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 2015 - March 2017

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This document summarizes the principal research activities carried out in Italy about aeronautical fatigue in the period April 2015 – March 2017. The main topics covered are: operational load analysis, fatigue and fracture mechanics of metals, usage monitoring systems, fatigue and damage tolerance of composites, full scale testing.

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CONTENTS

1. INTRODUCTION

This paper summarises aeronautical fatigue investigations carried out in Italy during the period April 2015 to March 2017. The different contributions have been arranged according to the topics, which are operational load 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 (Leonardo Aircraft Division)

On AMX aircraft, fatigue monitoring is performed by means of classic mechanical g-meter readings and on the basis of 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, more than 200 thousand flight hours have been monitored since the aircraft entered into service. After a period between 2008 and 2014 when the monitored FH were not all the flown hours, now the life monitoring again covers all the activities.

The Load Severity Index (L.S.I.), defined as the ratio between the In-Service Life Damage and the Design Life Usage, is the parameter defined by Leonardo Aircraft Division for assessing the usage of the various aircraft. In the last period of observation, a tendency towards lower severity utilisation rates is evidenced, with an average value of 0.97 for the whole fleet, which anyhow means that the fatigue life consumption is substantially in line with design assumptions. The L.S.I. trend as a function of time (Fig. 1) shows a slight difference between the Strike aircraft (with a LSI index lower than 1) and the Trainer aircraft (which has on the contrary a LSI index higher than 1).

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.

2.2 - Life monitoring of the TORNADO fleet (Leonardo Aircraft Division)

Fatigue life monitoring has been performed by Leonardo Aircraft Division 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, more than 280 thousand flights hours have been monitored, up to March 2016, when a new, more sophisticated software for fatigue monitoring was introduced. 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.

It is worthwhile mentioning that a few years ago a number of machines of this multirole aircraft experienced a change in the utilization, associated with a longer duration sortie (with in-flight refuelling) but, above all, a different mission. Fig. 4 qualitatively shows how this event has modified the LSI trend. As an explanation of this change, Fig. 5 reports the relative percentage of various mission types (six, as shown in the legenda) with evidence that mission 1 has become by far the most flown, while others have almost disappeared.

2.3 - EF Typhoon life monitoring (Leonardo Aircraft Division)

Since 2003, 80 Euro Fighter Typhoon aircrafts (68 single seat and 12 twin seat) have been delivered to the Italian Air Force. Since entry into service (2005), more than 75000 flight hours (corresponding to about 50000 flights) have been flown, as for September 2016. The fleet leaders are now beyond 1300 FHs for SS and about 1100 FHs for TS.

Leonardo Aircraft Division 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.).

The in-service usage shows a spectrum shape similar to design assumptions, but less severe (Fig. 6). This trend is confirmed by Fatigue Indexes calculations, that are below the design values too (see Fig. 7); it is worthwhile mentioning that the usage in the last period is higher than the average of the cumulative data, as a consequence of two possible causes: a) a new version of the Flight Control System has changed the way in which some manoeuvres were performed; b) a few problems have been encountered in service by the on-board load monitoring system, with the consequence that the fatigue life of some flights has been estimated *a posteriori*, in a conservative way.

2.4 - Usage Monitoring System for EH101 helicopter (Leonardo Helicopter Division)

In the previous review, information was given about the progresses made by Leonardo Helicopter Division (formerly AgustaWestland) in the development of a Health and Usage Monitoring System (HUMS), a fundamental tool for the assessment of usage spectrum. At the beginning, the typical approach was based on the analysis of theoretical mission profiles and pilots' experience feedback, but nowadays HUMS systems are installed on a number of LHD helicopters and represent a robust instrument for the fleet usage definition, thanks to the Flight Condition Recognition tool (FCR).

For each helicopter, at least 300 hours must be gathered in service, for a robust statistical analysis. The data recorded is processed to determine the main parameters of usage, such as Take-off Weight and Centering Distribution, Density Altitudes, Start and Stop events (SS) and Ground-Air-Ground cycles (GAG). Furthermore, the FCR routine allows to determine the maneuver typology, monitoring the variation of some key parameters, like speed, acceleration, body angles, for similarity with the load survey flight tests. Whenever the flight maneuver does not reflect any laws of the banked control management, the condition is categorized as "Anomalous".

A recent work has concerned a whole AW101 military fleet deployed in mixed Search-And-Rescue (SAR) and Utility scenarios represented by two different theoretical usage spectra. This variant is equipped with HUMS software acquiring data every Main Rotor revolution. More than 25000 hours have been processed, analyzing data of each helicopter. The study has highlighted irregular usage for three helicopters, that were later addressed by the Customer as temporary deployments. Particular care has been taken in the management of this result and a deeper analysis, considering the information received from the Customer, has confirmed short term differences from the norm. Finally, a unique usage spectrum has been defined based on the HUMS data, complemented by the pilots' information, whenever the FCR could not provide sufficient details.

The comparison with the theoretical assumptions has highlighted a less severe distribution of Take-off Weight and Altitude, but has also shown a more demanding usage in terms of standard maneuvered flight and low frequency occurrences. Despite the FCR is not designed to recognize aggressive maneuvers for special roles, it has been possible to reduce their theoretical occurrences, allocating conservatively the whole time assigned by HUMS to "Anomalous" conditions. The results of the spectrum analysis have been discussed with the Customer and the Military Authority and approved for the final development.

New fatigue lives have been evaluated, leading to a beneficial impact on the maintenance limits for all those components, like MR Rotating Controls, affected by the reduction of the time spent in high Take-Off Weight and high Altitude condition and by the reduction of aggressive maneuvers. On the contrary, components mostly stressed by low frequency loading cycles, like transmissions, have been subjected to a residual fatigue life decrease, caused by the higher SS and GAG occurrences. In this case, HUMS has demonstrated its effectiveness in preserving the aircraft safety on the basis of a correct estimation of the actual usage, Fig. 8.

Other customers have requested the HUMS data analysis to revise the theoretical usage spectrum. In some cases, the analysis has been complemented by a comparison with the flight log sheets, showing a general agreement with the manual recordings.

2.5 – C-27J Program (Leonardo Aircraft Division)

Information has already been given in previous National Review editions about the C-27J monitoring activity, which is performed through a specially developed I.A.T.P. (Individual Aircraft Tracking Program) software. The actual fatigue status of each aircraft is monitored on the basis of the actual mission profiles and load spectra, determined through the direct recording of in-flight parameters.

The usage severity is assessed by means of a Crack Growth Module, which performs the comparison between potential 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). Similarly to other usage monitoring activities performed by Leonardo Aircraft Division, for the main representative locations of structural items a Load Severity Index parameter (LSI) is defined, which is the ratio between the In-Service Life Damage and the Design Life Usage. Nine specific aircraft locations have been chosen as particularly significant to monitor the fatigue life of the entire aircraft structure, see Fig. 9.

Fig. 10 shows, for a number of individual airplanes, that the (slight) differences in the rate of residual life between the In-Service spectrum and the Design spectrum, in the nine locations selected, decrease in the last period of observation. With the exception of a particular aircraft, the others show that the actual rate of fatigue consumption is almost coherent with the predicted design usage.

3. METALS

3.1 - Fatigue behaviour of notched and un-notched materials

3.1.1 - One-Up assembly fatigue knock-down factor (Leonardo Aircraft Division)

The drilling of joints made of different materials produces 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. This effect is almost unavoidable in some manufacturing processes.

A test campaign was announced in the last National Review and in the last two years has been performed; in particular, a location where aluminium-titanium-aluminium are one-up drilled without performing the deburring of the holes on the titanium part was 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 joint specimens have been tested and a few examples of failed low-load transfer joints are shown in Fig. 11. The evaluation of the test results has pointed out that the effect of undeburred holes slightly reduces the fatigue life of open hole specimens, but anyhow the relevant knockdown factor is close to 1. Moreover, for the double shear joint geometry with low load transfer, the undeburred condition does not show any effect on the fatigue life (knock down factor = 1.0).

3.1.2 - Chromic acid anodising vs tartaric-sulphuric acid anodising (Leonardo Aircraft Division)

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. Leonardo Aircraft Division, in order to comply with the REACH regulation, has undertaken a large research activity to assess the influence on the fatigue behaviour of the TSA (Tartaric-Sulphuric Anodizing) process, that will replace the well-known, but banned, CAA (Chromic Acid Anodizing) process.

In the last National Review a large test campaign has been defined and outlined; it includes the most used aluminium materials: three aluminium alloy families, 2000, 7000 and 6000, have been selected, for an amount of about 900 specimens. 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 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

The first set of results provides evidence that the TSA 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. From the fatigue point of view, the two anodizing treatments show a substantially similar behaviour; Fig. 12 reports some results, in terms of ratio of the two knock down factors.

3.1.3 – Fatigue of gears (Leonardo Helicopter Division)

A long term test program is running at Leonardo Helicopter Division (formerly 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. This collaboration is becoming of growing importance, because helicopter manufacturers are addressing the fatigue evaluation of transmission elements and gearboxes 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 inspection programs are defined on the basis of fracture mechanics analyses, or fail safety or flaw tolerance to maximum likely damages.

In the period of the present Review, a test activity has been performed to validate processes for carburizing, heat treatment, and grinding of Vasco X-2M gear steel used on CH47F, since LHD is becoming supplier for CH47 gears. Gear teeth bending fatigue tests were carried out at Milan Polytechnic, according to the standard methodology already described in other National Reviews. The results obtained are fully consistent with US generated data, obtained with a different experimental approach and, consequently, also a different test rig.

