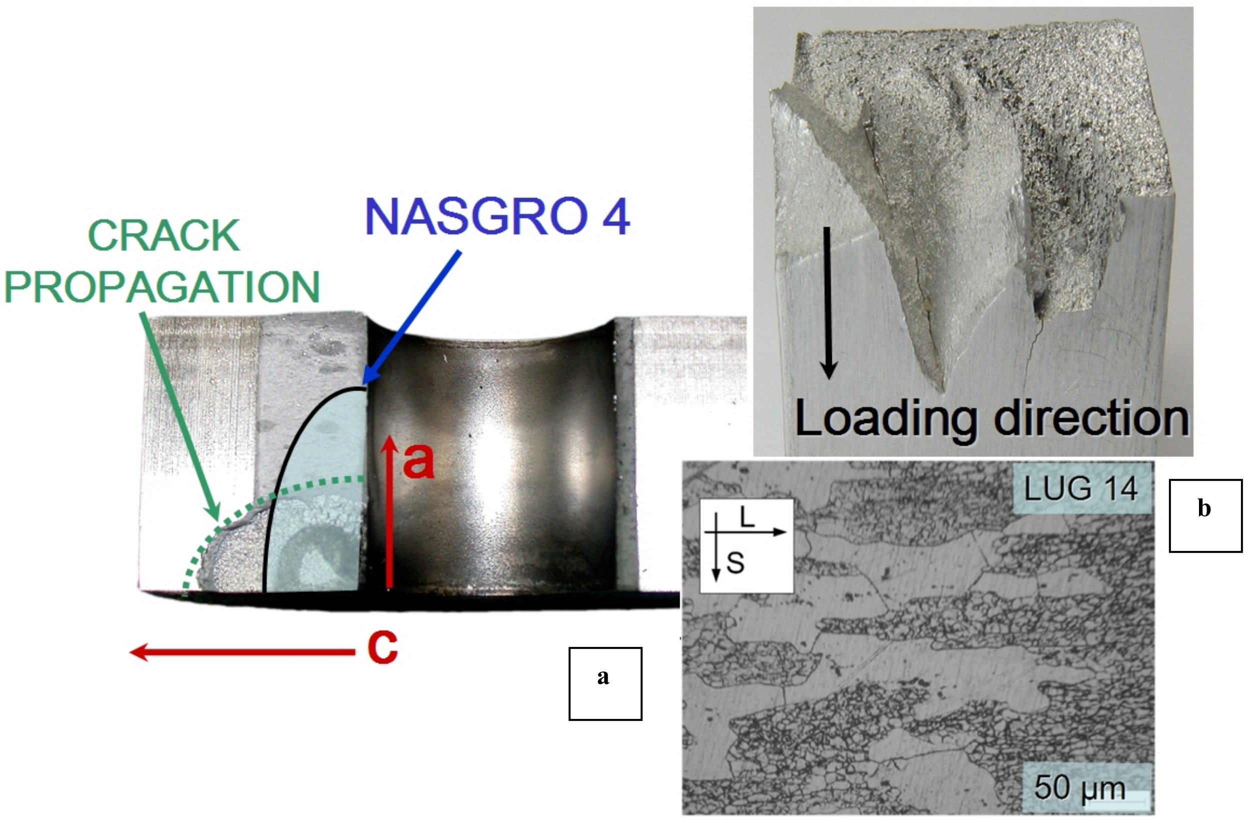

Fig. 21 - Anomalous crack propagation in thickness direction.

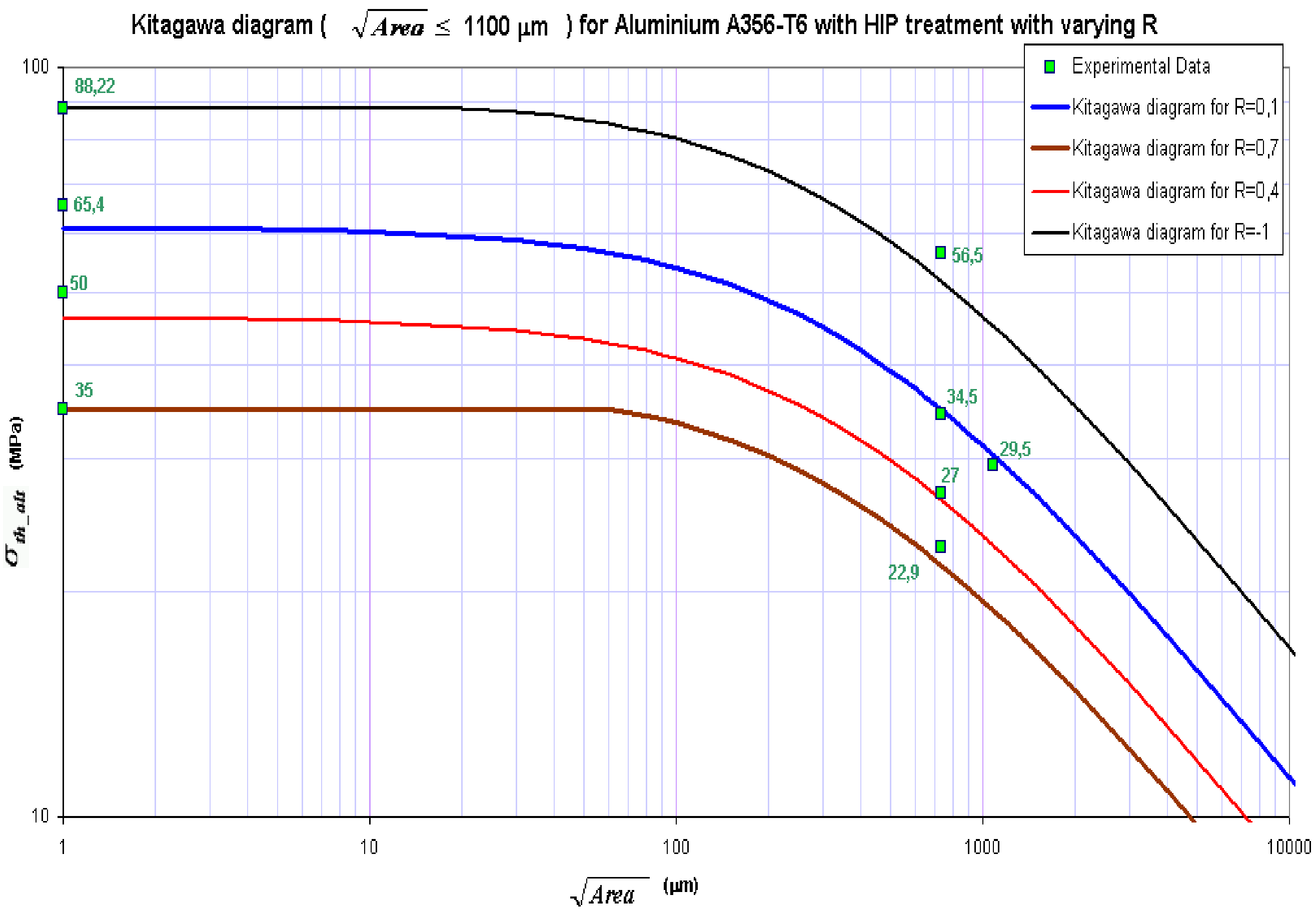

Fig. 22 - Kitagawa diagram for A356-T6, after HIP process, for various stress ratios.

