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

DEPARTMENT OF CIVIL AND INDUSTRIAL ENGINEERING - UNIVERSITY OF PISA

Review of aeronautical fatigue investigations carried out in Italy during the period April 2013 - March 2015

by
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This document summarizes the main research activities carried out in Italy about aeronautical fatigue in the period April 2013 – March 2015. The main topics covered are: load analysis, fatigue and fracture mechanics of metallic structures, usage monitoring systems, damage tolerance of composites, 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 2013 to March 2015. The different contributions have been arranged according to the topics, which are loading analysis, fatigue and fracture mechanics of metallic materials, fatigue and damage tolerance behaviour of composites and full scale component testing. Following the extension of ICAF areas of interest towards structural integrity, paragraphs dedicated to health monitoring systems and corrosion/fatigue interaction have been inserted. 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 author gratefully acknowledges 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 Aermacchi)

On AMX aircraft, fatigue monitoring is performed by means of classic mechanical g-meter readings and on the basis of provided information about configurations and mission profiles. On regular basis, every Italian National Review has given updated information on the rate of fatigue life consumption of the fleet. Up to now, 199956 flight hours have been monitored since the aircraft entered into service.

The Load Severity Index (L.S.I.), defined as the ratio between the In-Service Life Damage and the Design Life Usage, shows an average value (among the entire fleet) just below 1 (see fig. 1). Therefore fatigue life consumption is substantially in line with design assumptions. The L.S.I. trend as a function of time shows a slight difference between the Strike aircraft (which is characterized by a LSI index lower than 1) and the Trainer aircraft (which has a LSI index higher than 1). Anyhow, in recent years the tendency is stable, meaning a constant severity of usage of the fleet, see Fig. 1; this figure is an update of a similar one presented in the last National Review.

As an additional information, Fig. 2 shows the distribution of the L.S.I. index within the AM-X fleet: the usage severity is rather uniform, with the vast majority of the population in the range 0.7-0.9.

The LSI trend for the fleet leaders shows a constant rate for the Strike aircraft, and a slightly decreasing tendency for the Trainer.

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

Fatigue life monitoring has been performed by Alenia Aermacchi on I.A.F. Tornado, since its entry into service in 1980, by means of the own computer program that makes use of mechanical g-meter readings together with configuration/masses control. Results of this activity have been regularly presented in previous National Reviews; in total, 271205 flights hours have been monitored so far. Among the 5 (4 + 1 dummy) monitored locations, the lower wing panel remains the most fatigue affected. However, the load severity index, even with a small increase with respect to previous years, remains definitely below 1. Fig. 3 shows the L.S.I. distribution for the whole fleet, that includes Strike and Trainer aircraft.

Since the aircraft service life has been extended from 4000 to 6000 Flight Hours, the individual tracking will be maintained in order to assure that a correct fleet management is performed and any possible anomalous fatigue consumption is identified.

2.3 - EF Typhoon life monitoring (Alenia Aermacchi)

Since 2003, 73 Euro Fighter Typhoon aircrafts (61 single seat and 12 twin seat) have been delivered to the Italian Air Force. Since entry into service (2005), a total of 53000 flight hours (corresponding to 37800 flights) have been flown, as for September 2014. The fleet leaders are now beyond 1300 FHs.

The Production Major Airframe Fatigue Test (PMAFT) is ongoing within BAE Systems facilities at Brough (UK). At the moment 5/6 of the target safe fatigue life have been simulated (with design spectrum). Fin buffet is also introduced by means of a dedicated arrangement, that makes use of a dynamic shaker.

Alenia Aermacchi is engaged in an activity for the fleet fatigue and usage support by means of the Structural Health Monitoring system (SHM), that provides data for the Individual Aircraft Tracking Program (I.A.T.P.); Alenia Aermacchi is involved also in the analysis of the SHM data. The SHM system provides:

- the **Fatigue Index calculation** for 10 structural significant locations, selected to represent the main loading actions on the airframe; the value of the F.I. indicates the fatigue life consumption;

- the **Auxiliary Data** relevant to flight data (g, roll rate, Mach, weight, altitude, etc): these data are not directly used for fatigue calculations, but can be used for specific analyses. This information is used by the operators to assess possible exceedance of the Allowable Load Envelopes.
- the **Event Monitor** that points out any significant structural event compared to pertinent envelopes.

Fatigue formulas are directly correlated to PMAFT evidences, allowing to update at any time the calculation of fatigue safe life consumed by each single aircraft.

The in-service usage shows a spectrum shape similar to design assumptions, but less severe. This trend is confirmed by Fatigue Indexes calculations, that are below the design values too (see fig. 4).

2.4 - Usage Monitoring System for AW101 helicopter (AgustaWestland)

In the previous review, information was given about activities carried out by AgustaWestland for the development of Enhanced Structural Usage Monitoring (ESUM) and Transmission Usage Monitoring (TUM) to improve the evaluation of fatigue loading spectra. These usage monitoring systems are installed on AW101 variants, AW139 and NH90.

In the period of the present Review, it is worth mentioning that Operational Data Recording (ODR) of UK Merlin fleet, both RAF and Royal Navy operated, was carried out by direct instrumentation of some relevant structural components in service environment. New SOIU (Statement of Intent Usage) were issued for both variants and fatigue re-assessment was required.

Also EH101 Canada SAR and Denmark DMRH expressed interest and requested to update the fatigue evaluation of their fleets, according to usage data recorded by Usage Monitoring System.

2.5 – C27-J Program (Alenia Aermacchi)

The C-27J monitoring activity is performed through a specially developed I.A.T.P. (Individual Aircraft Tracking Program) software, that has the aim to monitor the actual fatigue status of each aircraft based on the actual mission profiles and spectra loads determined through the direct recording of in flight parameters.

I.A.T.P. is a software running on ground, which performs the comparison between the aircraft in-service life consumption and the design life usage. This allows to plan and manage the fleet usage and the inspection tasks keeping into account both the economic and the safety point of view.

The software monitors the main representative locations of structural items through the calculation of a parameter, LSI (Load Severity Index), similarly to other activities monitored by Alenia Aermacchi, which is the ratio between the In-Service Life Damage and the Design Life Usage.

$$LSI = \frac{In - ServiceLifeDamage}{DesignLifeDamage}$$

The LSI allows to “convert” the in-service flight hours, actually flown by each aircraft, into “equivalent” flight hours flown according to the design usage. The Design Life Damage is the fatigue damage calculated under theoretical mission profiles and mixing, which were applied during the full scale fatigue testing.

Nine specific aircraft locations have been chosen as particularly significant to monitor the fatigue life of the entire aircraft structure, see fig. 5. The nine locations have been chosen in order to cover all the possible fatigue loads sources:

- Flight Loads
- Maneuver Loads
- Ground Loads
- Pressure Loads

The conversion of flown FH into design FH is performed by means of a Crack Growth Module, which performs the comparison between In-Service Crack Growth Rate (SCGR) and Design Crack Growth Rate (DCGR), in order to determine the Residual Growth Life (Actual) versus the Residual Growth Life (Design).

The design crack growth data have been calculated in the design phase, while the in-service ones are calculated based on data coming from actual aircraft flight profiles.

Fig. 6 shows the residual life for the nine locations, in various aircraft of the fleet. The lower residual life is for the Wing Upper Panel location, in all aircraft; this result is under evaluation.

3. METALS

3.1 - Fatigue behaviour of notched and un-notched materials

3.1.1 - Evaluation of mechanical milling solutions instead of chemical milling (Alenia Aermacchi)

Information had already been given in the last National Review about an experimental test program started by Alenia Aermacchi to evaluate the substitution of the chemical milling process for skin panels with the mechanical one, for reasons of costs and of production rate. The Mirror Milling System (MMS) procedure has been selected and a few words of description were given in the last National Review.

To produce the evidences for certification purposes, an experimental activity has been carried out using 2024-T3 and 7075-T6 specimens. Three loading levels (low – medium – high) for each material have been used. In the last Review it was already shown that macro images of the fillet radius area gave evidence of a smoother ramp for the CHM process, which was reflected in longer fatigue lives. Therefore, in order to obtain a better comparison of the two processes alone, without any difference attributable to geometry of the ramp, a new specimen configuration was defined.

The results obtained for both materials are characterized by a standard deviation of about 0.045, acceptable for aluminium alloys, and have confirmed the preliminary impressions that were reported in the last Review, highlighting a better fatigue behaviour of MMS with respect to the CHM process. Moreover, the base radius of 4.0 mm gives acceptable performance in terms of fatigue life and so it will be the one chosen for production and certification testing.

Two macro images of the surface microstructure are shown in figs. 7, with evidence of a better finishing of the MMS surface.

3.1.2 - Fatigue behaviour of 7075-T73 coupons in high temperature (Univ. Pisa)

Fatigue tests were carried out on aluminium alloy 7075-T73 specimens, in the framework of a collaboration with AgustaWestland. The specimens were machined from a 500x500 mm plate, having thickness of 100 mm. The plate was obtained by forging a casted billet so to have a significant reduction ratio.

Two different specimens were used in the program. The first was an un-notched specimen, with threaded ends. The diameter of the gauge length was 6 mm, fig. 8a. The second specimen was notched, as shown in fig. 8b. The corresponding stress concentration Factor is Kt=3. The diameter of this specimen in the gauge length was 10.9 mm.

The specimens were machined in the Longitudinal (L) direction of the plate.

The mean value of the roughness measured on the surface of the un-notched specimens was Ra=0.8-0.9 µm.

The tests were carried out in a 25 KN hydraulic actuator available at the Department of Civil and Industrial Engineering – Aerospace division, of the University of Pisa. The specimens were clamped to two threaded Inconel 718 extension bars; this configuration was necessary, because the specimens were too short with respect to the length of the oven used for the high temperature tests. The same configuration was maintained also for the room temperature fatigue tests. Locknuts were fixed at the ends of the specimens, to prevent unscrewing during the tests: this system has proved to be simple and absolutely reliable.

High temperature fatigue tests were carried out by enclosing the specimens and the extension bars inside an oven; this equipment is composed by two half-shells, so that the working area was completely free while mounting the specimens. Fig. 9 shows a photograph of the test equipment.

The temperature of the specimens tested at high temperature was controlled by means of a thermocouple mounted near the specimen. The thermocouple was not directly fixed to the specimen, as it could be the cause of fretting failures, but it was located in one locknut. To evaluate the homogeneity in temperature distribution on the specimen, preliminary tests were carried out to correlate the temperature measured by a thermocouple directly positioned in the specimen central section and the thermocouple mounted inside the locknut.

A group of un-notched specimens was fatigue tested at room temperature, (RT), under a stress ratio R=-1. The results obtained are given in fig. 10, compared with the fatigue results of some specimens accurately polished to reduce further the surface roughness. The operation was performed by using very fine emery paper, grade 800 and a lubricant. This procedure is not representative of aerospace components machining, but a remarkable effect was obtained.