3.2 - Crack propagation and fracture mechanics

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

A collaboration between Airbus Deutschland and the Department of Civil and Industrial Engineering - Aerospace Division of the University of Pisa is in progress, for the study of the fatigue crack growth of corner cracks in cold expanded holes. Experiments have been carried out on open hole specimens in 2024-T351 aluminium alloy and were described in [1]. In the last two years, another test campaign has been launched to extend to other situations the experimental database: open hole specimens, 10 mm thick, and a number of pin loaded cases (100% load transfer, in 2, 6 and 10 mm thick elements). The test activity is still in progress; the experiments on open hole specimens are carried out with a test procedure similar to the one adopted and described in [1], while for the pin loaded holes, due to the non inspectability of the crack tip, a marking load (60,000 cycles at R=0.9) block has been interspersed in the constant amplitude R=0.1 sequence (Fig. 13).

Moreover, a numerical strategy has been developed, based on the use of Finite Element approach to evaluate the residual stress field after the application of the split-sleeve cold expansion, followed by another numerical analysis for the assessment of the stress intensity factor along the crack front. Two codes, written in Python and Mathlab, allow to manage the crack growth analysis of a 3-D defect like a quarter-circular corner crack in an automatic way. The numerical approach will be presented in detail in a paper at the Symposium, [2].

3.2.2 - Development of an integrated Fracture Mechanics and Finite Elements tool (Leonardo Aircraft Division)

Commonly used Fracture Mechanics analysis calculation approaches make use of simple consolidated models, that well represent locally the crack behaviour, and apply them to large and complex structural configurations. In this scenario, clear engineering assumptions and evaluations are necessary and may translate in limiting the theoretical results applicability.

Potential areas of development were investigated: the improvement of integration between LEFM and Finite Element method was identified and dedicated activities were put in place by Leonardo and MSC Software.

This integrated methodology is expected to deal with Fracture Mechanics analyses related with the following topics:

- Complex geometry of structural items;
- Crack path not defined in advance;
- Long and complex load spectra (thousands of cycles);
- Multiple cracks initiation.

The activity was arranged in 3 phases:

Phase 1) Validation of the methodology by comparison with currently used LEFM calculations methods (2D). Simple geometries are used (free edge, open hole, filled hole).

Phase 2) Validation with 3D crack models (free edge, open hole and filled hole); Crack initiation: corner; Tri-dimensional FE elements; Possibility to use Automatic Re-mesh options in an effective way even on large FE models.

Phase 3) Test the methodology on complex structural items; Geometry and FE model dimension representative of real primary structure items and FE models generally used.

For the evaluation of the Stress Intensity Factor, the Virtual Crack Closure Technique has been selected, while for the evaluation of crack growth a Paris-like law has been adopted. An iterative procedure has been set-up to perform a complete crack growth analysis.

A preliminary validation phase has been performed, in order to assess the accuracy and reliability of the integrated approach with respect to traditional methodology: results from simple cases like open hole, edge cracks, etc. have been successfully compared with those obtained with the integrated FE/FM approach (Fig. 14 shows an example of the results obtained). After the successful evaluation of the first two phases, the third one (dedicated to the analysis of complex structural configurations and crack path not defined in advance) is in progress. The VCCT in combination with dynamic (concurrent) Finite Elements re-meshing capability shall be deeply investigated. Presently, dynamic and automatic Finite Element model re-meshing utilities are being tested with medium complexity models, in order to establish the impact in terms of computational cost and results. Preliminary results show that the possibility exists for an efficient compromise between CPU time and VCCT results accuracy.

3.3 - Corrosion and fatigue

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

In the last National Review, a paragraph was added on this topic, because during AW189 and AW169 Type Certification, EASA specialists requested additional information on "Fatigue and Corrosion of PSE".

Test data were produced from coupons obtained from retired components (minimum 8 years and 600 flight hours) and demonstrated a similar fatigue strength of 2014 specimens with corrosion pits and of specimens with sharp flaws (scratches), giving evidence that flaw tolerance tests cover also the corrosion phenomena.

Data from periodic inspections were checked for verification of corrosion "acceptable for repair" and those causing discard. As an example, Fig. 15(a) shows a swashplate with evidence of corrosion, while in Fig. 15(b) the same swashplate location after treatment with fine sandpaper and scotch brite is shown. Helicopters operate in a very corrosive environment; initially, a periodic inspection every two years was required for swashplates, but the rate of discharge with a two years inspection interval was too high and so an inspection every 12 months has been introduced, to improve reparability.

4. COMPOSITES AND FIBER METAL LAMINATES

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

Nowadays, aircrafts are required to withstand different ranges of impact severity during their operational life, but there is still a lack of basic knowledge on how the typical aeronautical materials respond, in particular composites: design standards, in fact, envisage high safety factors, which reduce the proper application of such advanced materials.

Aircraft structures are exposed to many different causes of impact events that could have different energies, velocities and location. Damages induced by these impacts can lead to brittle and sudden failure, up to a catastrophic event. Therefore, it is important to understand composite materials characteristics against this threat, in order to be able to design safer and lighter structures.

One of the most dangerous impact type is the Low Velocity Impact: in fact, this may cause no or feeble damage on the hit surface (which could be easily missed during normal visual inspection) but extensive internal degradation. The latter could deeply influence material characteristics leading to unsafe operative conditions.

This threat was widely addressed in an activity carried out on impact damage tolerance at the University of Bologna MaSTeR Lab, trying to analyse it from experimental and numerical points of view. The activity was focused on a carbon/epoxy material system, namely Tenax-J UTS50 fibres in DT120 epoxy resin: two experimental campaigns were conducted on cross-ply laminates, involving different thicknesses (2.9 and 5.5 mm) and impact energies (3, 5 and 7 J). The purpose was to identify the influence of low energy impacts on the compressive residual strength of a carbon/epoxy laminate, depending on material thickness and impact locations. This experimental activity proved that even a low energy impact, which does not cause evidence on laminate surface, can result in a significant reduction of compressive residual strength (Fig. 16). For instance, a 31% compressive strength reduction, evaluated by means of CLC tests carried out according to ASTM D6641, was observed for 2.9 mm laminates impacted near-edge with a 5 J energy. Moreover, a near-edge impact resulted in a higher reduction with respect to a central location (only 14% reduction, for the same specimen type as before), giving evidence of the impact location importance. This becomes even more relevant when it is considered how more common are near-edge impact on an airplane, compared to central ones.

It was also proved that not every low energy impact influences material characteristics: there is an energy threshold under which, even if a damage is created, this is irrelevant (the compressive residual strength remains within the material data scatter). This threshold depends on composite characteristics, laminate stacking sequence and thickness.

Numerical analyses were also carried out, by means of Abaqus. Both near edge and central impacts were simulated, using 2D shell elements for the laminae and 3D cohesive elements for the interface (Fig. 17). The explicit solver was used, and the duration of the impact step was set 0.01 sec, in line with the experimental measured data. A good agreement was obtained between delamination extension and impact energy; more details can be found in a paper presented at the Symposium, [3].

It was, therefore, necessary to figure out which improvements were possible to increase the composite impact resistance. Thanks to a collaboration between Forlì research group MaSTeR Lab and Structural Integrity and Composites group at the Aerospace Engineering Faculty of TU Delft, it was possible to start a research on Fibre Metal Laminates. This hybrid material shows good properties, combining metal foils and composite plies advantages.

A Quasi Static Indentation experimental campaign was conducted on four different laminates: they were made of carbon/epoxy fabric and Aluminium 2024-T3 foils, which were located in different positions inside the stacking sequence. This led to an evaluation of Al layers position influence on material indentation resistance. The results showed that a carbon/epoxy laminate, reinforced with Al layers on the external, has a better behaviour due to a more stable failure mode and a higher resistance. Therefore, this should be the preferred Al location for a better impact behaviour (literature papers show accordance between Quasi Static Indentation and Low Velocity Impact tests results). Moreover, an external Al layer can give more chances in impact individuation due to plastic deformation.

A numerical investigation was also carried out, using Abaqus software. Two models were developed: the first one was intended as a preliminary analysis of software reliability on impact event simulation; in the second, Fibre Metal Laminates were modelled. In both models, cohesive elements were used in order to simulate laminae interface damages and, therefore, delaminations. Good accordance with experimental tests was obtained and, therefore, the models were considered reliable. A paper on this activity will be 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 Leonardo Helicopter Division (formerly AgustaWestland) and the Department of Civil and Industrial Engineering of the University of Pisa, 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 and has been recently oriented towards the assessment of new materials, that are proposed by the producers to LHD. The change of material will impact a number of Principal Structural Elements of major rotor parts of various helicopters:

MR Tension Link (AW109/109Power; AW129; AW139; AW149; AW169; AW189)

MR Blade spar (AW101; AW149; AW159; AW189; AW Lynx/SuperLynx)

The Certification approach, based on the test pyramid, requires the full re-assessment of the material properties (included those relevant to delamination resistance) and a number of component tests.

In the period of the present Review, a number of fatigue tests have been carried out on DCB and ENF specimens for the assessment of the number of cycles required to obtain a delamination growth such to induce a 5% stiffness reduction with respect to the initial value. Various material systems have been 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.

The mode I tests have been carried out following the ASTM D6115 standard (that does not consider a precracking phase), while the mode II tests were performed on preliminarily pre-cracked ENF specimen. The reason for this difference lays in the fact that there is a wide literature on the considerable influence of the resin rich pocket at the insert end on mode II interlaminar fracture toughness.