Grade	Sub	Prepreg thickness [mm]	Metal sheet: alloy & thickness [mm]	a [mm]	σ_{max} [Mpa]	R
Glare 3		0.125	2024-T3, 0.3	15, 30, 45	140	0.1
		0.125	7475-T761, 0.3	15, 30, 45	140	0.1
Glare 4	4A	0.125	2024-T3, 0.3	15, 30, 45	160	0.1

Table II – Standard Glare grades used in the fatigue crack growth tests and load conditions.

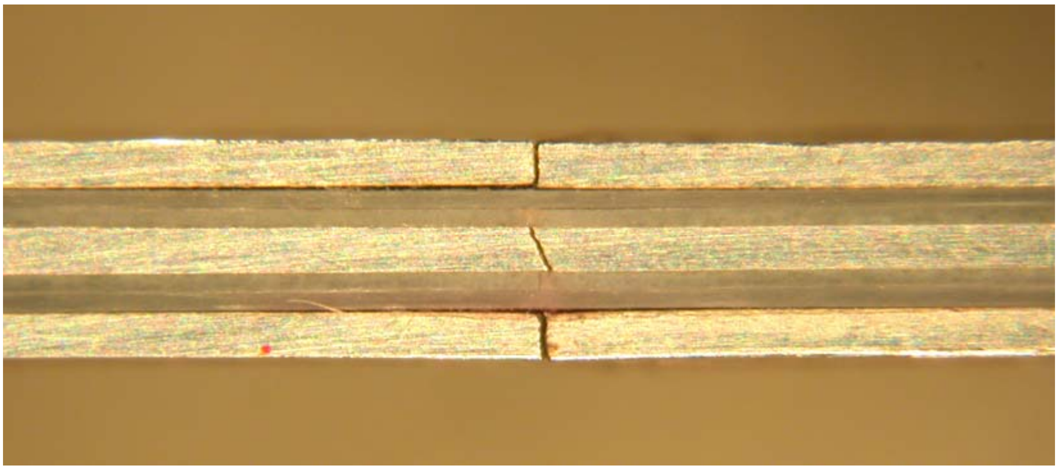

Fig. 23 - A microscope image of a cracked Glare3 strip

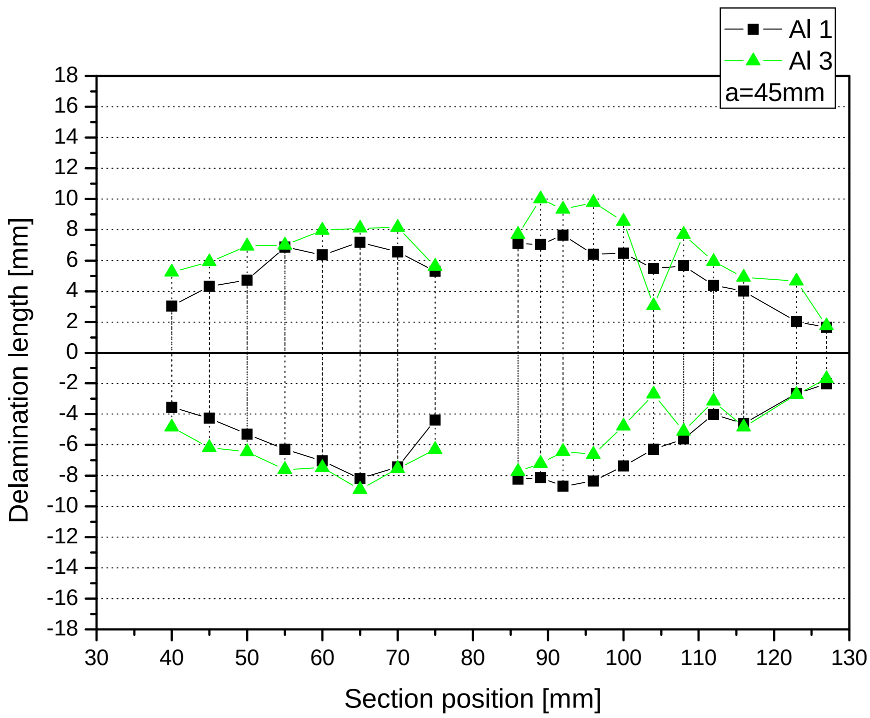

Fig. 24 - Delamination length vs. position on the specimen

(Glare 3 with 2024-T3, a=45 mm).

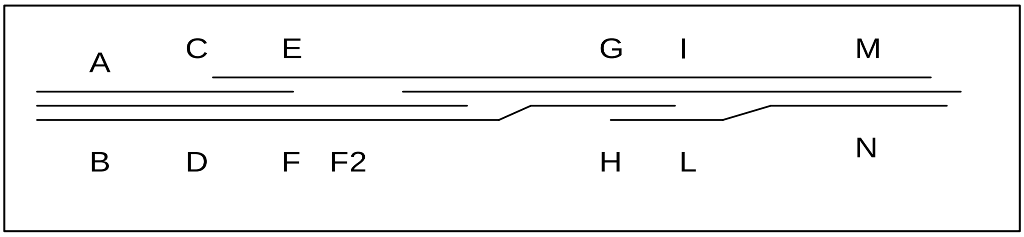

Fig. 25 - Sketch of the internal splice configuration.

Material System	A		B	
Specimen Type	Splice	Basic	Splice	Basic
Average	817.6	918.3	681.6	1066.9
St. Dev.	19.2	35.1	20.8	17.0
C. V. (%)	2.3	3.8	3.0	1.6
Joint efficiency	89%		64%	

Table III – Results of static tests on internal splice specimens, in terms of F/w (N/mm).