Two groups of specimens were tested at high temperature, 155 and 140°C. Two specimens were tested at 130°C, after pre-exposure for 3 hours at 155°C. The results obtained are given in fig. 11, compared with the results obtained at room temperature. High temperature testing has a detrimental effect on the fatigue resistance, at the higher number of cycles. The results of the tests performed at 130, 140 and 155 °C are fully comparable, so to be represented by only one best fit curve.

One group of specimens was tested at Room Temperature (RT) after a pre-exposure of 3 hours at 155°C. The results obtained are given in fig. 12 compared with the results of the specimens tested at RT. The results obtained are fully comparable with the results of specimens tested at room temperature (without pre-exposure). As a consequence, the 3 hours pre-exposure seems to have no effects on the fatigue resistance.

3.1.3 - Effect of LSP-generated residual stresses on fatigue crack propagation in thin panels (Univ. Bologna)

Laser Shock Peening (LSP) is a relatively new technology which has shown to be very effective in introducing compressive residual stresses in bulk metallic structures, thereby retarding the fatigue crack nucleation and its subsequent local propagation. It is widely used to increase the fatigue performance of turbomachinery components, airframe structures, wing attachment lugs or gears. Furthermore, experimental evidence has shown the positive effect of LSP generated compressive stresses on the fatigue life of thin aluminum panels, in terms of the retardation of fatigue crack nucleation and the extension of fatigue crack growth life of the specimens.

However, the transient nature of the LSP phenomenon and the high pulse/rate frequency of the laser are causes of extreme difficulties in making measurements of the laser/material interaction. Due to such difficult measurements, and the high cost associated with the experiments, reliable analytical and numerical methods for predicting the LSP effects are needed, for an optimum application of the process.

The work carried out in Bologna University – Forlì Campus aims at predicting the residual stress field after laser shock processing by means of Finite Element (FE) modelling. Starting from the estimated residual stress distribution, the reduction in the crack propagation has been analytically evaluated in flat specimens and compared with experimental results, showing good agreement.

The starting point of this investigation is a paper presented at ICAF 2013 Symposium [1], where a numerical analysis of the LSP process was developed, using the commercial finite element code ABAQUS and the Johnson Cook's (JC) model, capable of describing the behaviour of materials under high strain rate loading. The study about the material properties highlighted a gap in the simulation of the surface conditions, which suggested the opportunity of including the ablative layer in the model, commonly a very thin sheet of pure aluminium.

In the last two years, further activities have been carried out: an improved model has been developed, following a deep investigation on the material modelling in single and multiple spots with overlapped laser layers. A parametric study has been performed to investigate the influence of specimen's thickness on the stresses distribution along the treated surface and within the specimen. In order to simulate the material behaviour, three models have been used: the Johnson-Cook constitutive model and two Kinematic Hardening plastic models, with one and three backstresses respectively, to model the cyclic loading of metals due to the back-forth moving of shock waves resulting from the peening process. Fig. 13 shows a comparison of the predictions.

The 3-backstresses model resulted to be more reliable; a numerical assessment of the self-balancing residual stress distribution along the entire specimen width has been carried out. The fatigue crack growth through a peened flat thin aluminium panel with a central crack has been analytically evaluated and compared with experimental results, showing good agreement. The comparison highlighted the sensitivity of the fatigue crack propagation to the selected LSP pattern configuration (i.e., the width of the LSP treated strip and the relative position to the crack centre) which have to be accurately setup in order to exploit the full potential of the LSP process and to avoid an undesired reduction of the component performances.

As a conclusion, the results showed that the LSP is an effective method to introduce significant compressive residual stresses in fatigue sensitive areas of metallic structures, postponing fatigue crack nucleation and reducing fatigue crack propagation. The achieved results showed that, to extend the fatigue life of a thin component, the LSP treated/processed area should be placed close to the crack origin, and a wide treated area should be used.

More detail on this activity can be found in a paper presented at the Symposium, [2].

3.1.4 - One-Up assembly fatigue knock-down factor (Alenia Aermacchi)

The drilling of joints made of different materials produce burr at materials interface. If the parts cannot be separated for cleaning and deburring the holes before the fasteners installation, a penalization in the fatigue behaviour occurs and therefore a knock-down factor needs to be evaluated.

To investigate this effect, that is almost unavoidable in some manufacturing processes (see fig. 14), a test campaign has been planned; in particular, a location where aluminium-titanium-aluminium are one-up drilled without performing the deburring of the holes on the titanium part has been considered for assessing the knock-down factor. For comparison, the fatigue behaviour is also investigated for situations where the titanium hole has been deburred, to establish a reference basic fatigue property.

Open holes and joints specimens will be tested; typical specimen geometries are shown in fig. 15. The tests are in progress.

3.1.5 - Chromic acid anodising vs tartaric sulphuric acid anodising (Alenia Aermacchi)

The current international environmental regulation (REACH **– R**egistration **E**valuation **A**uthorization of **Ch**emicals, issued by the European Union in 2006) requires the progressive elimination of products declared harmful to the environment and the human health. The salts of chromium are included among these products and in particular the hexavalent chromium, also used in the chromic acid anodizing process. Alenia Aermacchi, in order to comply with the REACH regulation, will replace CAA (Chromic Acid Anodizing) process with a more ecological one, called TSA (Tartaric Sulphuric Anodizing).

A large test campaign has been defined and its performance is in progress, to determine the fatigue behaviour of selected aluminium alloys for both TSA and CAA oxidation process, in order to compare the detrimental effect on the fatigue behaviour.

All the Alenia Aermacchi proprietary programs have been evaluated and the most used aluminium materials have been selected. Three aluminium alloy families, 2000, 7000 and 6000, for an amount of about 900 specimens, are the object of this test program. The fatigue behaviour is also investigated for materials without surface treatment in order to estimate CAA and TSA knock down factors with respect to basic fatigue properties.

The results of the fatigue tests will be used for the creation of a database and to provide evidence to the Certification Authority that the new process does not adversely affect the fatigue characteristics, showing the compliance with CS 25.571 amendment 15 and JAR 25.571 change 14 and 15.

The list of the selected materials is the following:

2024-T3	bare sheet	per AMS-QQ-A-250/4
2024-T351	plate	per AMS-QQ-A-250/4
6061-T6	bare sheet	per AMS-QQ-A-250/11
2219-T62	bare sheet	per AMS-QQ-A-250/30
7075-T73	bare sheet	per AMS-QQ-A-250/12
7075-T7351	plate	per AMS-QQ-A-250/12
7475-T7351	plate	per AMS 4202
7050-T7451	plate	per AMS 4050
7085-T7651	plate	per AMS 4329
2124-T851	plate	per AMS-QQ-A-250/29

3.1.6 – Fatigue of gears (AgustaWestland)

A long term test program is running at AgustaWestland for the assessment of the fatigue performance of new materials or surface processes used in gears, in collaboration with Milan Polytechnic, Department of Mechanical Engineering. Within this program, many different manufacturing processes or parameters have been evaluated so far, including the finishing, the quality of the original material (VAR or VIM-VAR), various shot peening intensities, surface coating, and so on. Just to quote some of the late results, an investigation has been carried out to assess the influence of shot peening, nitriding and carburising on the fatigue life of AISI 9310, a common steel used in these applications; fig. 16 shows the comparison of two groups of shot peened carburised gears.

Moreover, helicopter manufacturers are addressing transmission elements and gearboxes fatigue evaluation with particular attention, since the most recent amendment to EASA CS 29.571 clearly states that the PSEs must include “rotors, rotor drive systems between the engines and rotor hubs, controls, fuselage, fixed and movable control surfaces, engine and transmission mountings, landing gears and their related primary attachments”.

For each of them, appropriate inspections and retirement time must be established. In practical application, the retirement times are established by means of safe life or flaw tolerance safe life methods, while for the definition of inspection programs fracture mechanics analyses are used, or fail safety or flaw tolerance to maximum likely damages.

The criterion applied by AgustaWestland to transmission gears considers that a crack, originated on the tooth surface or from the tooth bottom due to bending, does not propagate in radial direction, causing failure of the whole gear or case.

The transmission gear integrity monitoring is carried out by means of magnetic chip detectors, that capture small metallic particles that may detach for spalling or other surface fatigue phenomena, and activate an alarm system visible to the pilot. Moreover, the use of accelerometers can allow the detection of anomalous vibrations.

In a laboratory test, a long working period has been verified for a transmission, after the failure of a Gleason crown starting from a threaded hole, used to fix it to the shaft. Figs. 17 show photographs of the cracked crown. During the test, the bolt, detached from the cracked crown, has damaged an engine inlet, making the test even more critical. The test has been stopped when the signal of presence of metallic particles in the lubricating oil occurred repetitively, in a systematic way; this happened more than 80 hours after the first signal, with a total of 9 signals.

3.2 - Crack propagation and fracture mechanics

3.2.1 - Fatigue crack propagation of 3-D defects in cold expanded open holes (Univ. Pisa)

Within the framework of a collaboration with Airbus Deutschland, an experimental program has been performed at the Department of Civil and Industrial Engineering - Aerospace Division of the University of Pisa, aimed at assessing the fatigue crack growth of corner cracks in open hole specimens in 2024-T351 aluminium alloy, in order to assess the influence of the residual stress field introduced by the split sleeve cold expansion process.

The objective of the activity was to collect test data for the calibration of prediction models that Airbus is developing. For this purpose, Constant Amplitude fatigue tests have been performed on open hole specimens, made of 2024-T351, of different thicknesses (2, 4 and 6 mm specimens were available), where a small quarter-circular corner notch had been introduced by Airbus by means of Electro Discharge Machining. A drawing of the specimen is shown in fig. 18.

Typically 3 samples were tested for each condition, i.e. differing for the thickness or for the cold expansion degree (three options were available: basic material, 3 % expansion and 4 % expansion). The various groups had been tested under a R=0.1 stress ratio loading, with only two exceptions, namely two groups of specimens that were tested under a R=0.7 stress ratio (2 mm thick specimens, without CX process and with 3% expansion).

It was considered of great importance to collect information on the crack growth in both directions: on the front surface of the specimen (“c” dimension) and in the thickness direction, inside the hole (“a” dimension). Therefore, a special set-up was developed, with three cameras looking at different positions of the crack tip. Two cameras were positioned on an aluminium plate fixed to the columns of the test rig, and were oriented one perpendicularly to the front surface (to observe and document the “c” growth) and the other inclined at 45 degrees with respect to that face to better observe the growth of the tip inside the hole (“a”). These two cameras were identical, of the same type, i.e. Imaging Source GigE model DFK 23G274, with a 1600 x 1200 pixels resolution. A third camera was positioned, looking at the back surface of the specimen for the purpose of catching pictures of the tip when it became visible on the back surface (to avoid confusion, this dimension was named “b”). Also this camera was an Imaging Source GigE, but had a lower resolution (1280 x 960 pixels, model DFK 23G445). After the start of the experimental activity, it was clear that a higher resolution was beneficial to the measurement accuracy, and so the front picture (“c” dimension) was taken by a photo camera Canon Eos 605D, 5184 x 3456 pixels. A picture of the test set-up is shown in fig. 19.