Some results are shown in Figs. 18 and 19, where a reasonable agreement is observed; it should be kept in mind that the fabric material shows a higher static toughness, in comparison with unidirectional materials.

4.3 - Effect of interleaving on mechanical behaviour of a graphite/epoxy fabric (Milan Polytechnic)

An experimental research program has been developed and is in progress at the Department of Aerospace Sciences and Technologies of the Milan Polytechnic on the effect of interlayers addition on the interlaminar fracture toughness of composite materials. To this end, a graphite/epoxy system has been selected, namely a 5 harness satin of AGP-280 fibres in 8552 resin, toughened with thermoplastic particles dispersion. With this material, reference specimens have been manufactured, together with a number of interleaved configurations, obtained with the addition of an interlayer of Xantulayr, a mat made of continuous Nylon 6,6 fibres, produced by electrodrawing. Preliminary measurement and weighting operations have shown no appreciable effects of the interlayer addition on the thickness and weight of the laminates. A wide test program has been planned and is in progress, comprising basic mechanical tests (tensile, in-plane shear, compression after impact, interlaminar shear strength), together with fracture mechanics and fatigue tests (DCB, ENF, fatigue of open hole specimens). All these tests are being carried out in various environmental conditions: RTD and RTW for all the types of tests, and moreover HTD (80 °C, no conditioned coupons) for all the tests, except CAI and fatigue. The complete set of results will give a clear view of the effects of interleaving on composite materials, considering many aspects. To shorten the text, only DCB and ENF test results will be presented.

Four repetitions for each conditions (RTD, RTW and HTD) have been performed. The ASTM-D5528 standard practice has been developed for unidirectional materials, but it has been followed in this case, as well. In the case of DCB, for instance, the load-displacement plot is rich in peaks, with a slip-stick growth characteristic, while a smooth curve is normally shown for unidirectional material. A considerable bridging effect is also observed, due to the intrinsic nature of the fabric style. The effect of interleaving is contradictory: almost no influence with respect to the reference material is observed in RTD tests, while a strong reduction (-28%) is observed in RTW and a strong increase in HTD tests (+32%).

Mode II tests were carried out by means of three point bending tests on ENF specimens, following the recommendations of ASTM-D7905. Since more than one value can be obtained from the same specimen, it was considered appropriate to increase the statistical significance by replicating three times the test for each specimen, keeping the same initial delamination length. It was observed that the three replicates gave increasing toughness values, which was attributed to the development of friction in the new, fresh interface area. It has therefore been taken the average value of the three, for comparison with the other situations. The interleaved material has provided an increase in mode II toughness with respect to the reference material of 13% in RTD conditions and 10% in HTD conditions, while no particular influence was noted in RTW conditions.

Impact tests have shown that interleaved laminates have a less evident damage than reference material; fig. 20 shows tomography images of the different damage patterns between reference and interleaved specimens, after a 10 J impact in RTD conditions and similar conclusions were obtained with optical microscopy. CAI tests results show an increase of strength for low intensity (10 J) impact energy, and a lower benefit for a visible impact (30 J).

Fatigue tests have finally been carried out on open hole specimens, with the intention to study the damage development and the stiffness reduction with constant amplitude loading. Non destructive analyses have been carried out by means of ultrasonic inspection, X-ray radiography and tomography, to evaluate the differences in damage progress. The conclusion is that the fatigue life is positively influenced by the interleave layer, and that environmental conditioning has a lower effect on the interleaved material.

The general conclusions of this activity show a global appreciation of the interleaving technique, maybe more slightly than expected, but this could be the consequence of the fact that the reference material has already a toughened matrix, and so does not receive big benefits (an old, brittle matrix would probably have received a higher benefit, in terms of increase in the performance).

4.4 - Fatigue behaviour of elastomers (Leonardo Helicopter Division)

Leonardo Helicopter Division uses elastomers for several rotor applications, such as spherical bearings (MR and TR), damper body and link (MR and TR), pitch link in the TR area. Typical aspects of the mechanical and fatigue behaviour of these materials were addressed in details, in order to have adequate confidence on their long-term behaviour. While different helicopter manufacturers have developed, based on their experience, different safety factors for elastomeric parts, LHD has decided to take into account the factor of 3 (for fail-safe components, with Ultimate Load capability) or 4 (assuming single load path + LL) to define inspection intervals from the outcome of damage growth tests.

Four criteria are used to stop :

- Failure of the component like debondings or cracks in metallic parts - not valid for elastomers;
- Loss of the minimum required performances – part normally rejected – redesign;
- Decay of 20% of the spring rate (application of static load is required to validate the test);
- Dimension of the crack: length and depth (static load required to validate the test).

Tests are performed to evaluate the crack growth rate in the rubber, which is related to the Strain Energy Release Rate, G (often called "tearing energy" in the rubber technical literature): Fig. 21 shows a typical experimental plot.

Specimens data was generated and analysed to confirm that progressive stiffness decay occurs, associated with the damage growth, which has in itself an important consequence, because the correlated progressive stiffness decay reduces the functionality of the elastomeric component. Therefore, tests have been carried out by monitoring the stiffness of the component (Fig. 22); when a 20% stiffness reduction was reached, the tests were interrupted. In no case an abrupt degradation occurred, but always gradual. In other words, the damage propagation is progressive, like for metallic materials. Moreover, the scatter in the damage propagation phase is significantly lower than in the damage initiation phase.

For a higher fidelity, the damage growth tests for certification of elastomeric materials are carried out using full scale components, at working loading frequency. The inspection interval is a fraction of the time between detectable damage and the end of the test, which is represented by the required residual strength or by the achievement of 20% stiffness reduction. To assess if the approach is suitable, a set of spherical bearings was evaluated, proving that the damage growth range from visible to 20% stiffness decay is affected by a scatter (CV) of 10-11%. Since the scatter in damage initiation is much higher, the first inspection is set equal to the repetitive inspection interval (Fig. 23). The safety factor of 4 plus LL capability is typically used, or 3 plus UL if occurrence of the benign failure mode associated with fail safety is proved.

The difficulties in managing elastomers components are increased by the peculiar behaviour of such materials, which increase their stiffness at low temperature. Flight data collected on AW139 prove the progressive warming up by hysteresis and that the cooling aerodynamic effect has to be taken into account to adjust climatic chamber data.

5. COMPONENT AND FULL-SCALE TESTING

5.1 – ATR Main Landing Gear support life extension (Leonardo Aircraft Division)

As already presented in previous ICAF Symposia [5], 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, since it is a safe life item, 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 has 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 have been fabricated (see Fig. 24) and tested, with the objective of demonstrating 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. This was a strategic solution to simplify the test program and to reduce costs and time. In fact, it is just working in this way that has been possible to cover more locations, because fatigue rating allows the comparison of fatigue equivalent locations that are geometrically different.

To account for different in-service usage severities, three reaming levels have been investigated. The specimen is a simple lug, machined from the same material as the MLG Support Structure. The test campaign for the first reaming level has been completed and the trend shown in Fig. 25 has been observed: a deeper reaming level should be investigated to reach the objective.

5.2 – Development of the Bombardier C Series (Leonardo Aircraft Division)

Within the framework of this programme, focused on the design of a narrow body, medium range twin engine aircraft, Leonardo Aircraft Division 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 Leonardo Aircraft Division to characterize material, design choices and methodologies was already given in previous reviews. 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) and one for the metal structures (in progress). The differences in spectrum loading require the performance of two separate tests.

At present, the “metallic” HT test is in progress in Pomigliano d’Arco plant for the Durability and Damage Tolerance assessment. Three design lives have been planned (180000 flights); in the first two lives, the fatigue behaviour will be evaluated, while in the last one (from 120000 to 180000 flights) artificial cracks will be introduced on the test article to verify crack growth behaviour and residual strength conditions. Actually, the first design life has been completed without anomalies.

6. AIRCRAFT FATIGUE SUBSTANTIATION

6.1 - AW109 and variants (Leonardo Helicopter Division)

Following the initiatives already announced in the last National Review, a number of high maintenance or replacement cost components have seen an extension in their fatigue life, as a consequence of the completion of long experimental activities. For what concerns AW109 and AW119, it is worthwhile mentioning that in the last two years the MR blade retirement life for AW119 has passed from 10.000 Fh to 14.000 Fh.

A new AW109S variant has been developed, with skid landing gear, that allows to save costs and to improve payload; certification is expected within 2017.

6.2 - EH101 / AW101 helicopter (Leonardo Helicopter Division)

A new version of AW101 has been delivered to the Italian Air Force, with a Combat and Search And Rescue (CSAR) mixed role. The operator has requested the capacity of Air-To-Air Refuelling, night and day. Due to the differences in the load spectra associated with the two basic missions that can be operated by this machine, the next step will be to improve HUMS to manage flight time spent in the combat role.

For what concerns the AW101 SAR for the Norway, the analysis of an alternate Gross Weight of 16000 Kg (with limited VNE and flight envelope for loading factor) has been required.

6.3 - AW189 / AW139 / AW169 helicopter family (Leonardo Helicopter Division)

AW169 received the type certificate in June 2016. It is the smallest of the family, with 4800 Kg MTOW and it is available in VIP, SAR and Utility configurations. Among its peculiarities, for noise reduction and performance optimization, it has a variable rotor speed for the different flight regimes; this characteristic makes the optimization and tuning of the active vibration reduction system, AVCS, more complex.