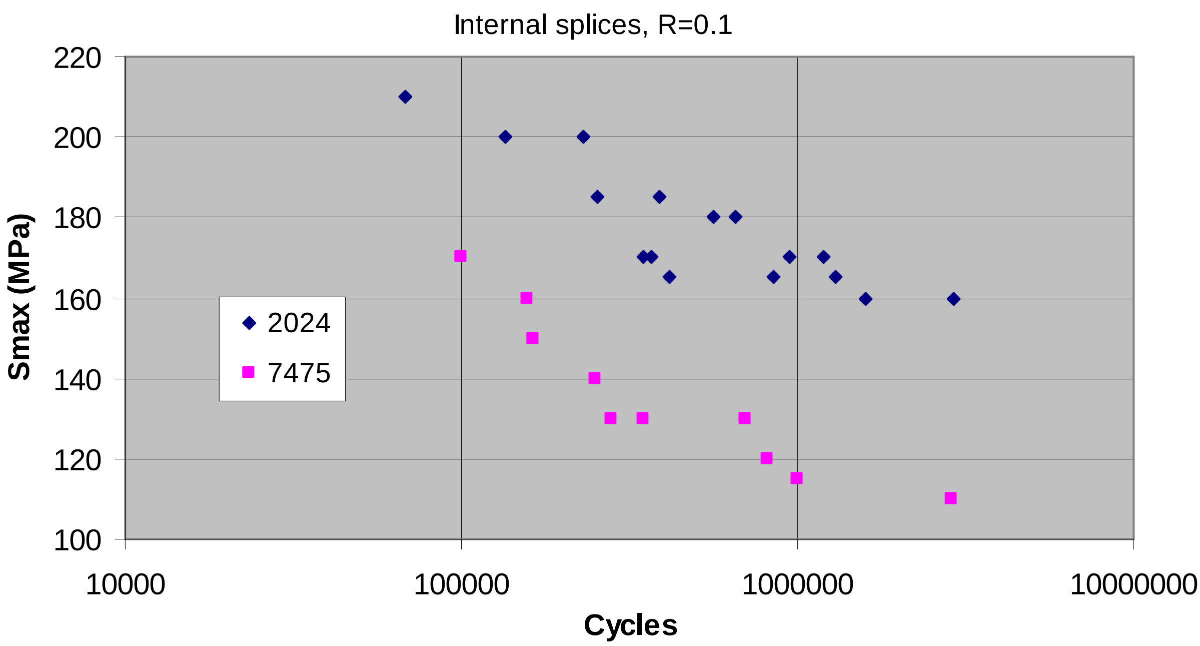

Fig. 26 - Results of fatigue tests on internal splice specimens.

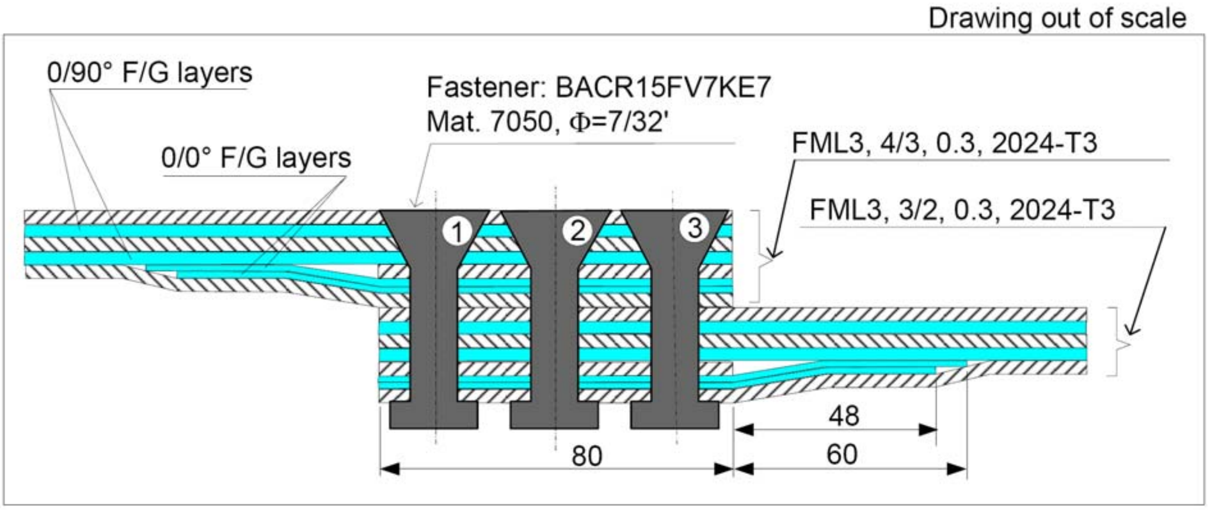

Fig. 27 - Schematic representation of the LAP1 joint specimen.