Pictures were taken every 1,000 cycles and stored in a PC hard disk; they could be examined at the end of the test, in a backwards sequence, taking the advantage in the measurements from the knowledge of the final crack path.

Other participants to the project were in charge of the residual stress measurements and of the development of a prediction methodology. The main results will be presented in a paper at the Symposium, [3].

3.2.2 - Fatigue crack growth and fracture toughness in corroded 2024-T351 alloy (Alenia Aermacchi)

An experimental activity has been carried out by Alenia Aermacchi in order to evaluate the influence of pre-exposure to corrosion on the fracture mechanics properties, namely constant amplitude fatigue crack propagation and fracture toughness. The activity is ancillary to evaluation of consequences of corrosion exposure in ageing aircraft.

To this end, Compact Tension specimens have been manufactured in 2024-T351 aluminium alloy, trying to be as faithful to the real structural situation under evaluation: same thickness of the real component, same machining process to obtain the specimen (with similar surface conditions). Afterwards, the specimens have been exposed to a corrosive environment, in order to reproduce the same typology and depth (about 1 mm) of in-service detected corrosion on both external surfaces of the coupons.

ASTM standards (E-399 for fracture toughness and E-647 for fatigue crack growth) have been followed for the definition of the geometry of the specimens as well as for the test performance (see fig. 20). The thickness of the specimens was 22 mm. Fatigue crack growth was carried out at three stress ratios: 0.1, 0.3 and 0.6; some un-corroded specimens were also tested, for reference.

The fracture toughness tests results (six tests per condition) did not show evidence of penalization of the corroded specimens, that provided even slightly higher average toughness values than un-corroded. Negligible differences were also observed in the fatigue crack growth results; three repetitions were executed for each condition and the resulting graphs were almost overlapped (see fig. 21). In conclusion, the test results relevant to fracture toughness are well in accordance with the material data for Tornado standard, while the fatigue crack growth results are in good agreement with standard calculation tools (NASGRO data base).

3.3 - Corrosion and fatigue

3.3.1 – In-service survey of corrosion occurrence and effects on fatigue life (AgustaWestland)

During AW189 and AW169 Type Certification, EASA specialists requested additional information on “Fatigue and Corrosion of PSE”. The document says:

“For corrosion it is requested to collect the in-service experience (including characterization of the damage) and to perform an assessment of the corrosion effect for steel, aluminium and magnesium”

“EASA required additional information on corrosion and how this is accounted for flaw tolerance”.

Legacy data are available from SCT (Surface Crack Tension) specimens, cut out from components corroded in service, compared with the behaviour of other pristine specimens having small crack-like defects of comparable depth. The test data point out similar fatigue strength, in Al 2014 alloy, between specimens having corrosion pits and specimens with sharp flaws, as shown by the results reported in fig. 22.

Data from periodic inspections were checked for verification of corrosion “acceptable for repair” and those causing discard.

An important issue to guarantee a long corrosion free life is the definition of preservation and storage requirements, in order to identify correct procedures to prevent corrosion of gears in storage:

1) Drain completely the lubricating oil;
2) Fill the gearboxes at the normal level with corrosion preventive compound;
3) Run the gearbox with almost no power;
4) Drain completely the corrosion preventive compound;
5) Cover openings with caps or lids.

Magnesium castings are often used for the gearbox case. The susceptibility of this material to corrosion is well known and so a dedicated test has been carried out to verify the effectiveness of different kinds of protection.

Seven batches (3 specimens each batch), each one covered by a different type of protection, have been exposed in salt-spray for 1000 hours. Fig. 23 shows a picture of the specimens, at the start and at the end of the test.

4. COMPOSITES AND FIBER METAL LAMINATES

4.1 - Damage Tolerance assessment of near-edge and on-edge impacts in CFRP structures (Univ. Bologna)

The challenging airworthiness requirements set on fully composite airplanes are mostly related to the demonstration of damage tolerance capability of their primary structures. In real life working conditions, a number of external factors can lead to impact damages, which must be shown not to put the aircraft safety at a risk.

A study has started at the University of Bologna – Forlì Campus to evaluate the effects of near-edge and on-edge impacts, which are inflicted quite commonly during the manufacturing or the service life of an aircraft. It is based on the experimental and numerical evaluation of these impacts on the damage tolerant properties of CFRP structures.

An experimental campaign was defined in order to characterize the behaviour of impacted CFRP specimens. Though many examples of transverse impacts exist in literature, very few can be found regarding edge impacts, mostly related to impacts in glass fibre composites.

This experimental activity is focused on near-edge impacts in CFRP panels and its objective is the residual strength characterization of the damaged coupons in comparison with the pristine ones. The tests have been performed on CFRP panels with different stacking sequences.

Different energy levels have been selected for these tests, keeping into account statistical data available on in-service impacts on composite aircraft fuselage. Different fuselage areas have been considered, in order to select in a realistic way the thicknesses and the stacking sequences of the coupons. The idea is to select two different stacking sequences based on those airplane areas where one or more of the following conditions are met:

- High compressive stress areas, such as the lower shell;
- Probable impact damage areas, such as cut-outs (door cut-outs and window belt).

Impact damages can also be introduced during the production and the assembly of the components. For this reason, also a thinner stacking representative of frames and stringers was selected, in order to be tested with lower energy level impacts.

Two systems for inflicting the impacts were assessed: a vertical drop weight and a Charpy pendulum. Pictures of the impacting systems are shown in figs. 24. Compression After Impact tests have been performed to assess the residual strength of the various laminates.

More details can be found in a paper presented at the Symposium, [4].

4.2 - Interlaminar Fracture Mechanics characterization of composites (Univ. Pisa)

In the previous National Review, a paragraph was dedicated to the description of the results of a collaboration between AgustaWestland and the former Department of Aerospace Engineering of the University of Pisa (now DICI, Department of Civil and Industrial Engineering) with the objective of characterizing a few composite material systems as far as their fatigue and static resistance to delamination growth is concerned. The activity is still in progress; various materials systems are being evaluated: three graphite/epoxy systems (a fabric 5H 8552S/AGP280, and two unidirectional systems, 8552/AS4 and 913C-HTA) and a glass fibre/epoxy Cytec S2-5216.

For each of them, static tests to evaluate the mode I, mode II and mixed mode I+II (with two different values of the mode partition ratio) G_c have been performed, using DCB, ENF and MMB coupons. Moreover, also the influence of environment has been assessed, by performing tests on saturated DCB and ENF coupons in high temperature (70 °C) conditions. A heated box has been used for this purpose, where only temperature control was carried out; the heating phase was of about 25 minutes, and it has been considered to have negligible effects on the moisture content, due to the short duration. The experimental results, obtained so far on the Hexcel 913C-HTA system only, show a contradictory influence of HTW conditions on the toughness values, in comparison with normal RTD laboratory environment data: the mode I results were about 50 % higher than the RTD values (average value of 374 N/m versus 245 N/m), while the mode II results were about 30 % lower than the corresponding RTD values (average value of 687 N/m versus 931 N/m). All the specimens have been tested after a pre-cracking procedure; for mode I tests, this is specified in the relevant ASTM standard, while for the mode II test, which is not yet ruled by an ASTM standard, it is well known that pre-cracking has a significant impact on the results.

4.3 - Fibre optic sensors application for structural health monitoring (Milan Polytechnic)

A research program is in progress at the Milan Polytechnic – Dept. of Aerospace Sciences and Technologies for the study of structural health monitoring by means of optical fibres. A significant part of this activity has been carried out within the SARISTU project, a VII EU Framework programme, but other significant contributions have been generated in various research activities, with different funding, all correlated with this technological development field.

A number of problems indeed have been progressively tackled and solved, during this research; just to quote the most relevant, sensors embedding, networking and integration; load monitoring, damage monitoring, process monitoring, signal decoupling and analysis. It is here worth mentioning the work related to sensors embedding and signal processing: how to embed them best, how to get multiple punctual measurements, how to reduce noise, how to deduce thermal strain from mechanical strain, and so on. A sort of building block approach has been followed, finding progressively solutions to problems of increasing complexity and moving from the feasibility study towards real applications. Within SARISTU, a spar has been used as a testbed for validating the technology, in terms of load monitoring and health monitoring, offering the possibility to assess the potentiality of such technology.

All these aspects have been studied and a synthetic description of the research can be found in [5], presented at the Symposium, together with a list of references dedicated to the solution of the various technological problems, above mentioned.

5. COMPONENT AND FULL-SCALE TESTING

5.1 – ATR Main Landing Gear support life extension (Alenia Aermacchi)

As already presented in previous ICAF Symposia [6], the ATR life extension program has the objective to extend the aircraft fleet design life from the actual 70000 flights to 105000 flights.

For what concerns the Main Landing Gear Support Structure, the target is to avoid the replacement of such structure; therefore, it has been agreed to get the life extension through a test campaign on fatigue equivalent coupons, to comply with the requirements of EASA CS 25.571 for safe life items.

The above test campaign will have the objective to demonstrate that an appropriate reworking can extend the life of the structure up to guarantee at least 105000 flights, without any significant structural replacement. Since the most fatigue critical locations in the MLG support structure attachment to the fuselage are lugs and holes, the most simple and efficient reworking that can restore the life of the structural details is the holes reaming to an oversize diameter. This operation will be carried out at the end of the original operative life (70000 flights), giving a new virginity to the hole; the process has been estimated as sufficient to gain another half safe-life increment (35000 more flights). Hence, fatigue equivalent coupons will be fabricated and tested in order to demonstrate the reaming benefits in terms of fatigue life.

In order to identify the coupons geometries representative of the MLG support structure, the most critical locations of truss shear member, front and rear spar fittings, struts and side brace fitting have been analyzed for a number of different aircraft versions, i.e. ATR 42, ATR 42-300, ATR 42-500, ATR 72-210A.

In order to reduce the number of tests, the locations have been grouped by means of a fatigue assessment, with the advantage that geometrically different situations, that on the contrary are similar from a fatigue point of view (similar stress concentrations and fatigue influencing parameters), can be analyzed by a single type of equivalent specimen.

To account for different in-service usage severities, three reaming levels will be investigated. The specimen will be a simple lug and will be machined from the same material as the MLG Support Structure.

5.2 – Development of the Bombardier C Series (Alenia Aermacchi)

Within the framework of this programme, focused on the design of a narrow body, medium range twin engine aircraft, Alenia Aermacchi is in charge for static and fatigue test development for material, structural details, component characterization and full scale tests on horizontal and vertical tails, that are both manufactured by making extensive use of composite materials.