Moreover, a number of improvements have been introduced on the three helicopters of the family (AW169 is the smallest and AW189 is the largest). They are often the consequence of the end of the certification test, with a clearance extended to a longer life for replacement. Some other life extensions were already announced by LHD and reported in the previous National Review. These extensions have a positive effect on the reduction of maintenance costs, without any negative consequences (such as increase in weight, higher fuel consumption, lower performance, and so on). In the following, some example of the fatigue related events in the last two years are given:

a) AW139

- Rotor run up in high wind, tests done improved clearance from 50 to 60 Kts max wind speed with no penalties up to 33 Kts
- Airframe inspection plan improved from 300 h to 1200 h
- Tail unit fatigue life from 19.000 Fh to 40.000 Fh
- TR Blade from 3.000 Fh to 40.000 Landings (rotor start)
- Tail Gear Box from 10.000 Fh to 15.000 Fh (equivalent to 2 TGB Overhaul)
- Landing Gear from 35.000 Landings to 50.000 Landings

b) AW169

- Airframe from 3.000 Fh to 10.000 Fh still provisional, test in progress
- Tail-Rear fuselage and Tailplane from 10.000 Fh to Unlimited
- MR Interblade Fluidelastic Damper from 1.200 Fh to 15.000 Fh
- MR and TR Blade life extension is in progress and should be concluded in early 2018; in combination with extension of MR Damper, it is estimated to produce a Direct Maintenance Cost reduction of more than 500 USD/Fh

c) AW189

- Airframe from 4.000 Fh to 8.000 Fh
- Rear-Tail fuselage from 3.000 Fh to 20.000 Landings
- MR Blade from 5.000 Fh to unlimited
- Tension Link from 3.000 Fh to Unlimited
- TBG from 1.100 Fh to 15.000 Fh

7. REFERENCES

[1] L. Lazzeri, D. Furfari, Q. Fu, A. Wetzel, M.B. Biasizzo, D.O. Busse: "Predicting fatigue crack growth emanating from cold-expanded holes", 28th ICAF Symposium, Helsinki, 3-5 June 2015.

[2] L. Boni, D. Fanteria, L. Lazzeri, D. Furfari: "Numerical prediction of fatigue crack propagation in cold-expanded holes", paper to be presented at the 29th ICAF Symposium, Nagoya, 7-9 June 2017.

[3] V. Ristori, E. Troiani, M. P. Falaschetti: "Damage Tolerance in CFRP structures - Numerical and experimental analysis of low energy near edge impacts", paper to be presented at the 29th ICAF Symposium, Nagoya, 7-9 June 2017.

[4] M. P. Falaschetti, C. Rans, E. Troiani: "On the Application of Metal Foils for Improving the Impact Damage Tolerance of Composite Materials", paper to be presented at the 29th ICAF Symposium, Nagoya, 7-9 June 2017.

[5] 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.

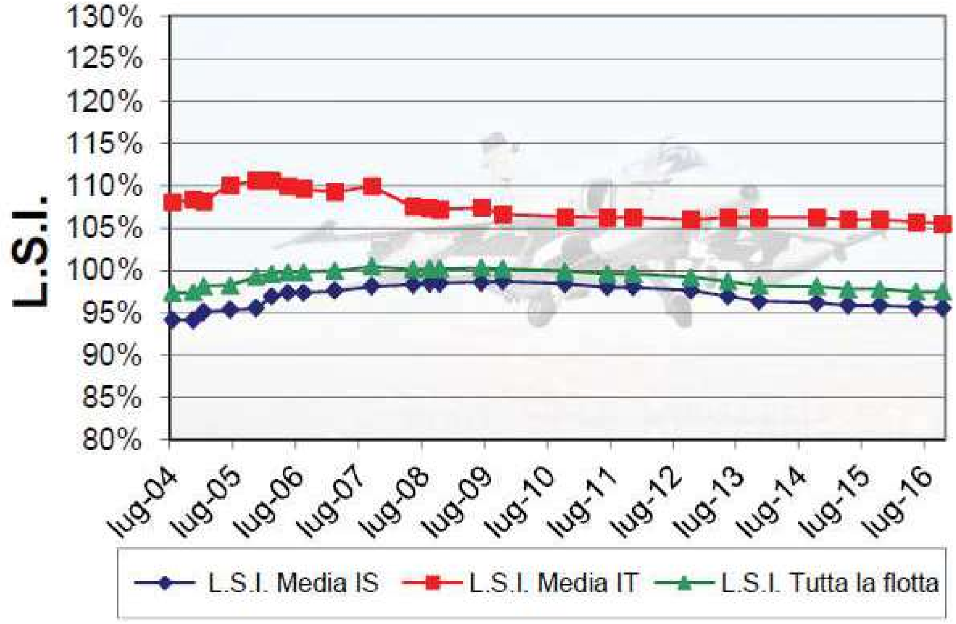


Fig. 1 – Trend of the global Load Severity Index for the AM-X fleet.
(IS: Strike aircraft; IT: Trainer aircraft)

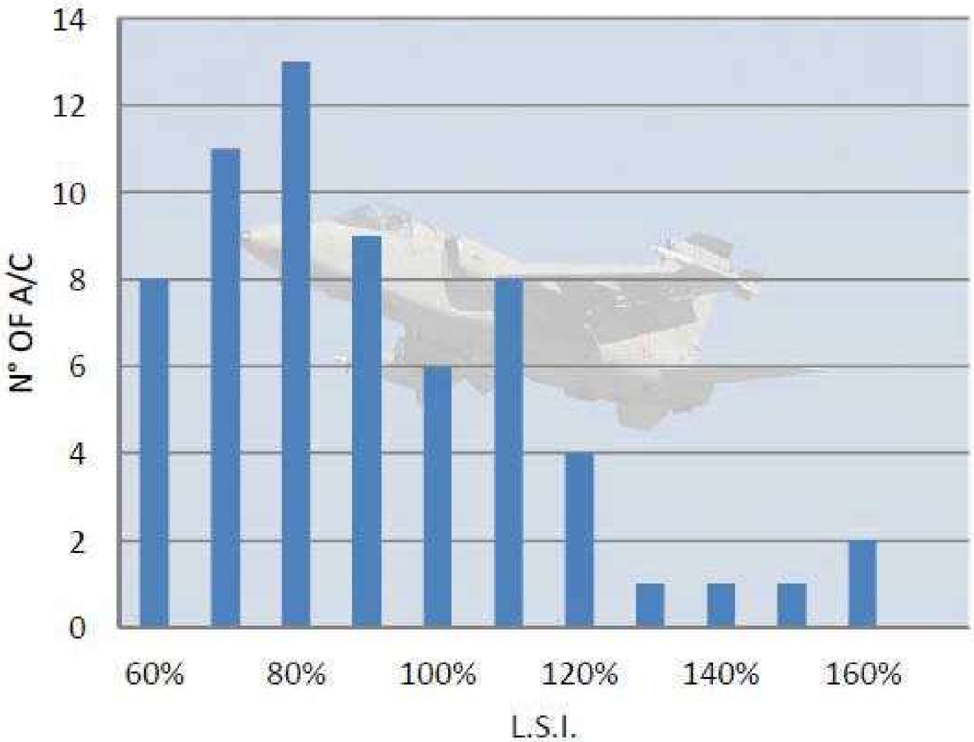


Fig. 2 - Load Severity Index distribution in the AM-X fleet.

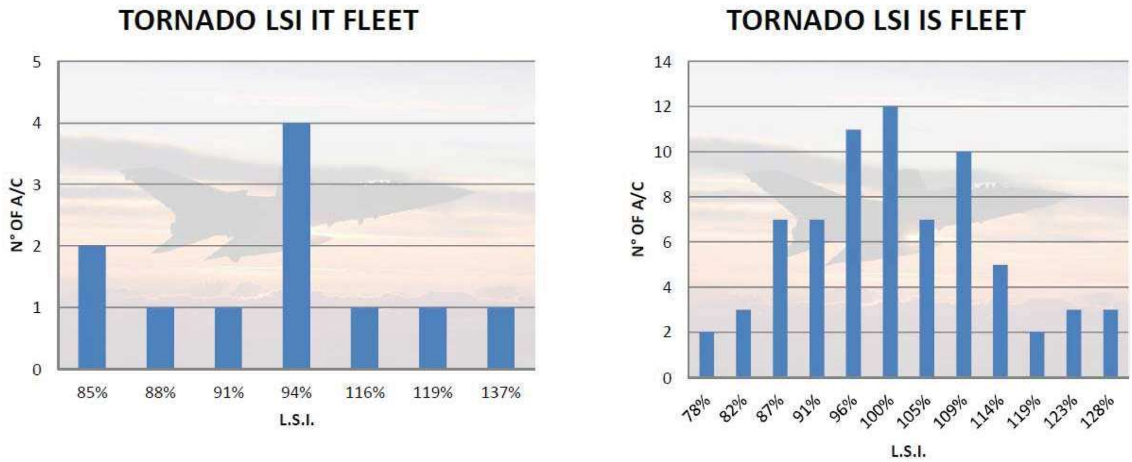


Fig. 3 - Load Severity Index distribution for the I.A.F. Tornado fleet.
(IT: Trainer aircraft; IS: Strike aircraft)