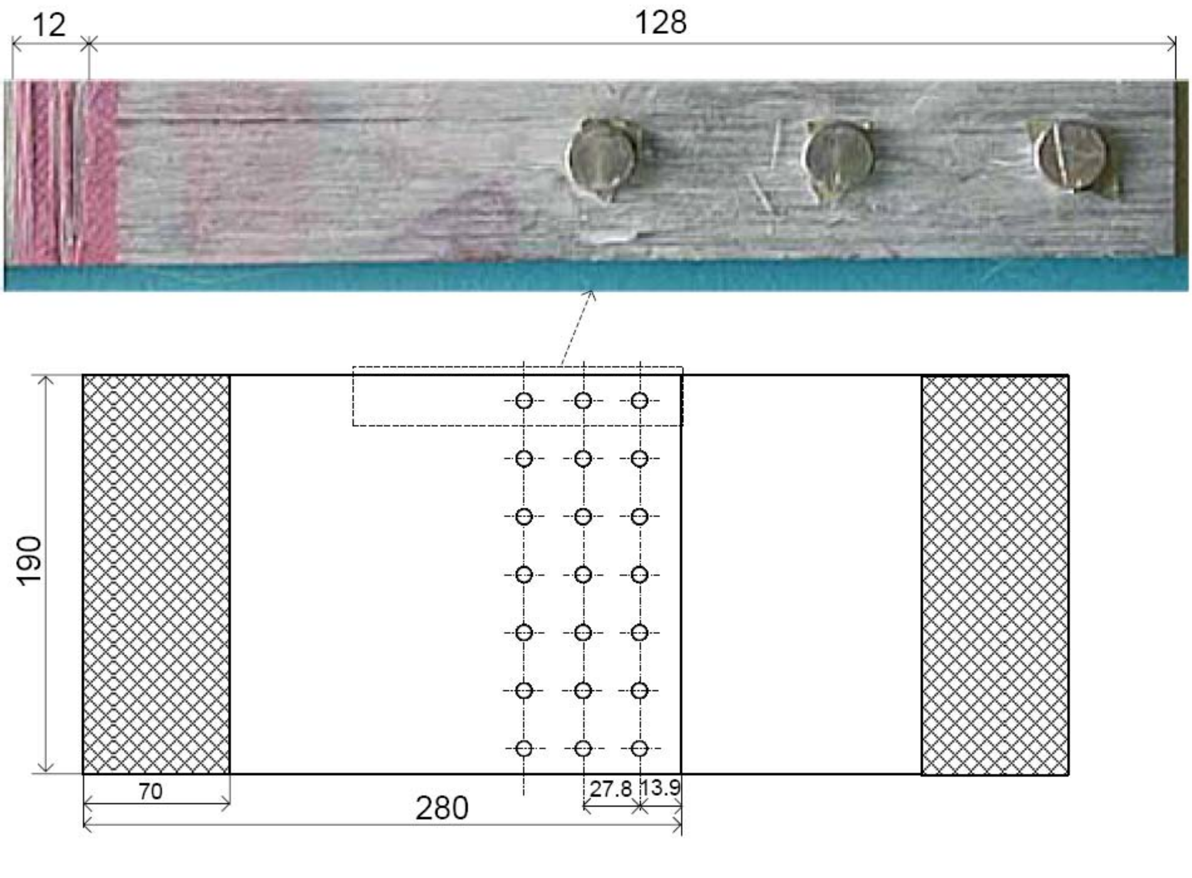

Fig. 28 - Dimensions of the 3 rivet rows lap joint

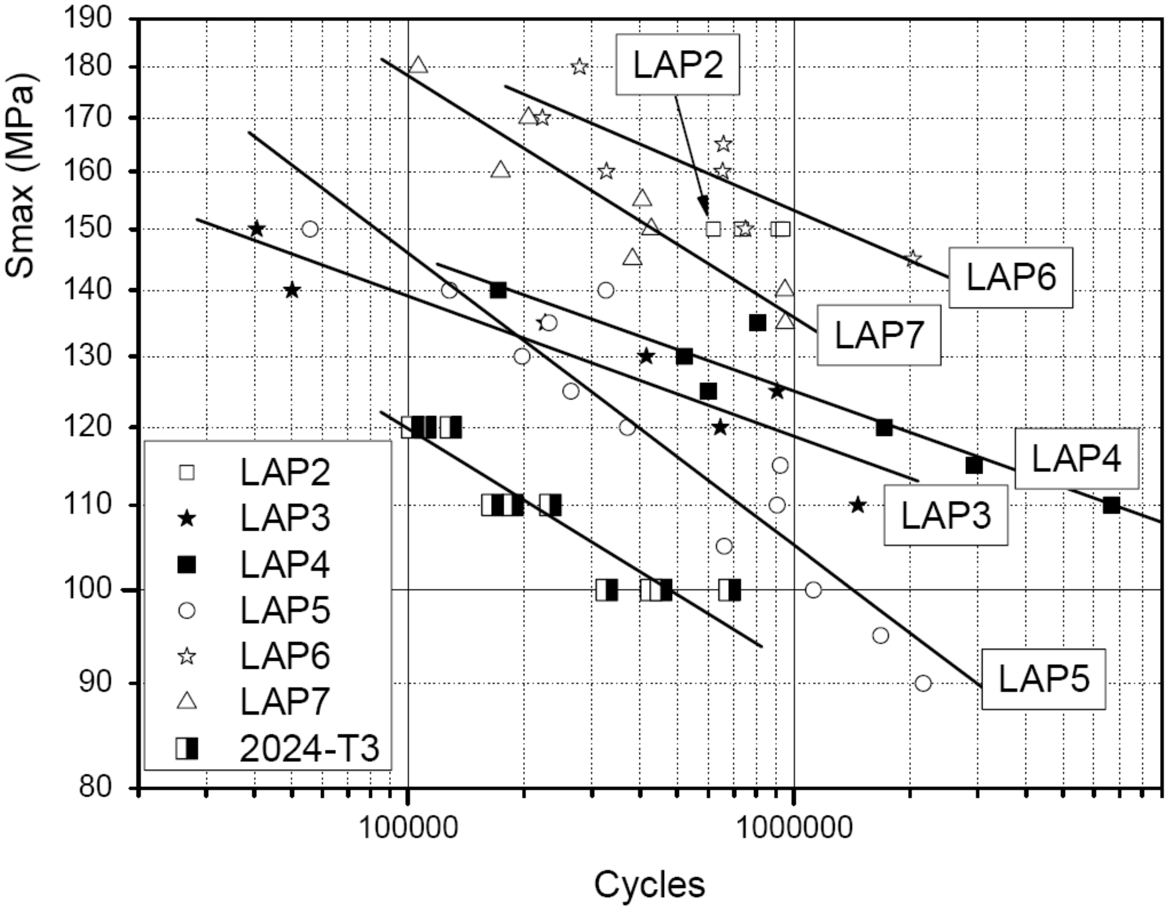

Fig. 29 – Fatigue test results of various riveted lap joint configurations (R=0.1)

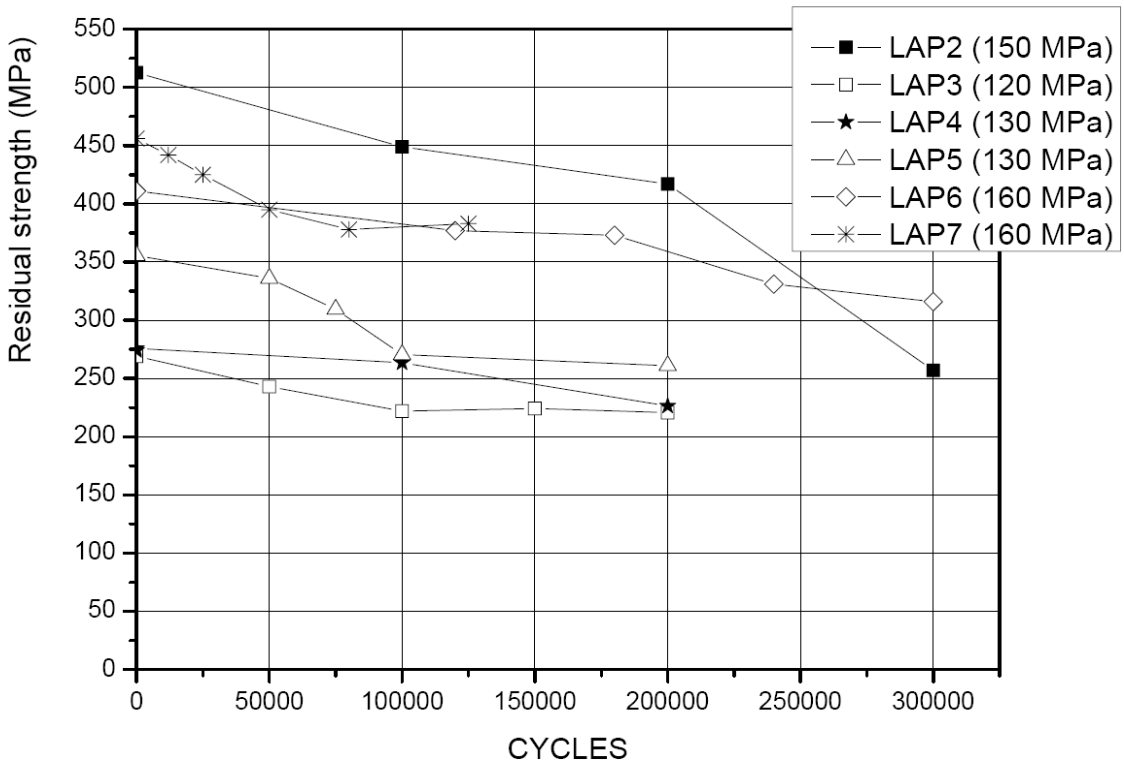

Fig. 30 – Residual strength decay of various riveted joint configurations. The specimens were subjected to a CA fatigue loading with the Smax indicated in the legenda and stress ratio equal to 0.1.

