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 2017 - March 2019

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This document summarizes the principal research activities carried out in Italy about aeronautical fatigue in the period April 2017 – March 2019. The main topics covered are: operational load analysis, fatigue and fracture mechanics of metals, fatigue and damage tolerance of composites, full scale testing.

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1. INTRODUCTION

This paper summarises aeronautical fatigue investigations carried out in Italy during the period April 2017 to March 2019. 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. A paragraph dedicated to corrosion/fatigue interaction has been inserted, on the basis of extension of ICAF interests towards structural integrity, in general. 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 216 thousand 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, is the parameter defined by Leonardo Aircraft Division for assessing the usage of the various aircraft. In the last period of observation, a slight tendency towards lower severity utilisation rates (already present in the last 5-6 years) is confirmed, with an average value of 0.96 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 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, on the basis of mechanical g-meter readings complemented by 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 (Ma.Re.S. – Maintenance Recorder System) was introduced.

To validate the system, during the flight activity carried out at the bases, Leonardo acquired:

- the “traditional” fatigue data modules, and
- the data generated by Ma.Re.S.

Through a program developed ad hoc, fatigue life consumption has been calculated and comparison between the two approaches has been performed. For each monitored component, the qualitative analysis allowed to visualize graphically the Ma.Re.S. and the IM consumption (validated by decades of operation “on the field“) and to gain confidence that the new system provides correct results.

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 (Leonardo Aircraft Division)

Since 2003, 90 Euro Fighter Typhoon aircrafts (76 Single Seat and 14 Twin Seat) have been delivered to the Italian Air Force. Since entry into service (2005), more than 94500 flight hours (corresponding to about 64600 flights) have been flown. The fleet leaders are now beyond 1950 FHs for SS and about 1500 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 SHM system considers 10 significant locations on each aircraft: for each location, a stress equation is used to compute the stress history, which is then analysed by means of the rainflow algorithm in order to calculate the in-service spectrum.

The in-service usage shows a spectrum shape similar to design assumptions, but less severe (Fig. 3). This trend is confirmed by Fatigue Indexes calculations, expressed as “Usage Factor”, defined as the ratio of the in-service usage rate (i.e. the hourly consumption) to the design usage rate. The results shown in Fig. 4 indicate that UF are well lower than unity; the lead location, for both SS and TS versions, is location 8. The trend is for a decrease in all locations, as can be seen from the fact that the column relevant to the value in the period (typically 6 months) is often shorter than the one relevant to the cumulated average, i.e. the average value from the beginning of the monitoring.

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

In the last National Review, a paragraph was dedicated to the development and application of a Usage Monitoring System, based on a Flight Condition Recognition (FCR) routine, installed by an increasing number of customers on their EH101 fleet. In the last period, more and more customers are requiring the HUMS data analysis in order to obtain a usage spectrum to fit the actual mission profiles of the fleet.

To date, the following EH101 usage spectrums have been revised:

- Denmark
- Canada
- Royal Navy

Future applications are under negotiation for the following machines:

- NH90
- AW249
- AW109

The benefits of the Usage Monitoring activity are highly appreciated by the operators. If the actual flown spectrum is more severe than the design one, a potential hazard situation is identified and an anticipated replacement can take place, so keeping safety under control. On the contrary, when the design spectrum is more demanding than the flown one, it is possible to extend the replacement life of the involved components, with an evident economic benefit, that translates into reduction of operative costs.

A case study is represented by an EH-101 mixed mode variant, a military version with two basic missions: Search-And-Rescue (SAR) and Utility, with limited Extended Take-Off Weight (ETOW) capability. More than 25,000 hours flown by the whole fleet have been processed, with minimum 1,400 hours accumulated per helicopter in about 5 years (reflecting the typical annual usage). All the hours have been flown in mixed role and refer to a unique usage spectrum. HUMS data are managed considering: (a) max HUMS value recorded, i.e. maximum occurrence of a given Flight Condition; (b) average of the HUMS values in the fleet; (c) weighted average, accounting for the hours flown by each helicopter. A first important result of the analysis is that the average flight duration is shorter than originally estimated, and this means that the number of Start-Stop cycles per Flight-Hour almost doubles (see Fig. 5). Another important result of the analysis of the HUMS data is that it revealed that two machines had been used for a limited period of time in special missions, characterized by quite different altitude profiles (which was confirmed by the operator). Fig. 6 shows the distribution of occurrences of flight altitude of the fleet. Therefore, a particular effort is dedicated by Leonardo HD for improving and refining continuously the Flight Condition Recognition software. Among current improvements, the following aspects have been taken into consideration:

FCR processing on ground;
Availability of source flight data;
Recording of parameter time histories;
Enlargement of flight data bank;
Availability of the number of events.