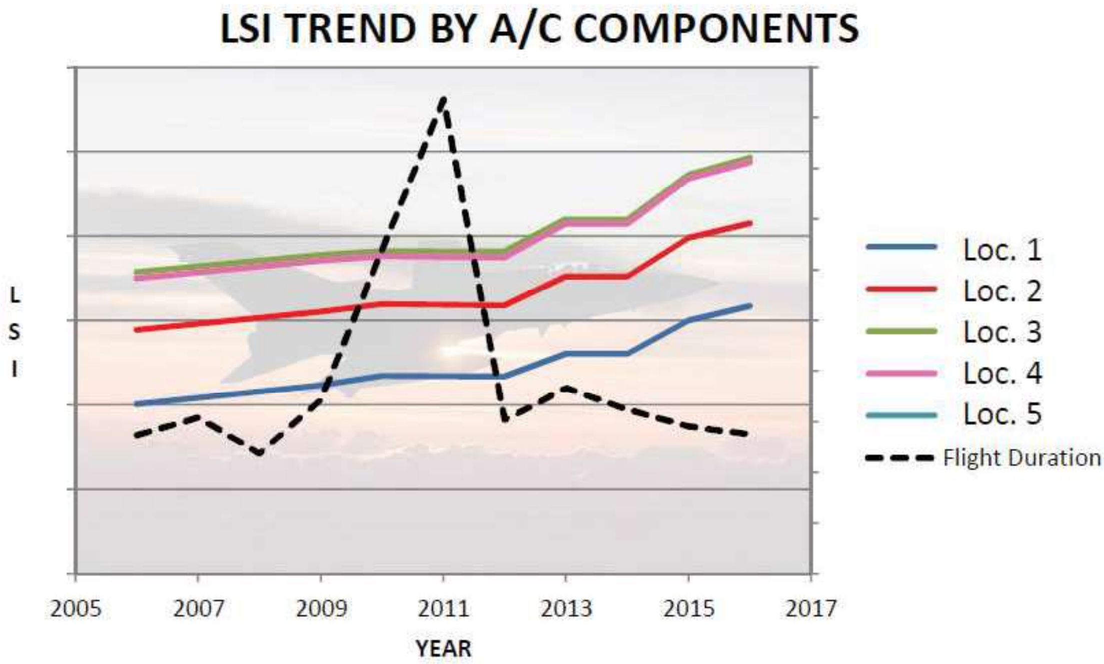


Fig. 4 – Change in usage of the IAF Tornado fleet.

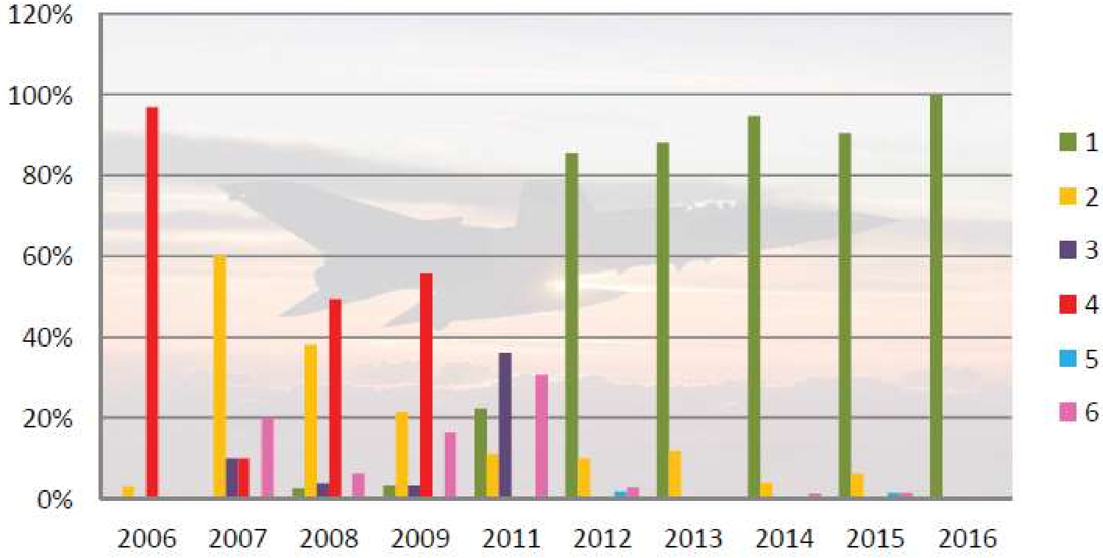


Fig. 5 - Differences in missions flown by the IAF Tornado fleet.

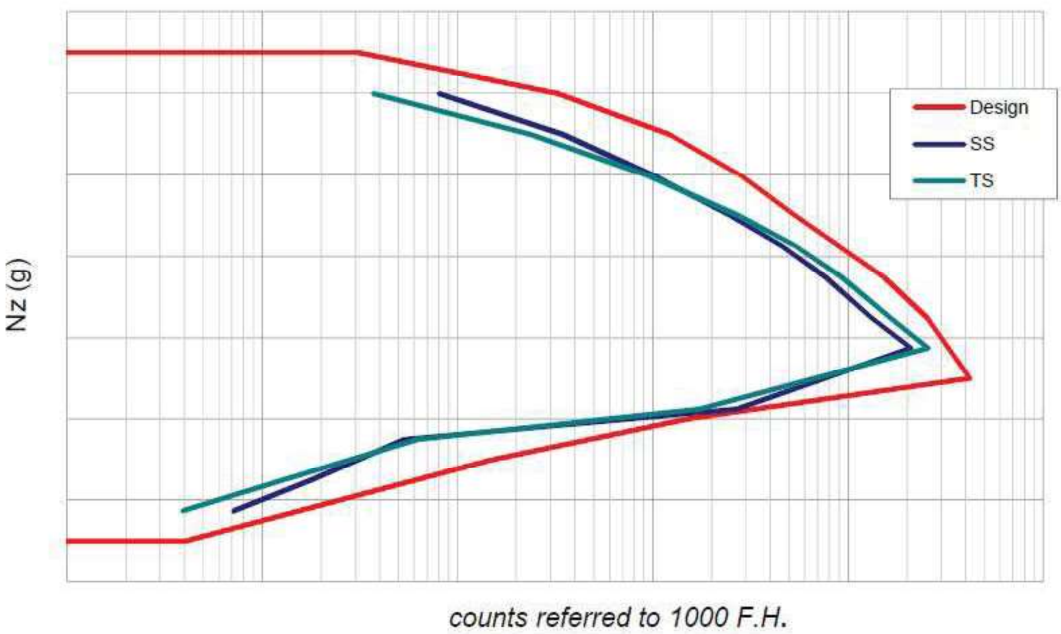


Fig. 6 – IAF Eurofighter Typhoon usage spectrum vs. design spectrum (dimensionless).

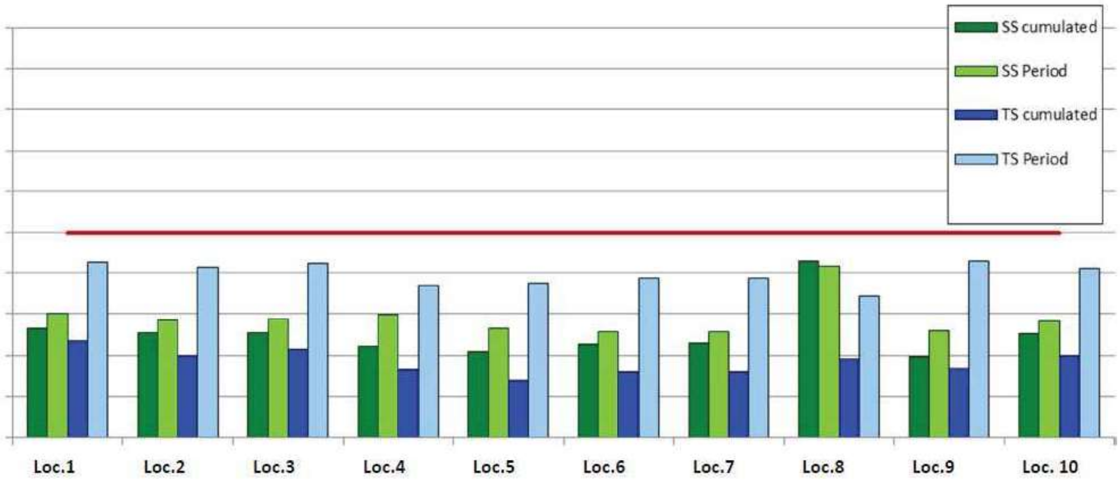


Fig. 7 - Fatigue Indexes values for IAF Typhoon aircraft.
(For location definition, see previous editions of National Review).

		%time Ground ops	Occurrences Rotor Start Stop per hour
HUMS	Average	16.66	0.92
	Max	19.82	**0.98**
	Weighted average	16.63	0.92
	Original Design SAR ref. [1]	2.080	0.50
	Original Design TTT ref. [1]	2.592	0.50

Fig. 8 – AW101 HUMS: comparison of some measured data with design assumptions
(higher occurrences of SS and GAG cycles).