Information about the Building Block approach used by Alenia Aermacchi to characterize material, design choices and methodologies was already given in the last review. After two years, the lower part of the test pyramid has been completed.

For what concerns the Fatigue/Damage Tolerance analysis and certification of the horizontal tail, two complete test articles have been tested: one was dedicated to the qualification of the composite structures (test completed, a static test up to ultimate load concluded the fatigue /damage tolerance phase, see fig. 26) and one for the metal structures (starting shortly). The differences in spectrum loading require the performance of two separate tests.

As far as the vertical stabilizer is concerned, Alenia Aeronautica is in charge of the qualification of the composite parts only. The test campaign is articulated into a DADT test of the composite structure, in the static tests and in a bird strike test. The experimental set-up is almost ready and the tests are programmed in the near future.

6. AIRCRAFT FATIGUE SUBSTANTIATION

6.1 - AW109 and variants (AgustaWestland)

Following indications from the market for a reduction of operative costs, a number of initiatives have been carried out by AgustaWestland, mainly with the aim of extending the fatigue life of components characterized by high maintenance or replacement costs. As an example related to all variants of the AW109 helicopter, a Main Rotor blade life extension from 8800 FH to 12000 FH has been demonstrated. This is the consequence of continuing test activity, that particularly in those cases where the test article must be conditioned in a climatic chamber is very time consuming, and provides useful results only after years. In this case, the life extension is not the consequence of a new design or the addition of reinforcement or introduction of new production processes; all these events may increase the cost, while in this case the life extension is just the consequence of fulfilment of experimental demonstration, and so the longer retirement life can be profitably used by the customer as an operative cost reduction.

Moreover, a new variant “Trakker” at 3175 Kg MTOW with landing skid has been developed (characterized by 40 Kg weight saving, no hydraulic systems for landing gear and cost reduction).

6.2 - EH101 / AW101 helicopter (AgustaWestland)

AW101 International at 15,600 Kg MTOW was delivered for Search And Rescue role (Algeria), VVIP (Saudi, Turkmenistan, ..) and fully developed and qualified for CSAR (Combat, Search and Rescue) multirole for the Italian Air Force.

UK RAF helicopters will be used by the Royal Navy and the UK Ministry of Defence is managing a large project (MLSP) to take into account role and configuration changes: all the RAF fleet will pass to the Royal Navy. The final configuration will have an increased MTOW at 15,600 Kg, full capability of shipborne operations (including foldable main rotor and tail unit), and new avionics. The machines will be a multirole CSAR, i.e. for logistic and tactical employment.

New fatigue life analyses were carried out for all variants and the related airworthiness limitations were issued.

6.3 - AW189 / AW139 / AW169 helicopter family (AgustaWestland)

AgustaWestland has developed the concept of helicopter family to follow more promptly and efficiently the requests of the market. The very successful model AW139 has therefore a bigger brother (AW 189, 8300-8600 Kg AUW) and a smaller brother (AW169, 4400 Kg AUW). More efficiency and cost reduction can be obtained by commonality of component and design features.

AW189, the biggest machine of the family with 8300-8600 Kg AUW, was certified by EASA in 2014 as basic transport plus some kits affecting fatigue:

a) single rescue hoist;

b) ETOW at 6800 Kg;
c) underbelly fuel tank;
d) dual hoist (for UK SAR variant).

The next activities will be concerning a kit for cargo hoist and FIPS and LIPS (Full and Limited Ice Protection System, respectively) certifications.

Dedicated usage spectra are evaluated for each kit and specific load surveys are carried out on a case-by-case basis to complement the flight data base. Fatigue and Flaw or Damage Tolerance evaluations are then carried out for all PSEs. Reporting for traceability of all data and analysis is always a relevant effort.

According to the present rules, the Airworthiness instructions account for retirement life and mandatory inspection for all the PSEs of rotors, transmissions and gears, rotor controls, airframe, servo-actuators and fixed flight controls.

Basic Type Certificate of AW169 is envisaged within a few months. This is the smallest helicopter of the family, with 4400 Kg MTOW, with VIP and Utility-Rescue configurations.

The AW139 fleet leader has reached in February 2015 the target of 10,000 flight hours, FHs.

The Main Rotor blade life has been extended from 10,000 to 16,800 FHs. Similarly, also the Tail Rotor blade life has been considerably extended, from 10,000 landings to 40,000 landings. Other PSEs with extended life are: Tail Rotor Hub (from 7,500 FHs to 11,250 FHs) and Tail Unit (from 10,000 FHs to 19,700 FHs).

All these life extensions, as already anticipated in the paragraph on AW109 helicopter, are at no additional weight or cost, and so they have a significant effect on the reduction of maintenance costs.

Lord Corp. AVCS (Active Vibration Control System) Omni is a common feature for the Family aircraft to improve passengers comfort and for vibration reduction. Linear variant is already used on AW139, but AW169 requires a rotating system to change tuning of the “blade passing frequency” since AW169 changes rotor speed to optimize performance and noise for the different flight phases.

AVCS is an active system and changes the loading environment of the cabin. This may effect the fatigue resistance of a PSE even in presence of proper functioning, not only in case of system failure; anyhow, a specific situation to be investigated is the degraded performance or malfunction. Two or more AVCS are typically used and degradation of some of them may be compensated by the others. This must be prevented or properly evaluated, being a source of loading change.

6.4 - AW609 development (AgustaWestland)

AW609 is the civil tilt-rotor developed by AgustaWestland from the past joint venture with Bell Helicopter. AW609 Tiltrotor will be civil certified with FAA in the USA.

A specialists’ team of AW personnel was established in Arlington, near Dallas (TX), to lead civil certification for AW-Philadelphia.

7. REFERENCES

[1] E. Troiani, C. Crudo, G. Molinari, S. Taddia: “Investigation on laser shock peening capability by finite element simulation”, Proceedings of the 27th ICAF Symposium, Jerusalem, 2013, pp. 567-582.

[2] E. Troiani, S. Taddia, I. Meneghin, G. Molinari, C. Polese: “Effect of LSP generated residual stresses on fatigue crack propagation in thin panels”, paper to be presented at the 28th ICAF Symposium, Helsinki, 3-5 June 2015.

[3] L. Lazzeri, D. Furfari, Q. Fu, A. Wetzel, M.B. Biasizzo, D.O. Busse: “Predicting fatigue crack growth emanating from cold-expanded holes”, paper to be presented at the 28th ICAF Symposium, Helsinki, 3-5 June 2015.

[4] V. Ristori, E. Troiani, M. P. Falaschetti, M. Montemurro, A. Baeten, G. Ivetic, G. Molinari: “Damage tolerance assessment of edge impacts in CFRP structures”, paper to be presented at the 28th ICAF Symposium, Helsinki, 3-5 June 2015.

[5] A. Airoldi, P. Bettini, P. Belotti, T. Loutas , C. Koimtzoglou, G. Sala: “Design of health and usage monitoring systems based on optical fibers for composite wing spars”, paper to be presented at the 28th ICAF Symposium, Helsinki, 3-5 June 2015.

[6] A. Minuto, M. Cajani: "ATR 42/72 ageing program finalised to the airframe life extension", Proceedings of the 24th ICAF Symposium, Naples, 2007, pp. 322-339.

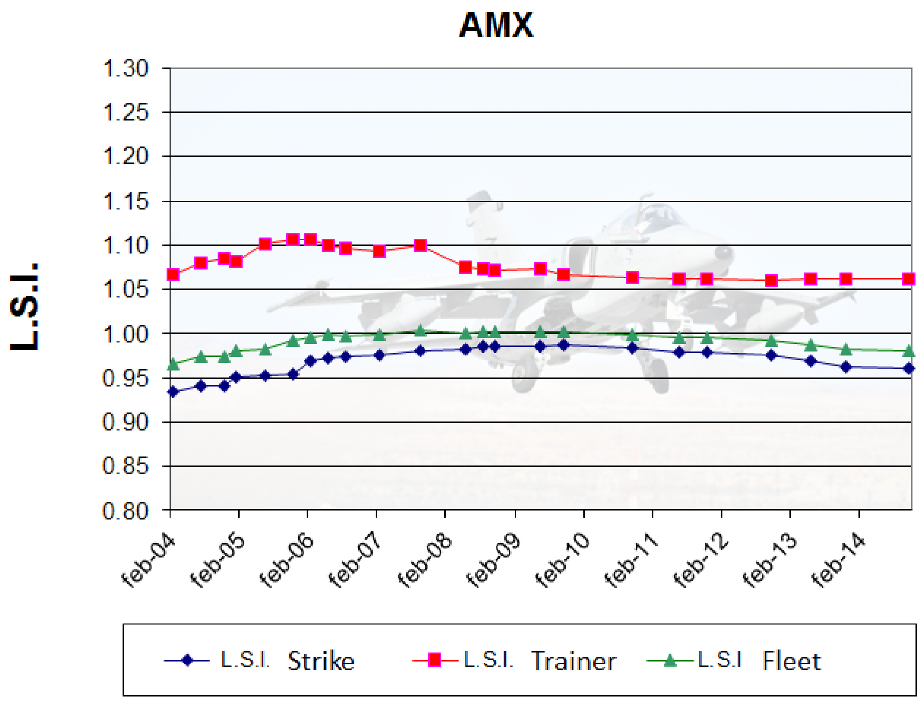


Fig. 1 – Trend of the global Load Severity Index for the AM-X fleet.

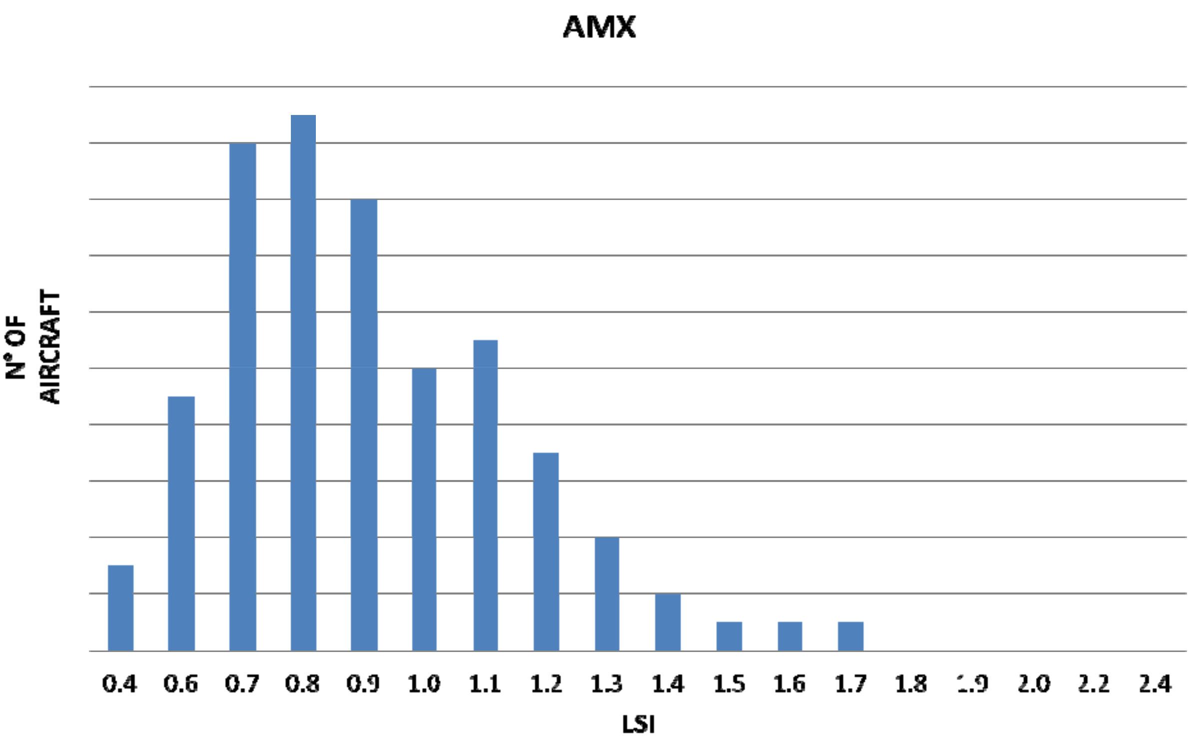


Fig. 2 - Load Severity Index distribution in the AM-X fleet.