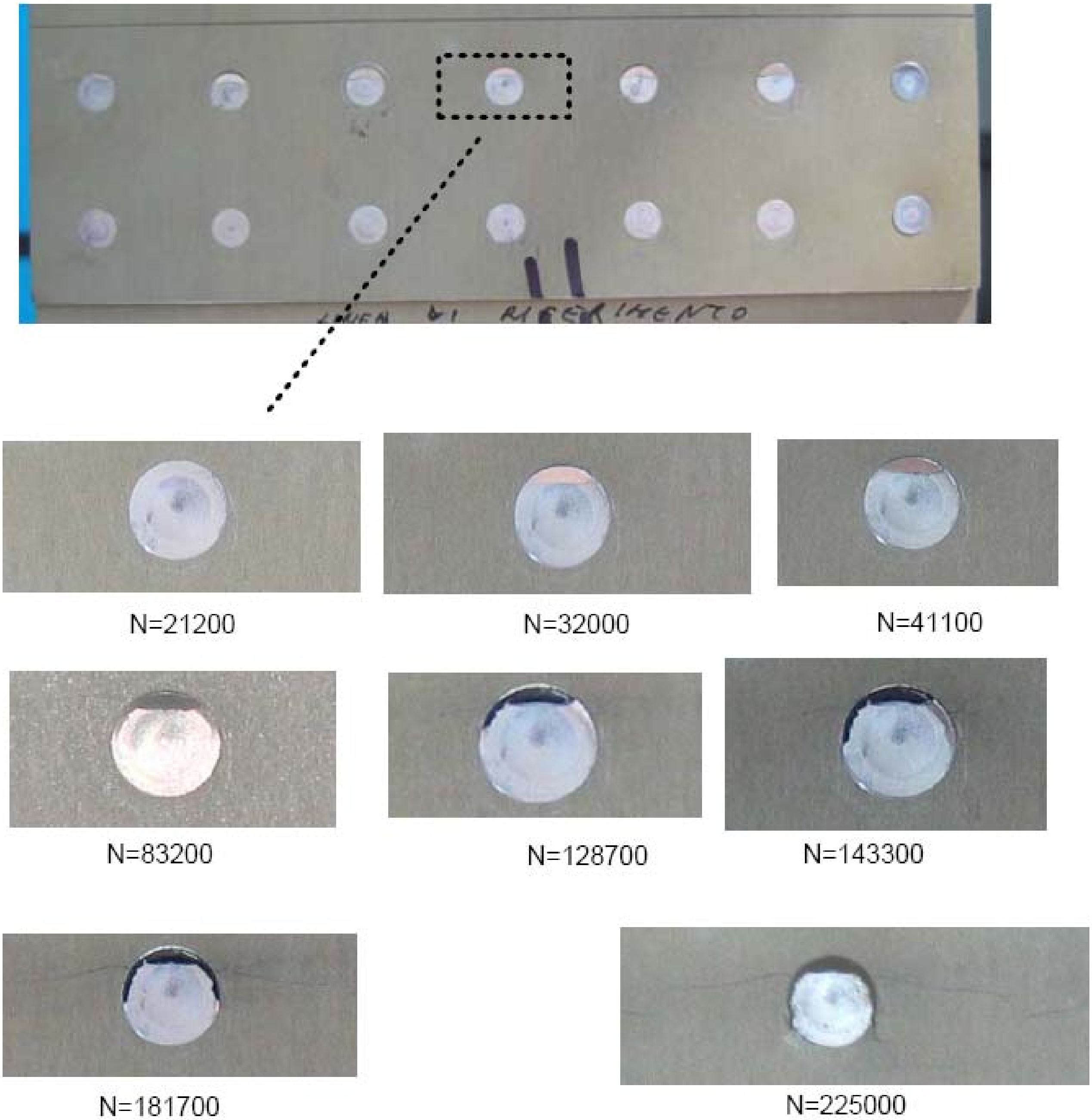

Fig. 31 – Fatigue damage evolution on the countersink rivet head in LAP3 specimens

	
Fig. 32 – Continuous FSW welded panel	**Fig. 33 – Step FSW welded panel**

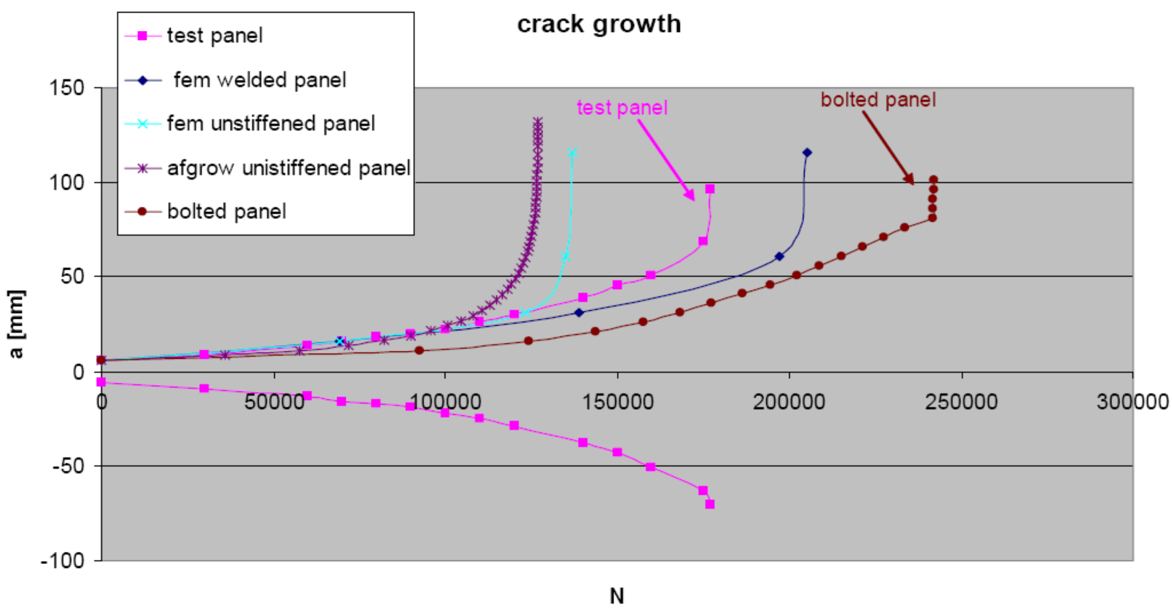

Fig. 34 - Fatigue crack growth in a FSW panel: test results and comparison with different types of predictions.