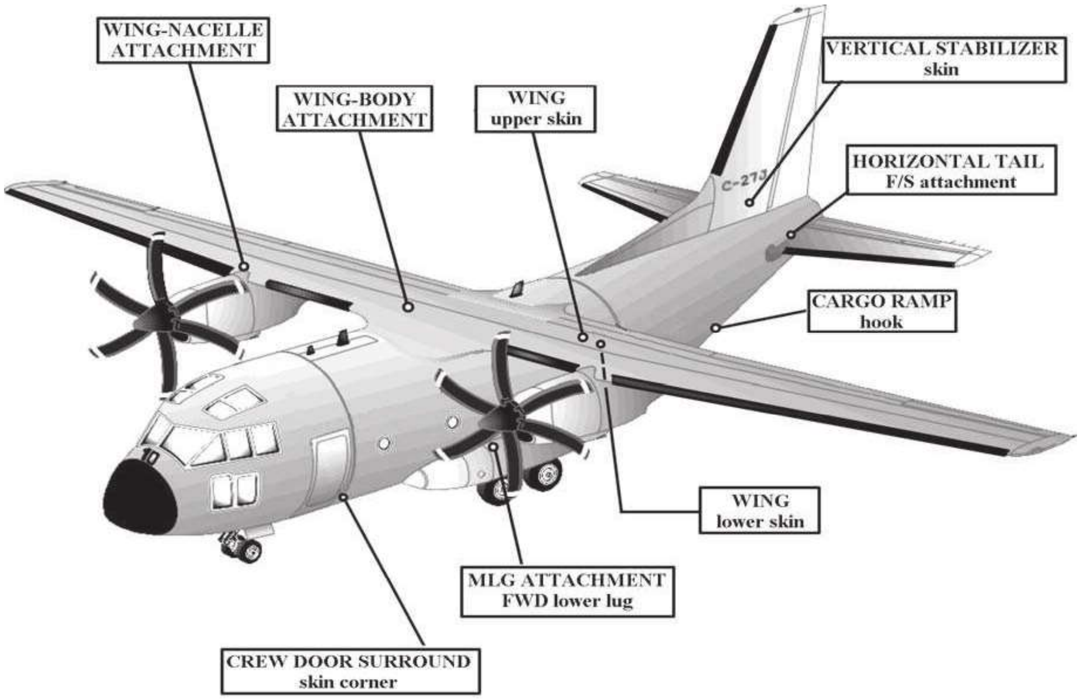


Fig. 9 – Nine significant structural locations for evaluating fatigue damage in C-27J IATP program.

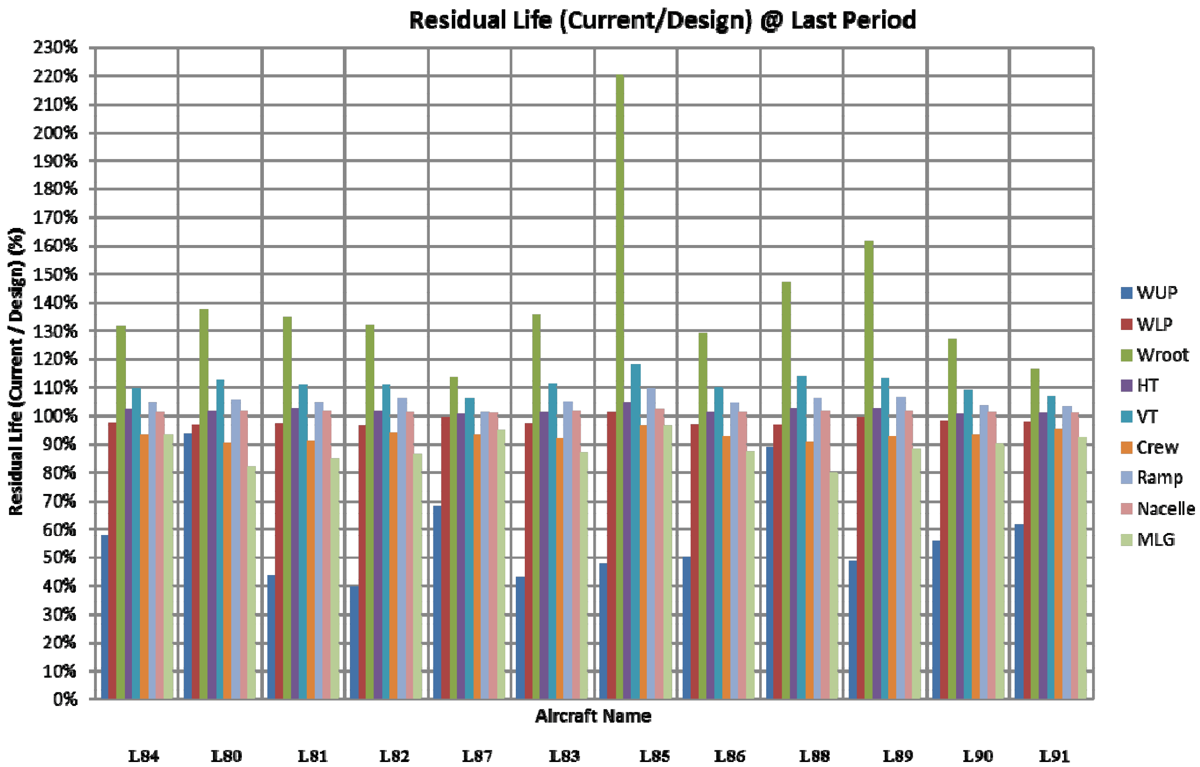


Fig. 10 – Residual life, as a percentage of original design life, of the control points in different C-27J aircrafts.

Fig. 11 – Low load transfer specimens used for assessing the one-up assembly fatigue penalization.

MATERIAL	STAT.	TSA/CAA
2024 T3 bare sheet	Mean	**0.99**
	95%	**0.99**
6061 T6 bare sheet	Mean	**0.97**
	95%	**0.99**
2219 T62 bare sheet	Mean	**0.95**
	95%	**0.95**
7075 T73 bare sheet	Mean	**1.03**
	95%	**1.06**
7085 T7452 Forging	Mean	**0.97**
	95%	**0.99**

Fig. 12 - Relative fatigue knock down factors for TSA and CAA anodizing processes for some Al alloys.

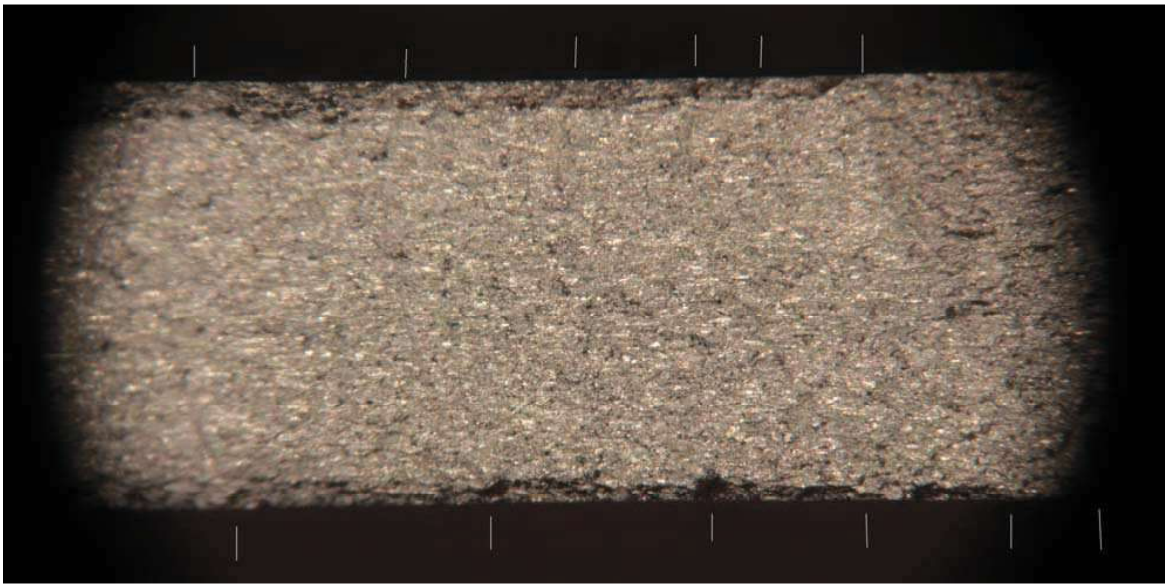


Fig. 13 - Evolution of the crack front, as evidenced by marker loads.