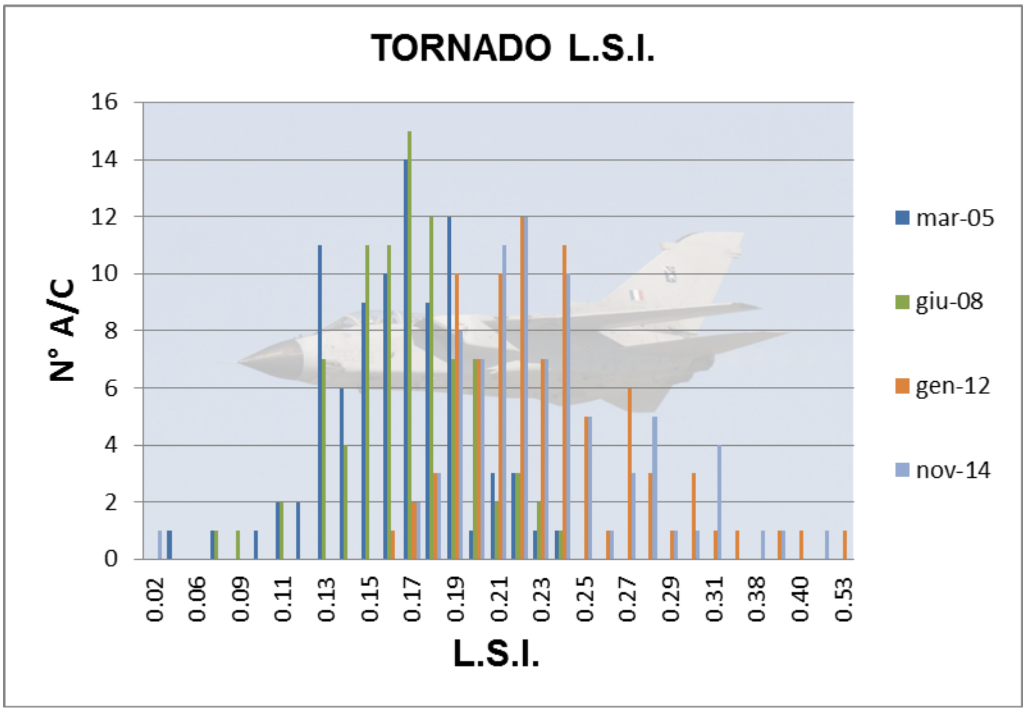


Fig. 3 - Load Severity Index distribution for the I.A.F. Tornado fleet, at different times.

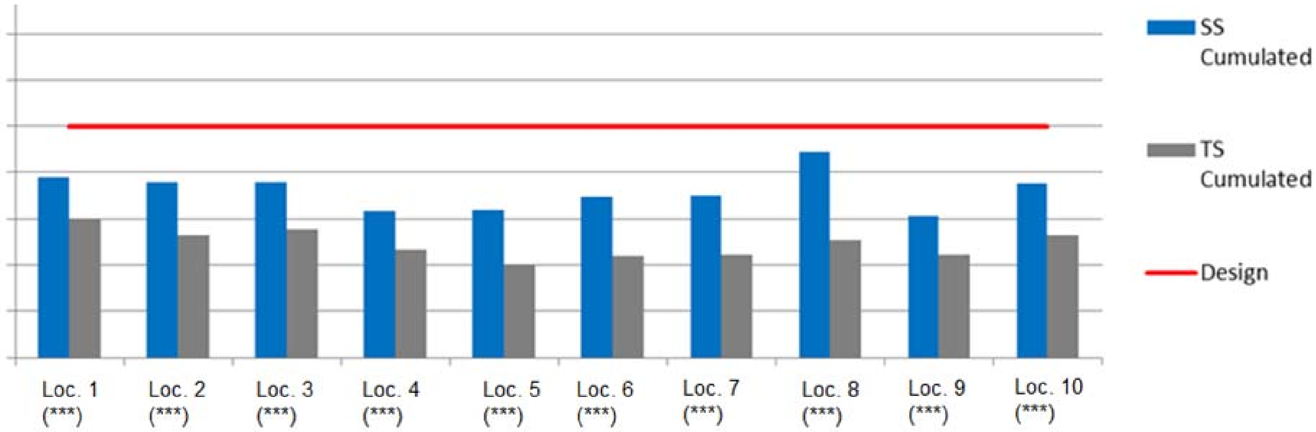


Fig. 4 - Fatigue Indexes values for IAF Typhoon aircraft.
(For location definition, see previous editions of National Review).

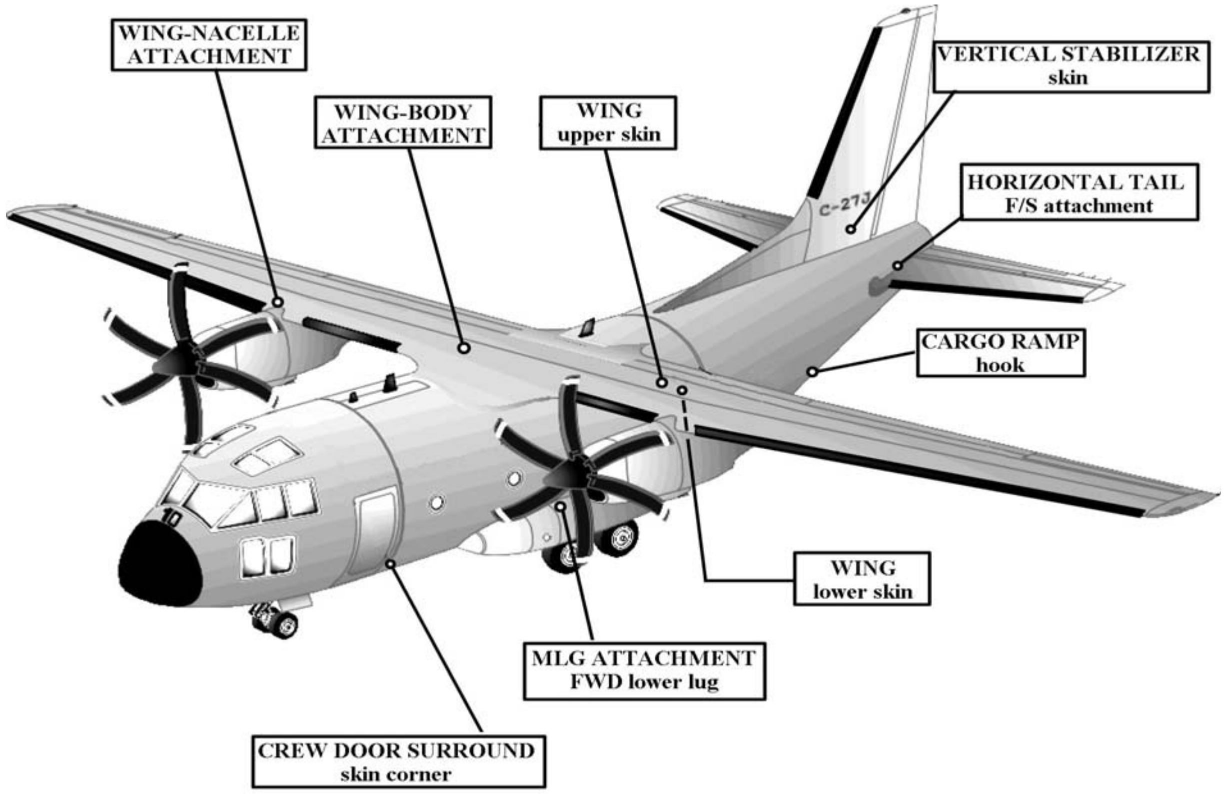


Fig. 5 – Nine significant structural locations for evaluating fatigue damage in C-27J IATP program.

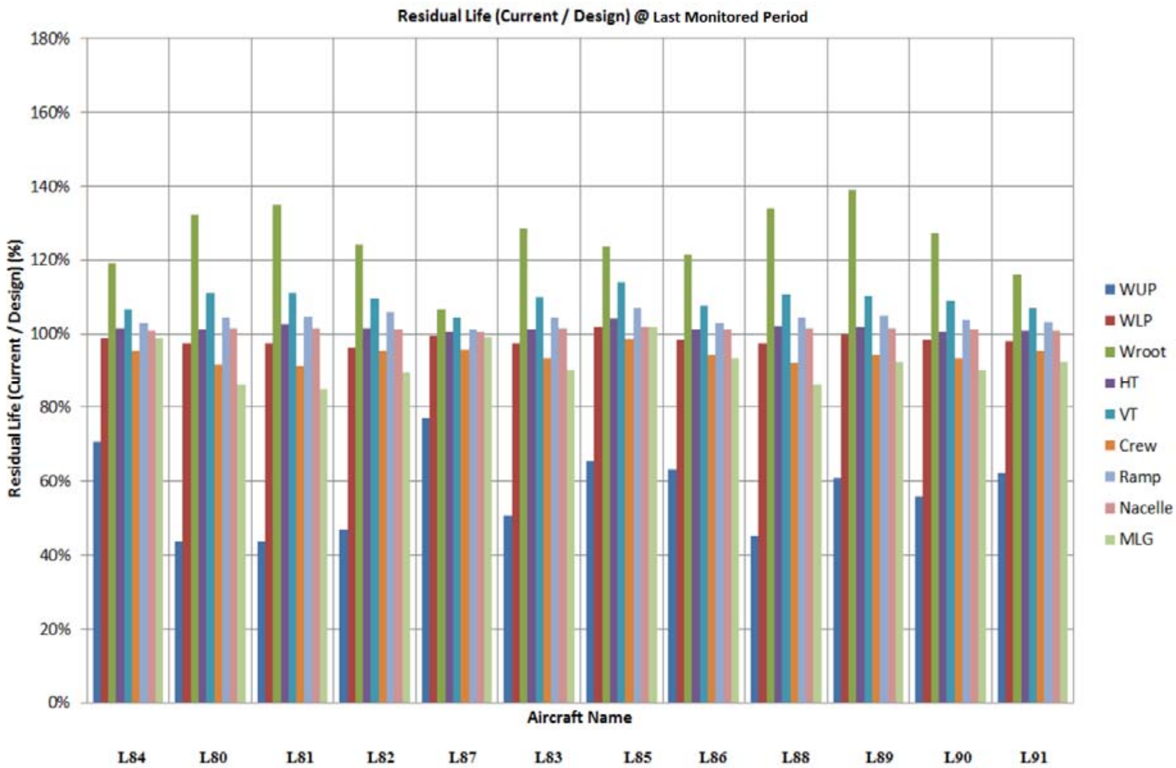


Fig. 6 – Residual life, as a percentage of original design life, of the control points in different C-27J aircrafts.