It is planned to record all the operational data, for the whole flight length, and then process the data on ground.

A dashboard for the HUMS data storage and management is under development. This tool would be used by the customer to monitor the fleet usage in comparison with the macro parameters of the flight envelope issued.

The last point is that also a serial number component control is going to be planned, a development highly appreciated by some customers but that requires the configuration control of each machine, a complex task.

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

Information has already been given in previous National Review editions about the C-27J monitoring activity, performed through a specifically developed I.A.T.P. (Individual Aircraft Tracking Program) software, that runs on ground; its aim is to monitor the fatigue life of each aircraft based on the actual mission profiles and load spectra determined by means of the direct recording of in-flight parameters. The I.A.T.P. software compares the aircraft in-service life usage with the design life usage. This allows to plan and manage the fleet usage and the inspection tasks keeping into consideration both the economy and the safety points of view.

The software monitors the main representative locations of structural items through the calculation of LSI (Load Severity Index), which is the ratio between the In-Service Life Damage and the Design Life Damage. 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 representative to monitor the fatigue life of the entire aircraft structure and their position has already been shown in previous National Reviews. The choice of such nine locations has been made trying to cover all the possible fatigue loads sources:

- Flight Loads
- Ground Loads
- Pressure Loads

The Crack Growth module performs the comparison between the In-Service Crack Growth Rate and the Design Crack Growth Rate, in order to determine the Residual Growth Life (In-service) versus the Residual Growth Life (Design). The design crack growth data have been used in the design phase, while the in-service parameters are calculated based on data coming from actual aircraft flight profiles.

Fig. 7 shows, for a number of individual airplanes, that the differences between the residual life calculated under the In-Service spectrum and the one calculated under the Design spectrum, in the nine locations selected, are quite small, with the exception of the Wing Root location parameter (its abnormal value is not meaningful and trivial reasons have already been identified).

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, as the ratio between the In-Service Life Damage and the Design Life Usage. Fig. 8 shows the variation of such parameters, in the last period, for a number of aircraft, object of the analysis of Fig. 7. With the exception of one machine, the differences are small or negligible, and this means that the usage has not changed significantly in the observed period.

3. METALS

3.1 - Fatigue behaviour of notched and un-notched materials

3.1.1 - Additive Manufacturing assessment (Leonardo Aircraft Division)

Leonardo Company has started a process qualification and a test campaign for the Additive Layer Manufacturing (ALM) Technology Process from metal powder (Aluminium and Titanium), with the objective of manufacturing some secondary items of M345 aircraft with such ALM Technology.

A static and fatigue test campaign has been initiated, about 800 specimens will be tested, of various types:

- Un-notched
- Open Hole
- Notched
- Lug
- Joint (Single Shear and Double Shear)
- Crack Growth and Fracture Toughness

Different characteristics and variable process will be analysed:

- Type of Powder (virgin and recycled)
- Fabrication plane (xy and xz)
- Fabrication angle position (0 degree and 45 degree)
- Thickness (1.5mm and 6mm)

Testing activity is in progress and some typical peculiarities have been encountered:

- Roughness (it depends on the angle and direction of plane deposition)
- Edges refinement (dependent on plane fabrication direction)
- Planarity
- Laser Overlap regions (dependent on fabrication positioning)

Preliminary results from specimens in Al alloy show a scatter higher than typical, but S-N curves are similar.