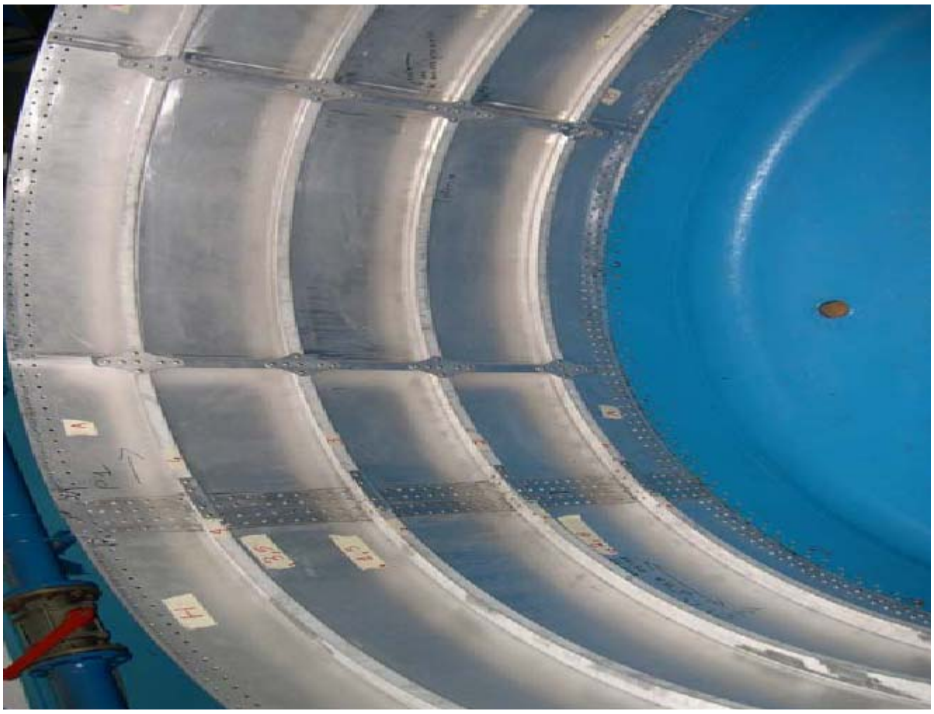

Fig. 35 - Detail of a FSW barrel.

Fig. 36 - Evidence of welding run in and run out.

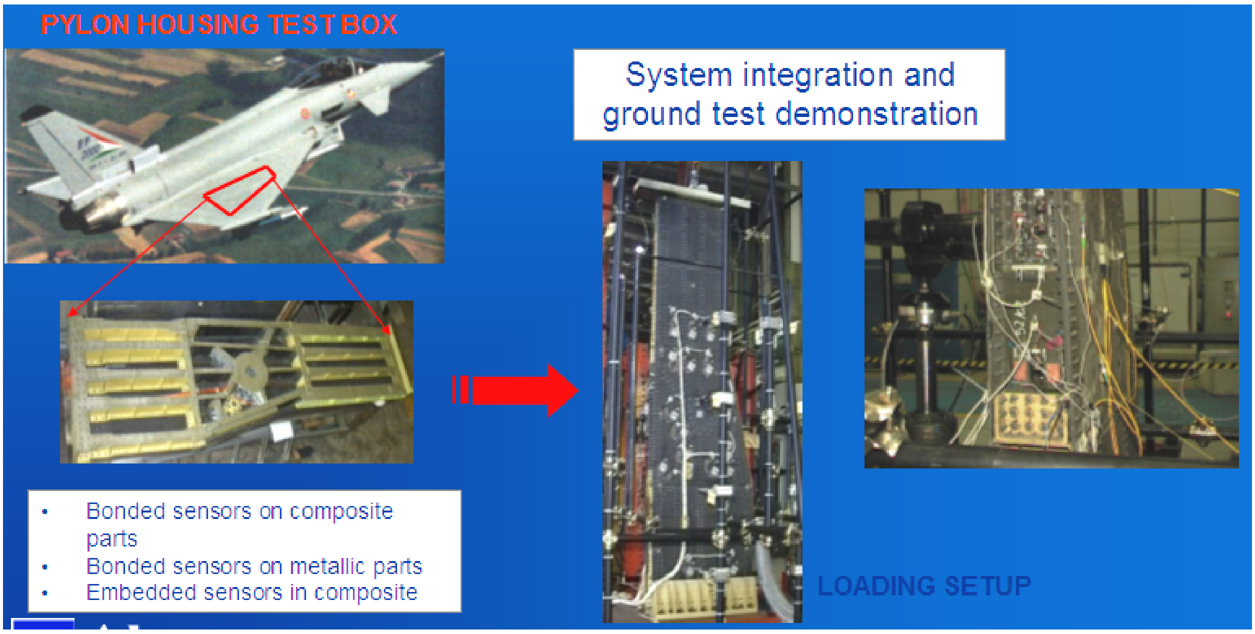

Fig. 37 - Instrumentation of an Eurofighter Outer Wing structure with FOBG sensors.