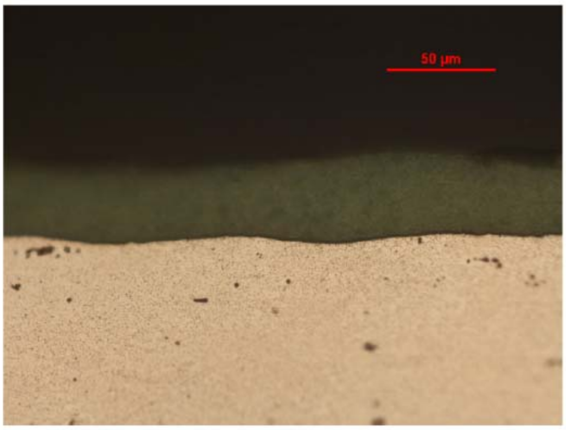
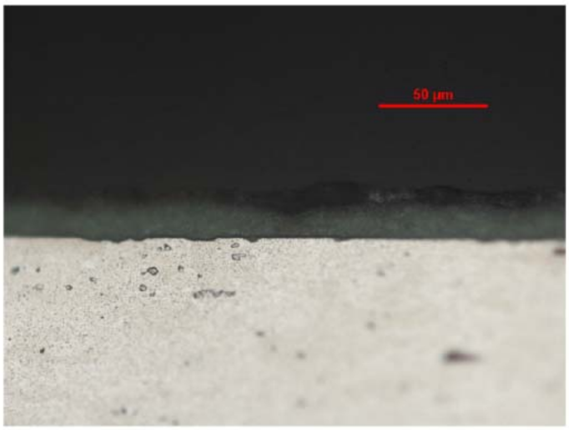
	
Chemical milled	**Mechanical milled**

Fig. 7 – Macro images of the microstructures after milling (Keller's etchant).

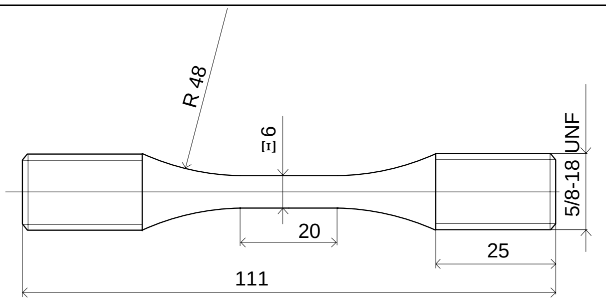
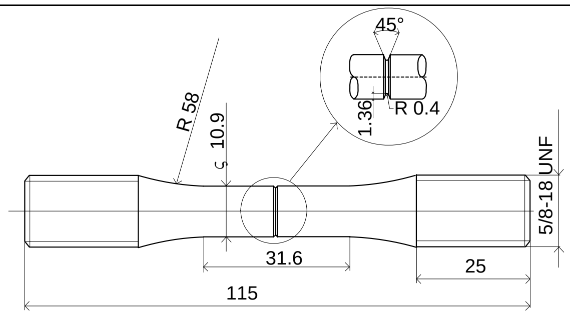
	
a) Un-notched specimen	b) Notched specimen

Fig. 8 - Geometry of the specimens used for assessing the fatigue behaviour of 7075-T73 in high temperature.

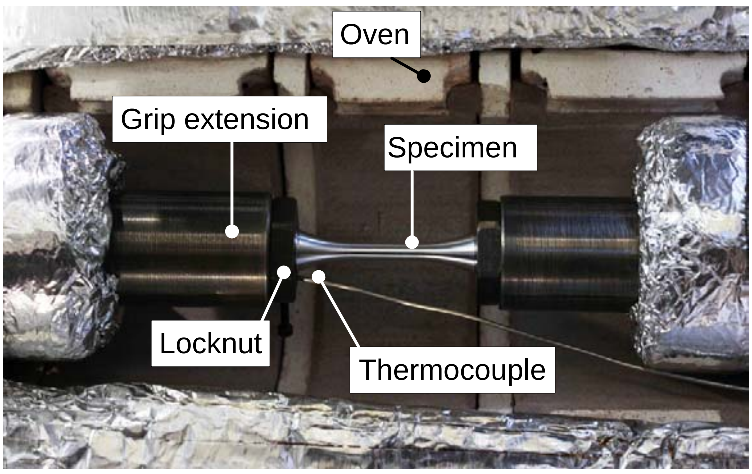


Fig. 9 - Oven for high temperature fatigue tests.

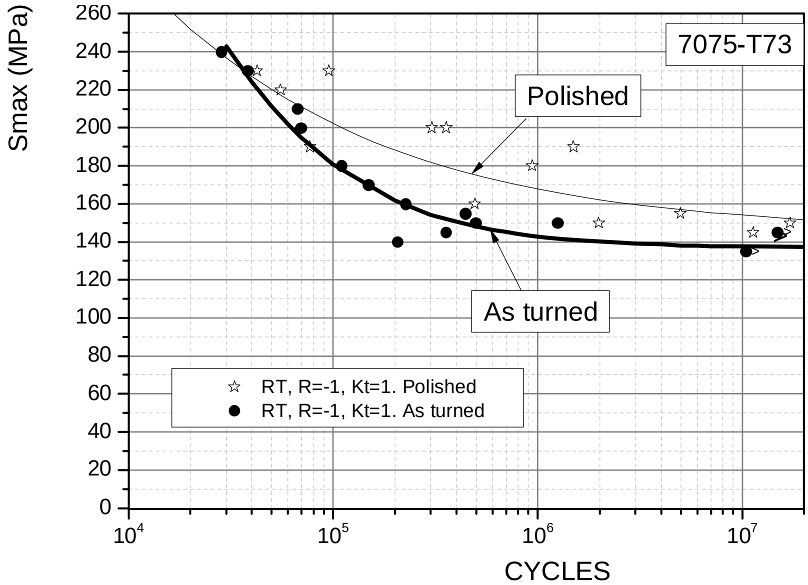


Fig. 10 - Fatigue test results of reference and of polished specimens in 7075-T73, Room Temperature.

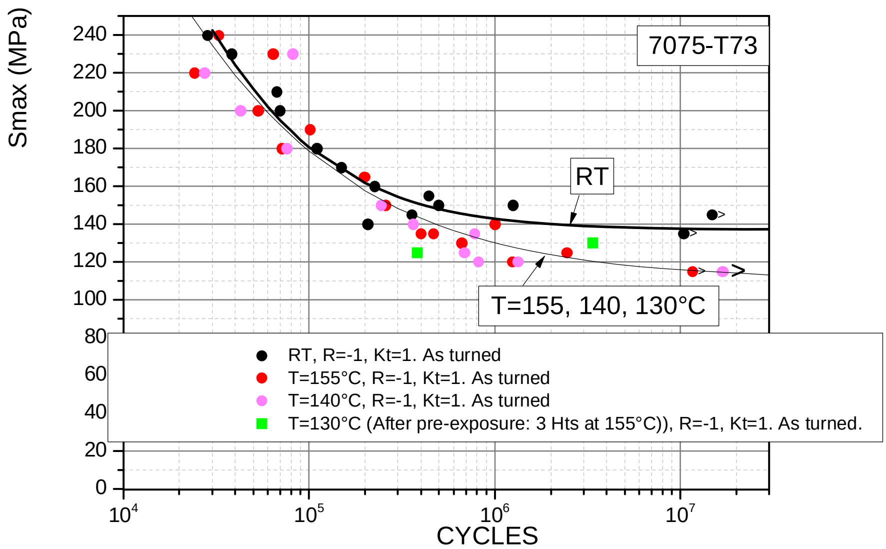


Fig. 11 - Effect of test temperature on the fatigue behaviour of un-notched 7075-T73 specimens.

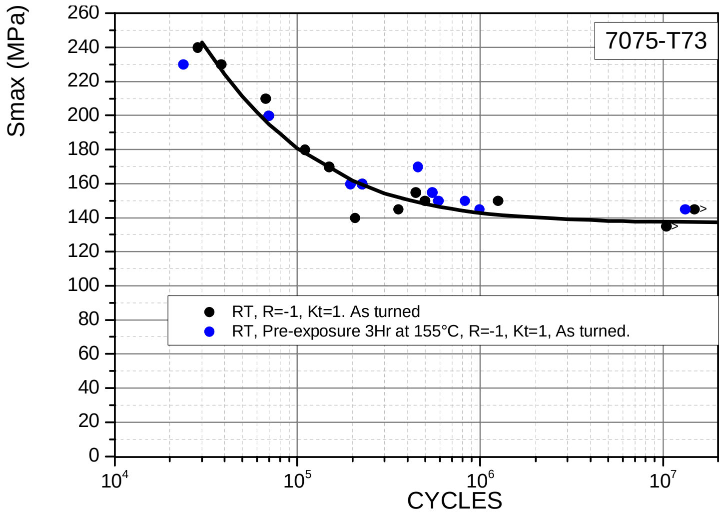


Fig. 12 - Effect of pre-exposure (3 hours at 155°C) on specimens tested at RT.