3.1.2 – Development of Additive Manufacturing process (Milan Polytechnic)

Additive Manufacturing (AM) processes have attracted much attention over the past fifteen years thanks to their apparent advantages compared to traditional industrial processes. Metal parts with complex geometry can be produced with a small Buy-to-Fly (BTF) ratio. Although AM technologies such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) have been consistently developed and improved, they are not widely adopted for primary aerospace structures due to the incomplete knowledge of the production processes, and in particular of the post-treatment effects. Therefore, it is important to understand the static and fatigue performance and the post-treatment effects of the material produced by these technologies.

In this view, the research carried out at Milan Polytechnic within the project AMATHO (co-funded by the UE within the framework of the CleanSky2 programme) investigates the mechanical performances of alloys of large interest in the aerospace sector. Al-alloy (AlSi7Mg0.6) and Ti-alloy (Ti6Al4V) specimens, manufactured by SLM and EBM, respectively, were tested under static and fatigue loading following ASTM standards. Samples were fabricated in three different orientations (0°, 45° and 90°) in order to test their mechanical properties according to the building directions. For each building direction, five samples have been used for the static characterisation, while twenty samples have been used to study the fatigue behaviour. Further parameters considered in the research are surface finishing and thermal treatments of the as-built components.

From static tests emerged that post-processing procedures established for standard technologies (e.g. T6 thermal treatment for Al-alloys) are not completely suitable for components produced by AM technique. Such treatments generally result in a reduction of tensile strength and hardness, with an increase of ductility, in comparison with the as-built condition. As far as the fatigue properties are concerned, in all the studied cases, defects in the outer region control the fracture behaviour (see Fig. 9). Pores or lack of fusion are more probable in that region, leading to a premature failure of the tested specimens.

As main conclusions, the tuning of processing parameters in the border region and dedicated post processing protocols have to be applied to optimize mechanical response of additively manufactured components. Further research is required to understand how both processing and heat treatments affect material microstructure and mechanical properties.

3.1.3 - REACH regulation implementation (Leonardo Aircraft Division)

The current international environmental regulation (**REACH** – **R**egistration, **E**valuation, **A**uthorization and Restriction of **Ch**emicals) requires the elimination of products declared harmful to the environment and the human health. The salts of chromium are included within these products and in particular the hexavalent chromium, used in typical metal surface protection processes. In the last National Review, information was given on the results of a wide research activity carried out by Leonardo Aircraft Division to evaluate the influence on the fatigue life of the TSA (Tartaric Sulphuric Anodizing) process, which has been adopted by Leonardo as a substitute of the banned Chromic Acid Anodization process. Moreover, in the last two years, Leonardo has carried out other research activities, with the aim of replacing the hexavalent chromium chemical conversion coating process of aluminium alloys with a more ecological one performed with trivalent chromium products.

<u>Chemical conversion coating process</u>

To assess the impact of the new coating process on the fatigue behaviour, Leonardo has planned a fatigue test campaign on selected aluminium alloys, the most used in Leonardo proprietary programs. This investigation led to choose two typical Al alloys, 2024-T3 and 7075-T6, for a total amount of 160 specimens.

Fatigue behaviour is also investigated for materials without surface protection in order to estimate the correction factors on basic fatigue properties.

<u>Thermal spray</u>

Hard chromium plating is used in Leonardo Company on steel alloys for the following functions:

- Increased surface hardness
- Improved wear resistance
- Friction resistance
- Improved corrosion resistance for non-corrosion resistant substrates
- Decreased friction coefficient
- Prevention of galling between metallic materials.

In order to satisfy the REACH requirements, Leonardo is investigating, developing and qualifying alternatives processes based on Thermal Spray Coatings, used on steel alloys to replace the Hard Chromium Plating. Thermal sprayed metallic coatings are produced by projecting the coating metal, heated to its molten state, in a stream of gas or plasma, onto the surface to be coated. This coating consists of a stacking of "splats" and is performed by several passages; each one deposits a layer of about 20 µm by piling up splats on a substrate surface. This process is also called HVOF (High Velocity Oxi Fuel), since the combustion gases are accelerated to supersonic speed.