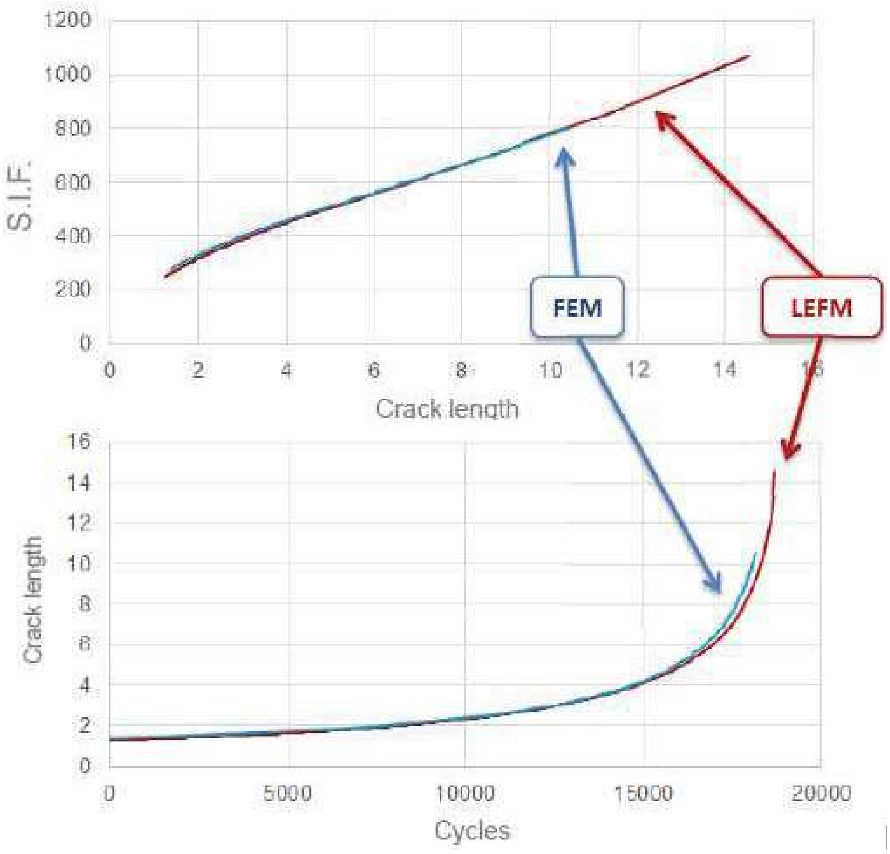
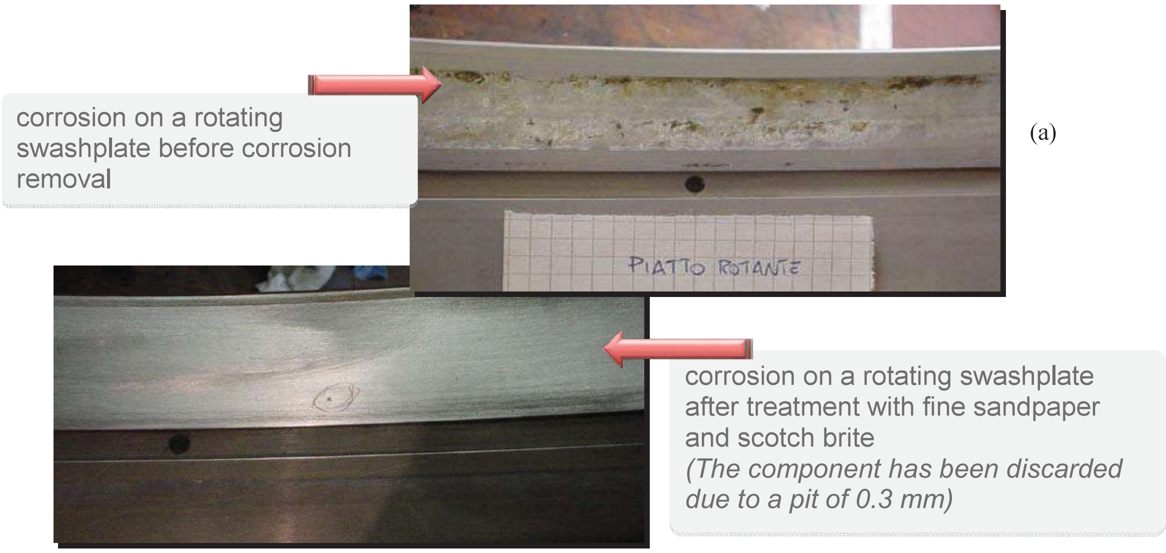


Fig. 14 - Comparison of results for the validation of the numerical FEM approach for crack growth analysis.



(a)

(b)

Figs. 15 - Corrosion removal in a swashplate.

Location / Energy	Compr. strength
Near Edge, 3 J	-11,36%
Near Edge, 5 J	-31,31%
Central, 3 J	-10,40%
Central, 5 J	-14.24%

Fig. 16 – Reduction in compressive strength after Near Edge and Central impacts (9 plies, 2.88 mm thickness).

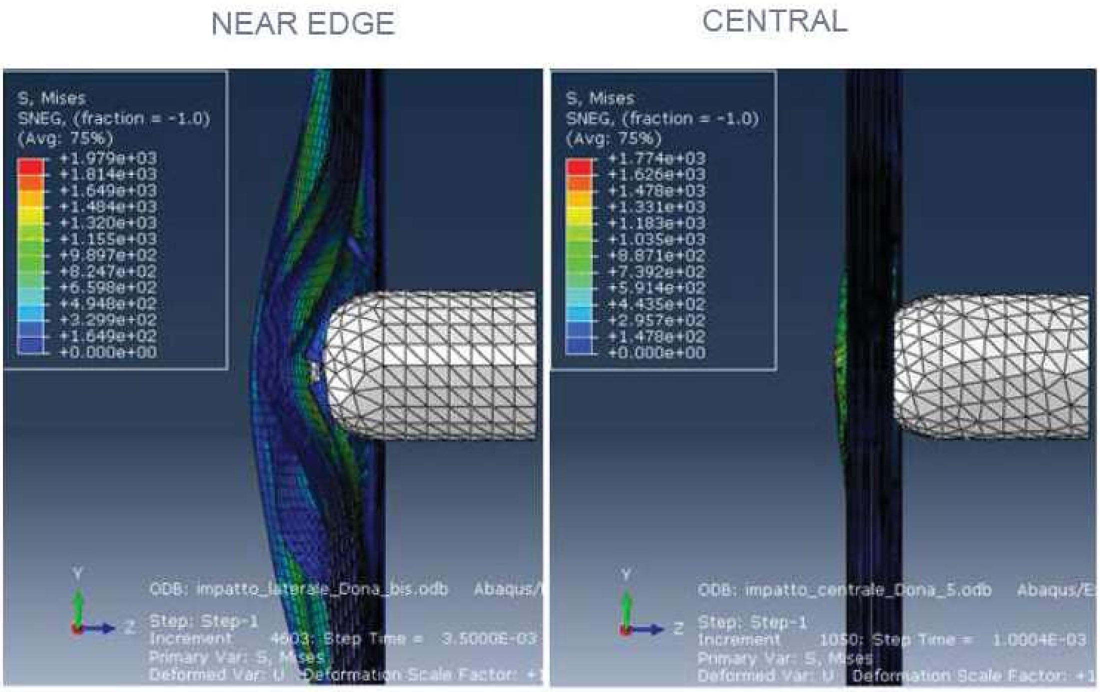


Fig. 17 - Numerical analyses for near-edge and central impacts in composite materials.

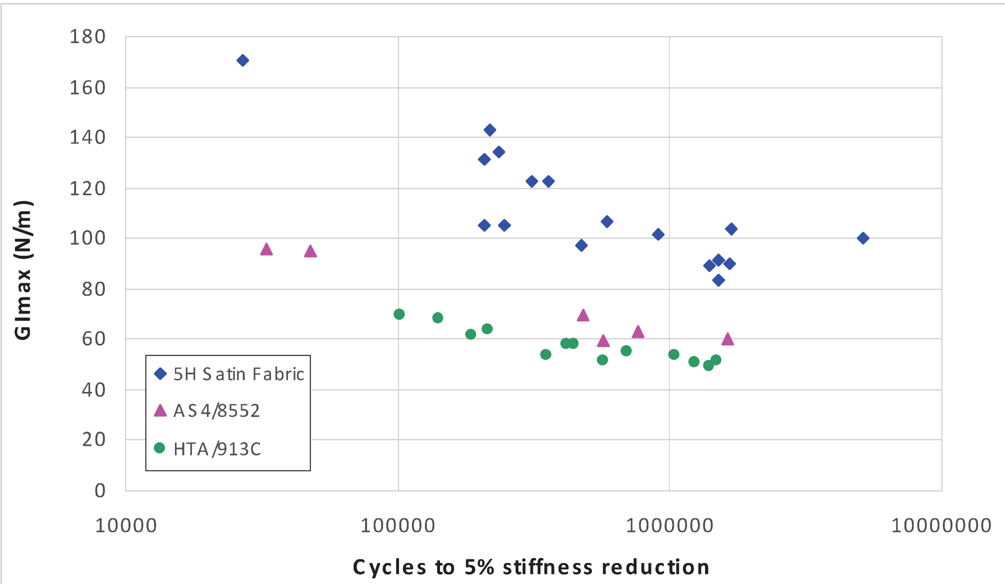


Fig. 18 - Fatigue tests results of delamination growth onset in DCB specimens (R=0.1; GI evaluated with the Williams-Kinloch formulation).