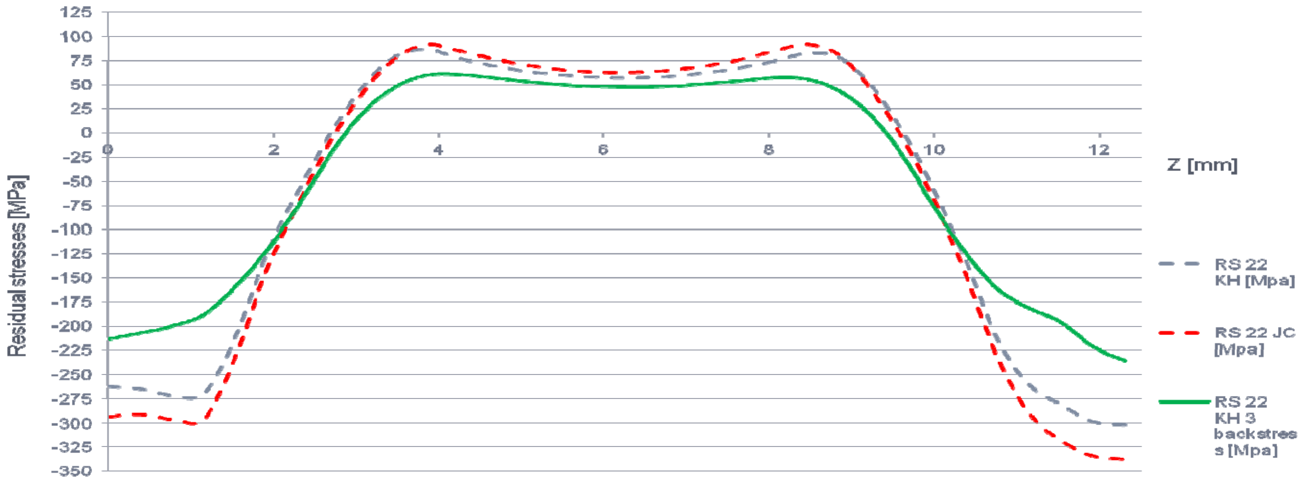
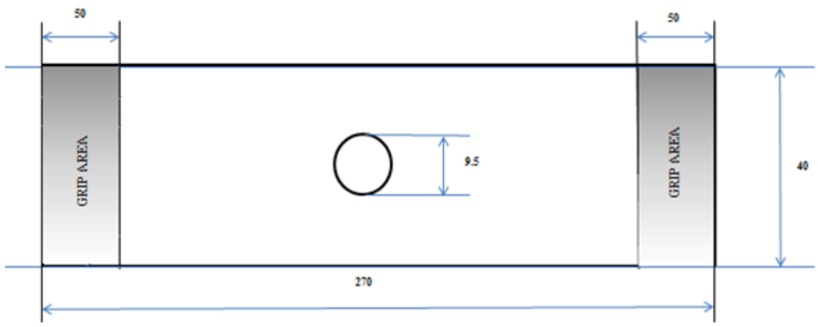
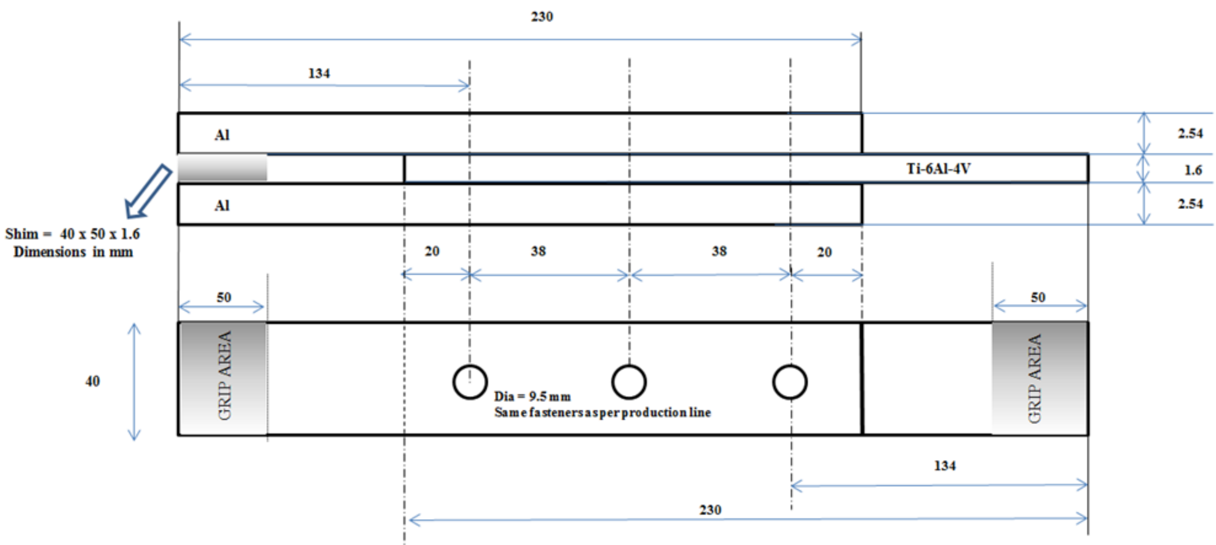


Fig. 13 – Comparison of self-equilibrated residual stresses distributions, after laser shock peening process, obtained by three different numerical approaches.

Fig. 14 - Typical component where Ti and Al sheets are drilled together.



Open Hole Specimen



Load Transfer Specimen

Fig. 15 – Specimens for assessing the one-up assembly fatigue penalization.

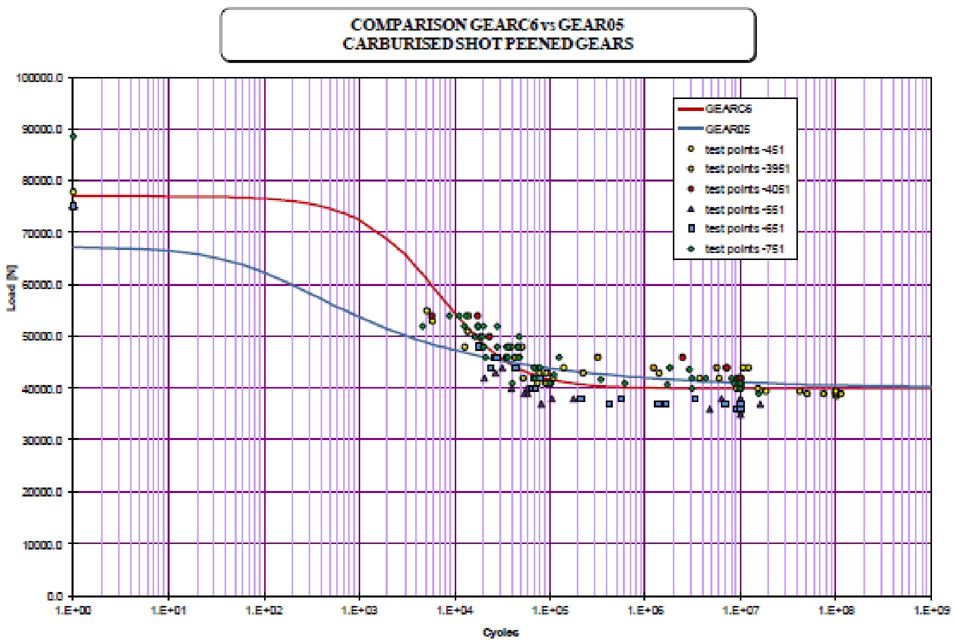


Fig. 16 – Comparison of S-N curves from two groups of shot peened carburized gears.

Fig. 17a – Fatigue crack originated in a threaded hole in a Gleason crown.

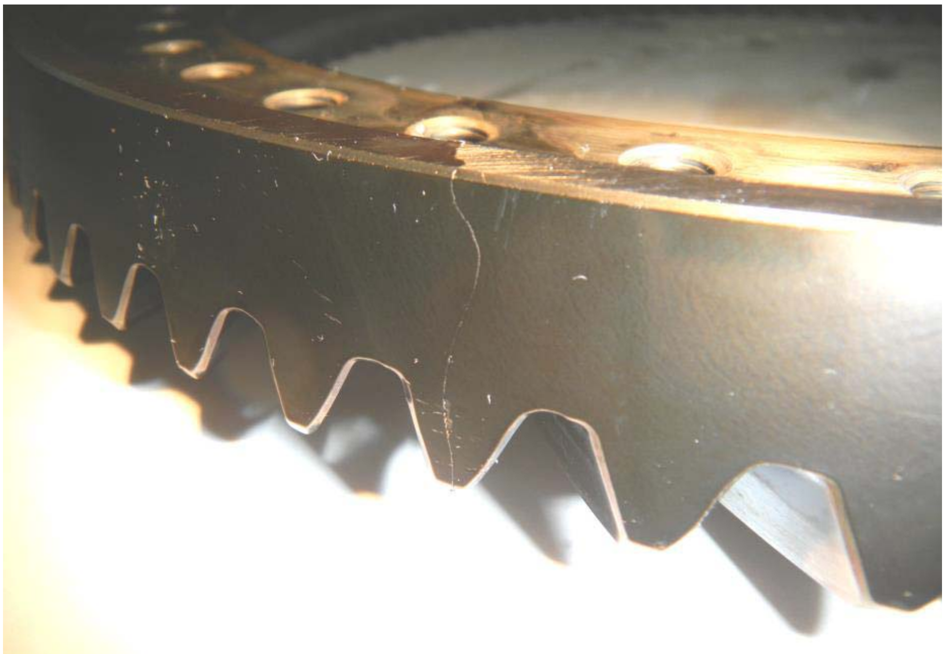


Fig. 17b – Crack originated in a hole and interesting all the crown.

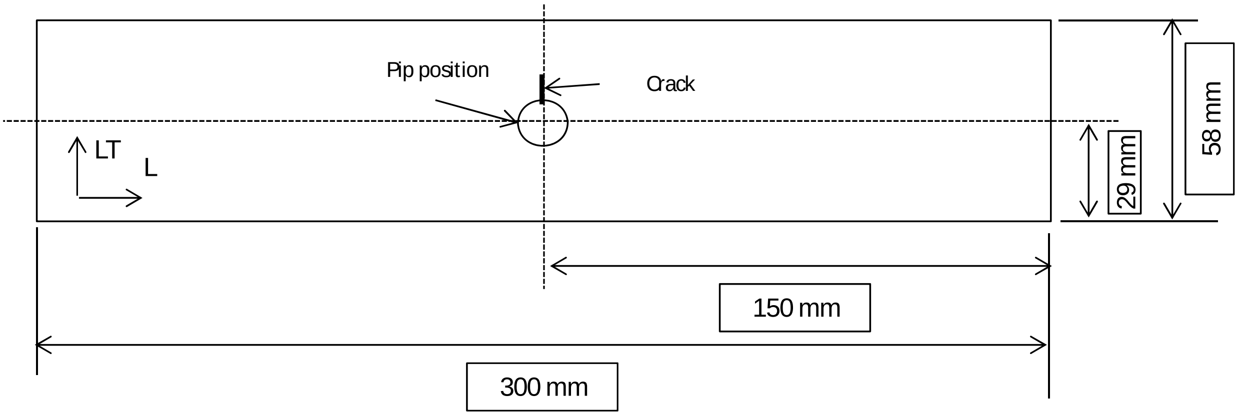


Fig. 18 – Geometry of the open hole specimen used for fatigue growth tests of corner crack in presence of residual stresses due to split sleeve cold expansion.