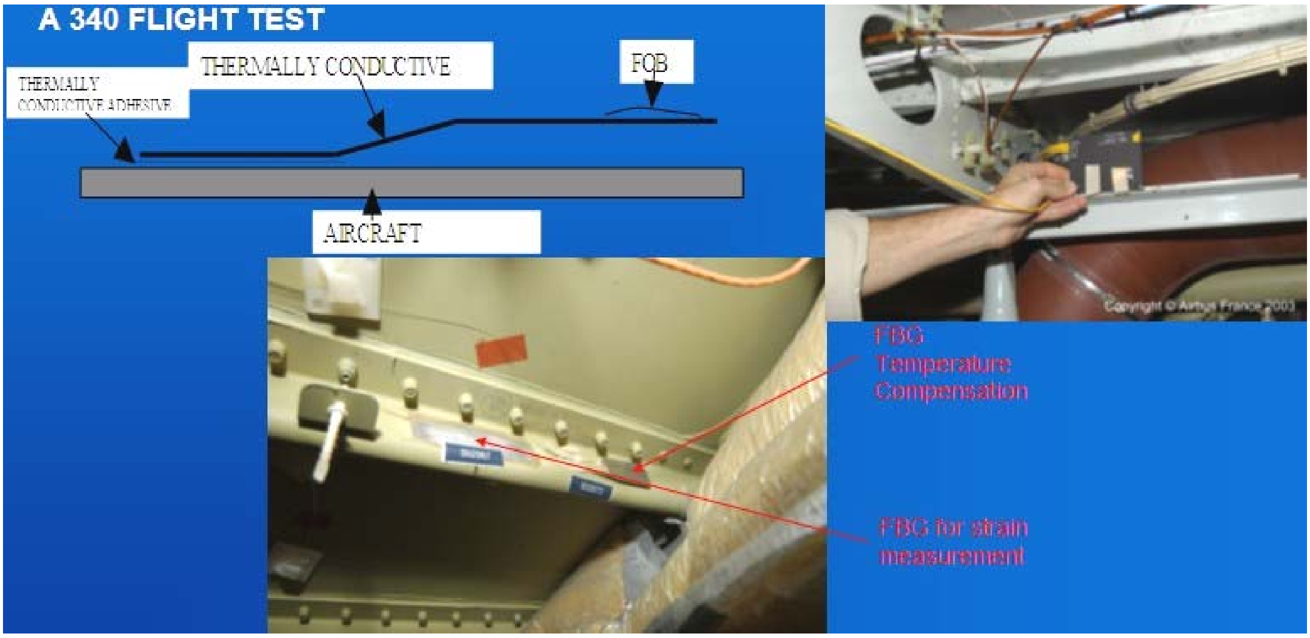

Fig. 38 - Instrumentation of an A340 Rear Fuselage structure with FOBG sensors

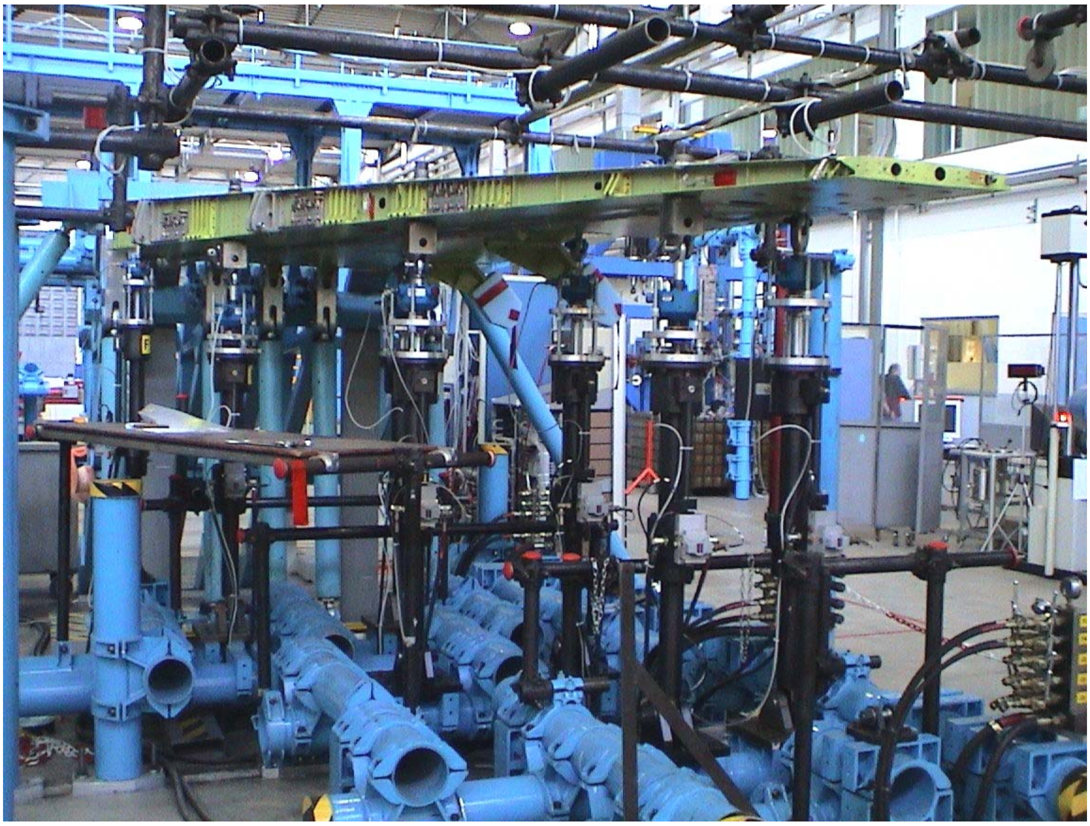

Fig. 39 - Development fatigue test of the LH wing of the M346 trainer.

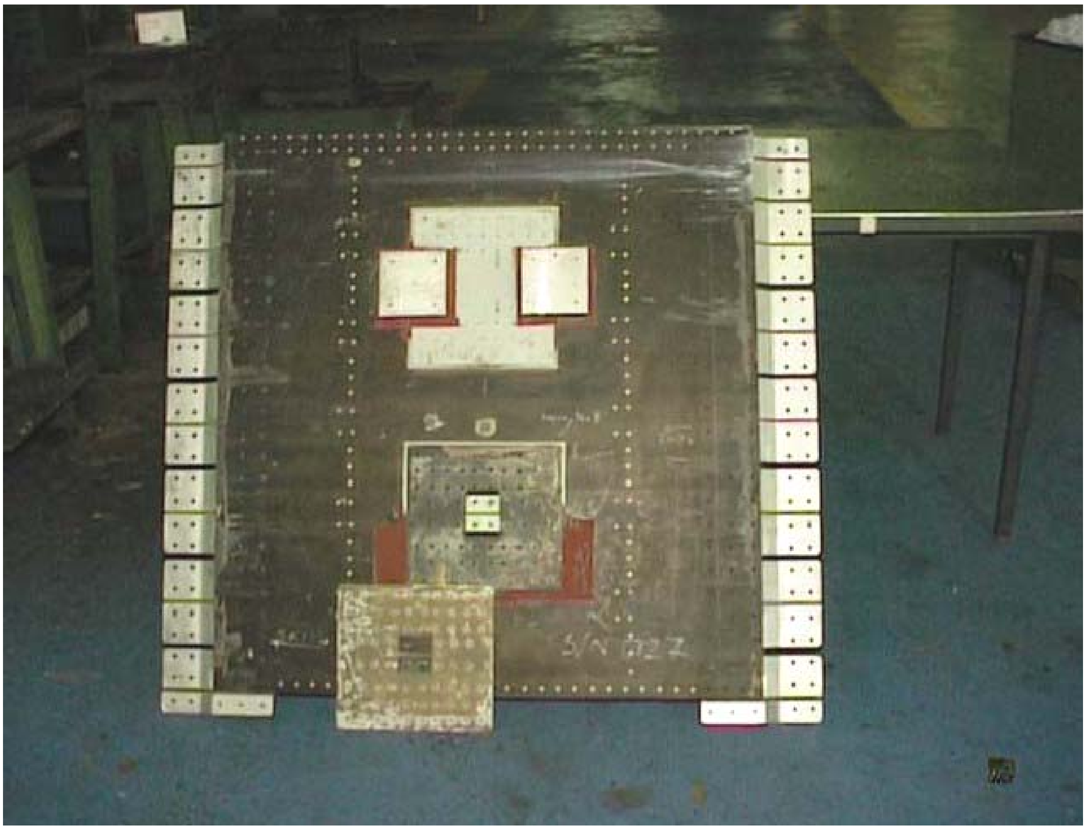

Fig. 40 - ATR 42 – ATR 72 Ageing program, test article for carbon/epoxy structure repair assessment

Fig. 41 – Detail of strain gauges installation in the B. 787 Horizontal Tail test article.

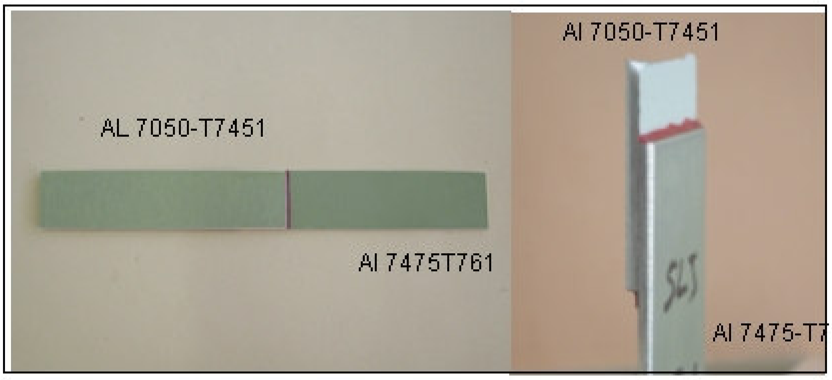

Fig. 42 - Bonded lap joint specimen of dissimilar materials.