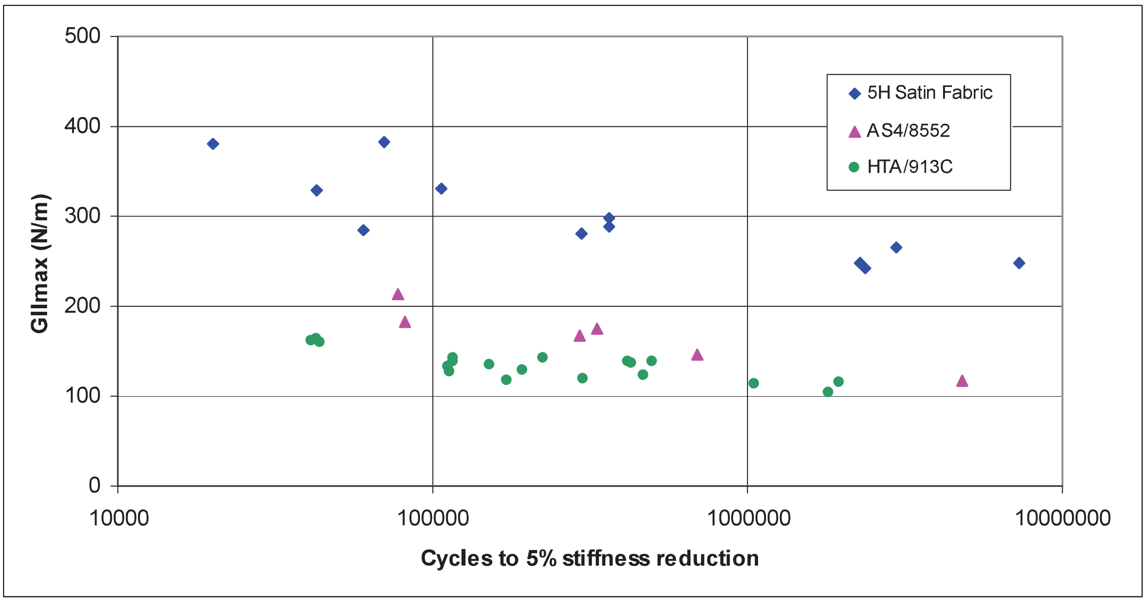
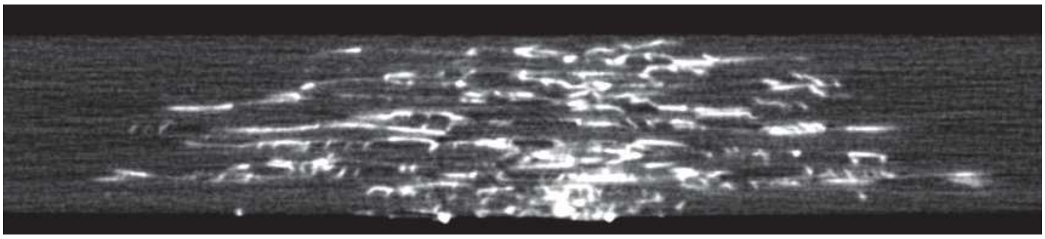
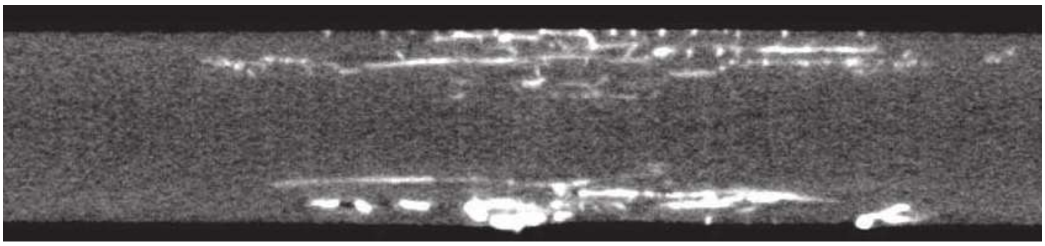


Fig. 19 – Fatigue tests results of delamination growth onset in ENF specimens (R=0.1; GII evaluated with the Williams-Kinloch formulation).



(a)



(b)

Fig. 20 – Tomography images of the reference laminate (a) and interleaved (b) after 10 J impact, RTD; the first one is typical, conical shaped, while the second one shows very limited damage in the central region.

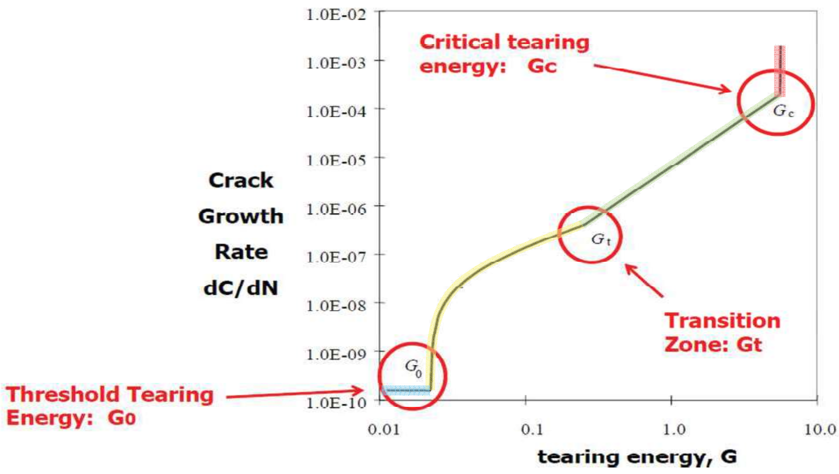


Fig. 21 – Typical plot of damage growth rate in elastomers as a function of G.

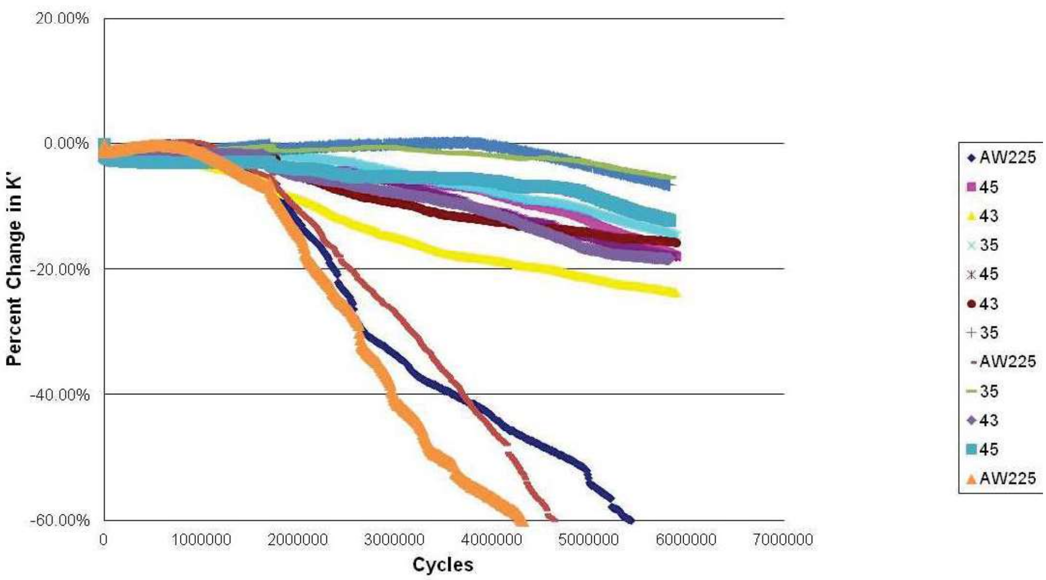


Fig. 22 – Stiffness decay as a function of number of cycles in an elastomeric component.

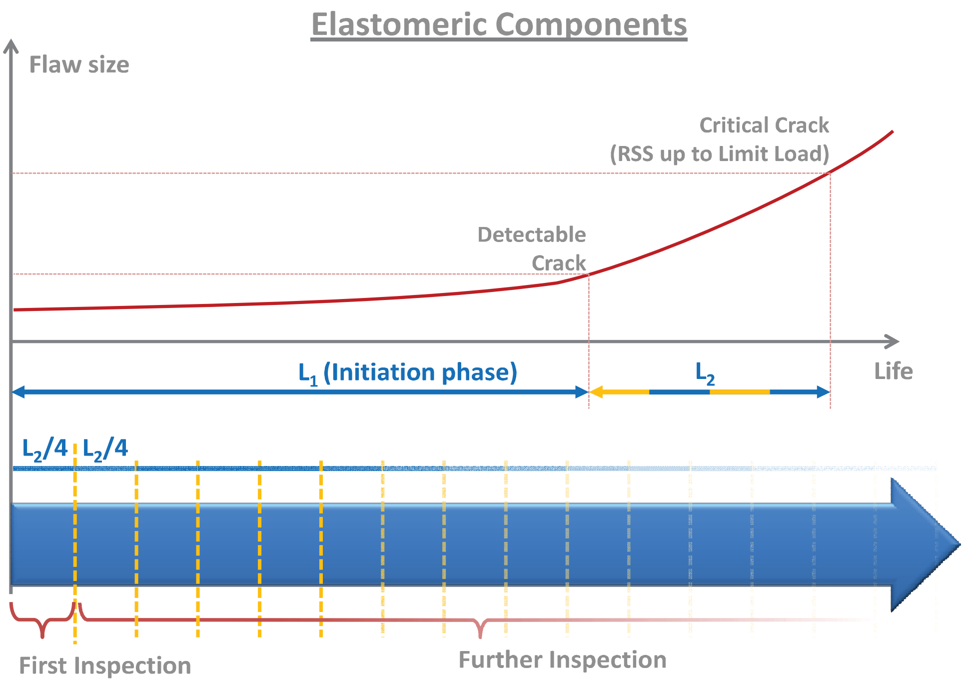


Fig. 23 – Inspection program definition for an elastomeric part.

Figures 24 – Specimens used for the evaluation of oversize reaming effects on the fatigue behaviour of lugs.

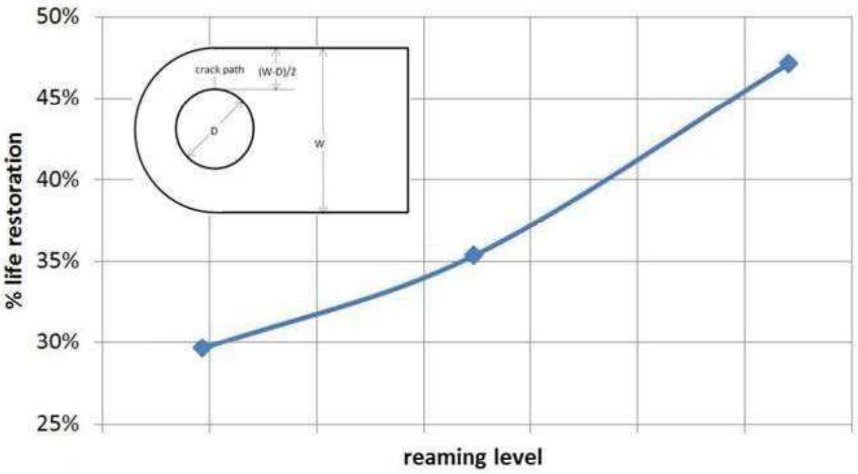


Fig. 25 - Benefits associated with reaming level on the lug life extension.