Fig. 19 – Photograph of the test set-up for fatigue crack growth of corner cracks in a open hole specimen.

Figure 20 – Fracture mechanics test set-up and fracture surfaces of corroded 2024-T351 specimens.

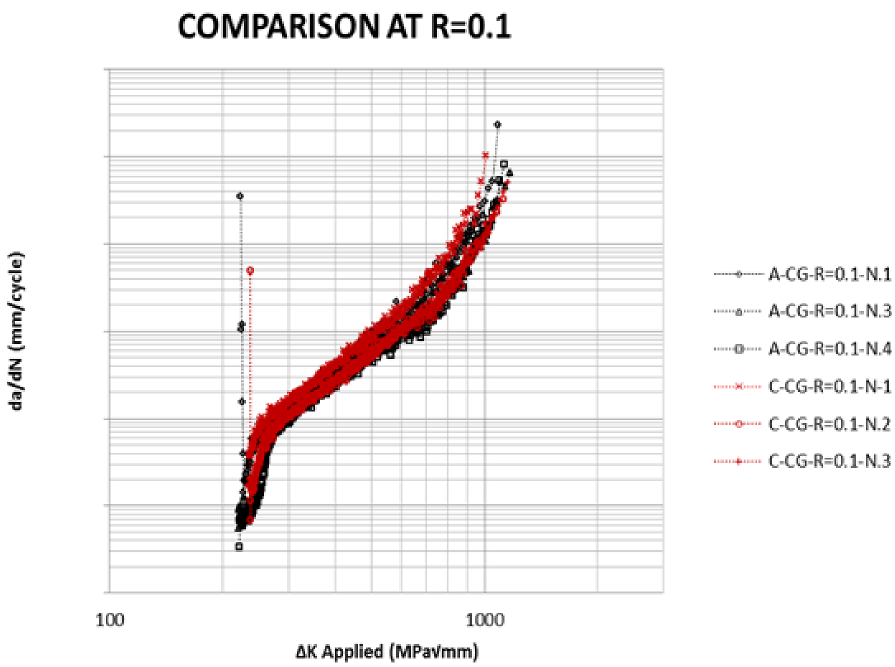


Fig. 21 – Comparison of fatigue crack growth results from corroded and pristine bare 2024-T351 alloy.

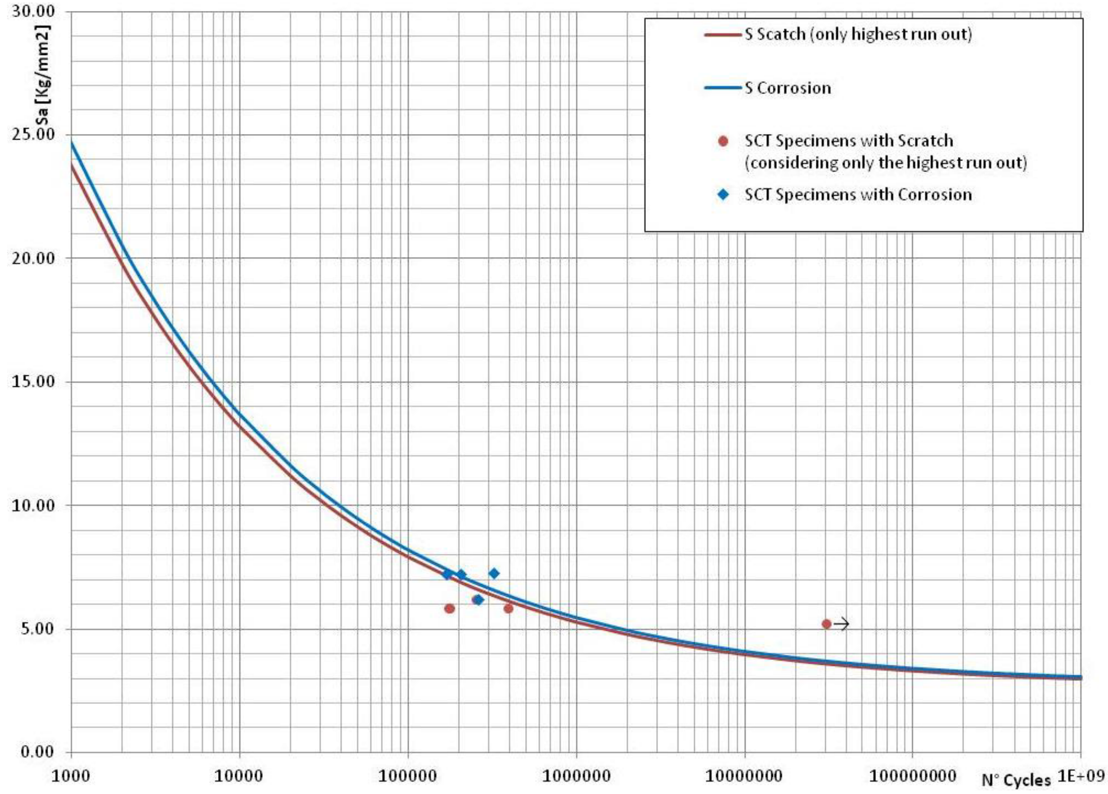


Fig. 22 – Assessment of influence of defects (corrosion pits and scratches) on the fatigue behaviour of 2014 alloy.

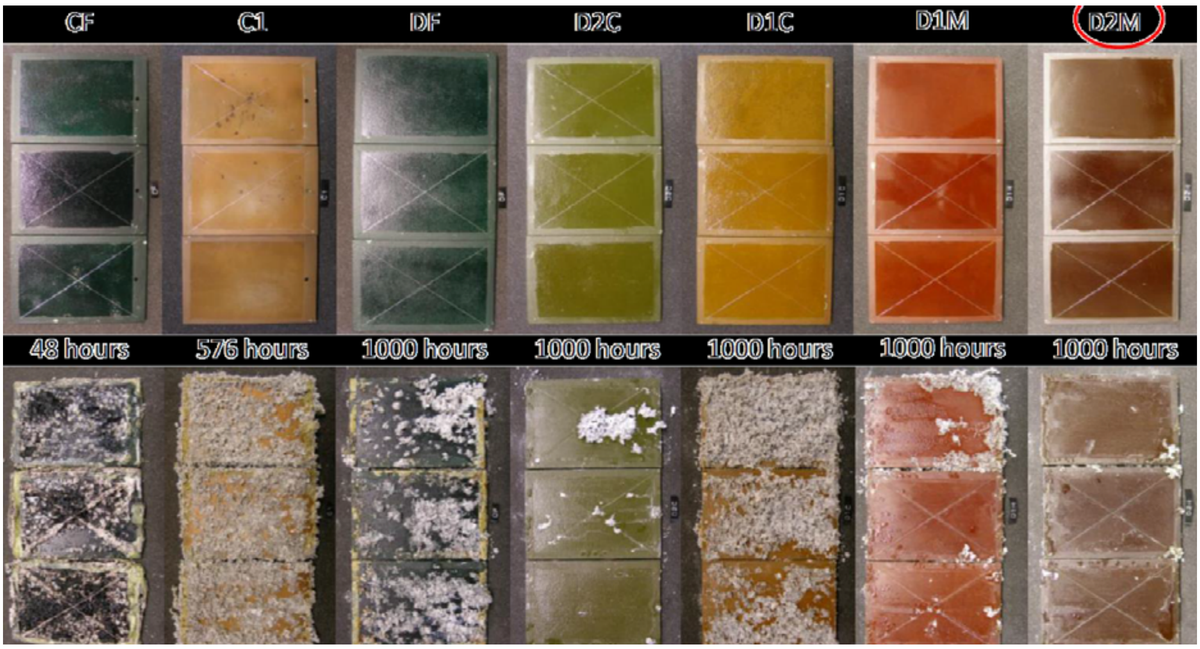


Fig. 23 – Evaluation of different surface protection systems applied to Mg casting alloy.

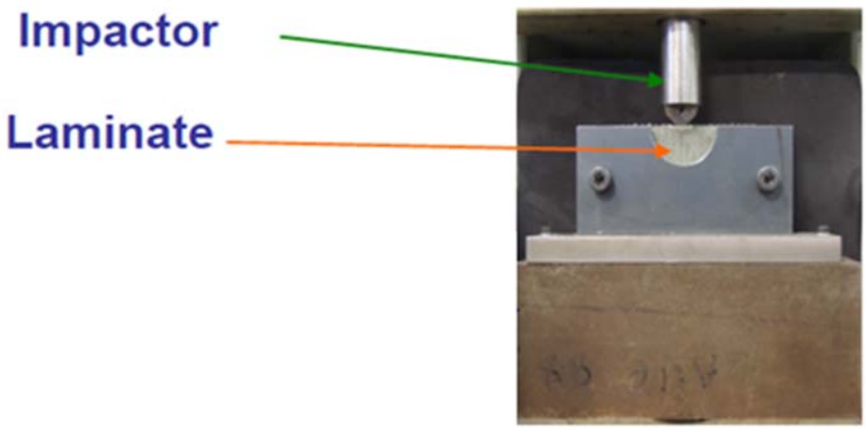


Fig. 24a - Vertical drop weight

Fig. 24b - Charpy pendulum.

Figures 24 – Systems for introducing edge impact damage in CFRP plates.

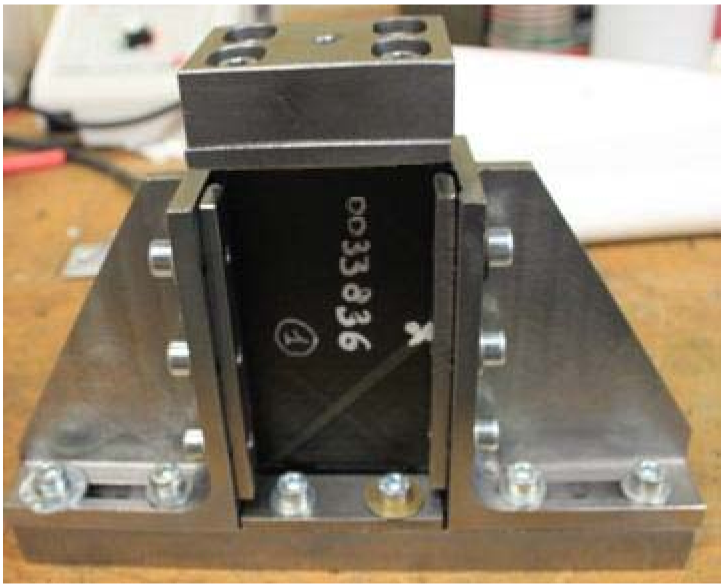


Fig. 25 – Compression After Impact test set-up for the evaluation of edge impact influence.

Fig. 26 – Full scale Fatigue and Damage Tolerance test of the composite structures of the Bombardier C Series Horizontal Tail.