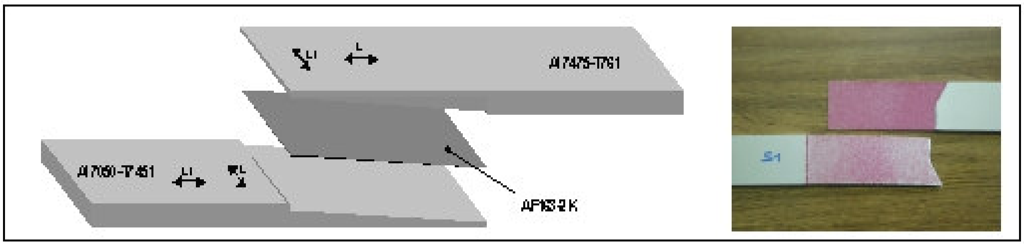

Fig. 43 - Scarf bonded joint.

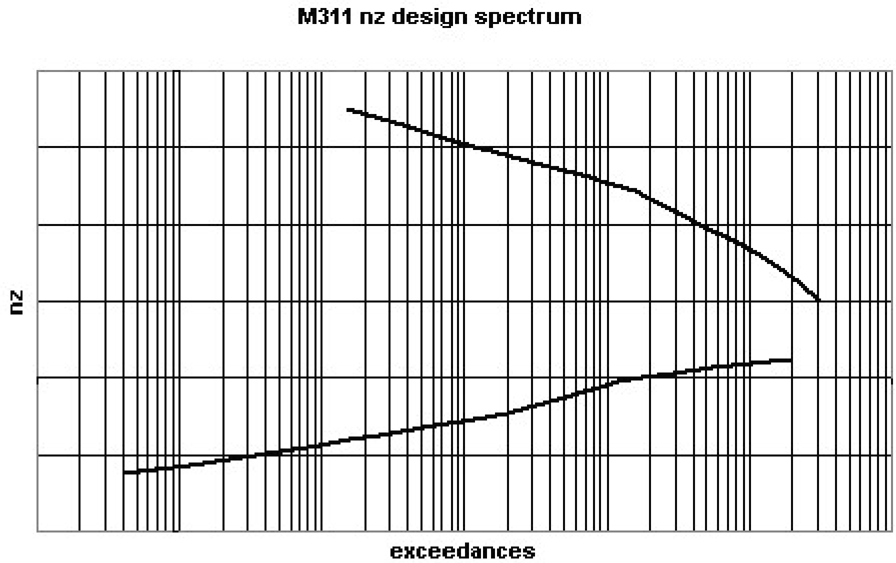

Fig. 44 - M-311 design spectrum

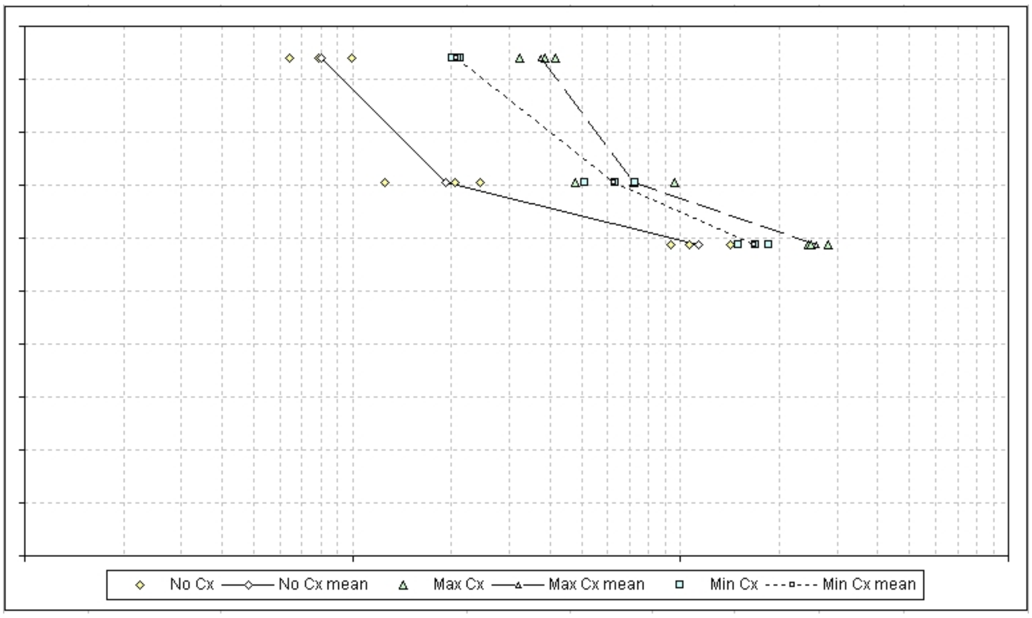

Fig. 45 - SF260EA - Cold working effect comparative curves

Fig. 46 – SF-260 EA wing attachment fatigue test.

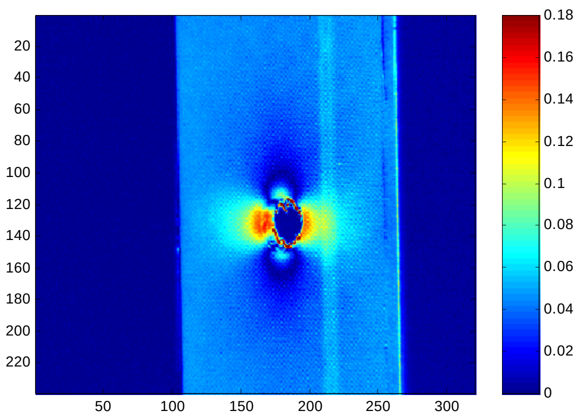

Fig. 47.a - The thermal map of the specimen shows a temperature concentration at the hole (Unidirectional Glass reinforced epoxy)

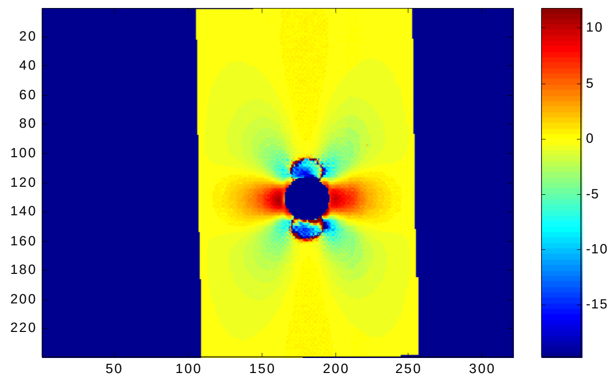

Fig. 47.b - Useful mechanical data are obtained after a specific elaboration of the thermal data