The fatigue test campaign planned by Leonardo aims at determining the fatigue behaviour of selected steel alloys subjected to both Hard Chromium and HVOF process. Although steel is not widely used for significant structural items, Leonardo proprietary programs have been reviewed and the most representative steel materials have been selected: AISI 4130 and 15-5PH, both in sheet form.

Fatigue behaviour will be investigated also for materials without surface protection in order to compare HVOF fatigue behaviour to basic fatigue properties. About 120 specimens will be tested.

At the moment the process is still in the tuning phase.

3.1.4 – Fatigue of gears (Leonardo Helicopter Division)

A Rotorcraft Transmission Safety Working Group (RTSWG) has been set up in 2017 with the major Helicopter Manufacturers and EASA to share information about transmission safety. The main attention is currently focused on epicyclical reduction stages and integrated race bearing; the interest in such components comes from the results of an Accident Investigation Board, which issued a report on a fatal crash in 2016, clearly attributed to a fatigue failure in the gearbox. For the various helicopter manufacturers this is an area of continuous efforts towards improvement, because designers look for lighter solutions with better performance, maintaining high safety standards. The RTSWG has issued two White Papers, pointing out some recommendations for design and indications for future developments, in order to prevent cracks on planet gear rim and transmission bearings failure.

The main recommendations are related to:

1. Design and sizing:
    - Separation of bearing raceway and the structure of the planet gear rim
    - Thicker rim based on damage tolerance criteria
2. Flaw tolerance demonstration
3. Health monitoring

Leonardo HD has a long term program, in cooperation with the Department of Mechanical Engineering of the Milan Polytechnic, already described in previous versions of the National Review. Such program has increased its importance since the last amendment to EASA CS29.571 paragraph, that widens the definition of Principal Structural Element also to gears, transmission elements and gearboxes. For each of them, appropriate inspections and retirement times 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. The approach followed by LHD has been to design gears in such a way that failure is limited to a single tooth, preventing the crack propagation through the web. Moreover, in the mentioned collaboration with Milan Polytechnic, single tooth bending fatigue tests have been performed with pulsator machines and in the last two years S/N curve-shapes for tooth failure for carburized shot-peened gears and nitrided unpeened gears have been drawn.

In addition to the tooth root (TR) crack, new phenomena of failure have been observed, characteristic of case-hardened gears with slender teeth, heavy loaded and with performing heat treatment:

(a) Tooth Flank Fracture (TFF): sub-surface initiated fatigue failure, at the case/core transition region;
(b) Tooth Interior Fatigue Fracture (TIFF): cracks starting at the mid-height of the tooth and propagating from the tooth centre towards the flank.

Some images of these types of failures are shown in Fig. 10.

The durability design is carried out on the basis of the following approach:

• S/N curve shapes are derived from Single Tooth Bending Fatigue test;

• Full scale fatigue tests: the minimum test conditions encompass the power levels for which repeated application in service is expected for each gear;

• The S/N curves are reduced by 1.4 safety factor for a single test (or lower safety factors, when more tests are available) which accounts for material and manufacturing variability, in accordance with the current AC 29.571.

• A new software tool has been implemented for improved fatigue damage calculation and the analysis is now fully consistent with that one for rotor components, replacing the condensed power spectrum with a detailed flight spectrum.

As far as the Flaw Tolerance design is concerned, it is performed on the basis of the following approach:

• Flaw tolerance requirements from CS 29.571 are obviously kept into consideration;

• Flaw tolerance Safe Life/No growth analyses are carried out, according to the threat assessment, taking into account material intrinsic flaws (VIM-VAR steels), defects for welded sections and induction of flaws during manufacturing/assembly operations.

- The Planet Gear of a Leonardo transmission has been tested with an artificial flaw, to investigate spalling at the outer race of the bearing, using a dedicated planetary rig, Fig. 11. The whole test has been performed proving the adequate performance for the maximum flight duration with safety margin, confirming the robustness of the design.

In conclusion, an in-depth review of the design process has been made at LHD and the following points summarize the way-out identified:

1. Design and sizing:
   - FE analysis for the determination of Hertzian pressure and local stresses: focus is placed on the internal bearing race of planet gear.
2. Fatigue characterization
   - Contact fatigue will be investigated by FZG tests, a typical protocol used for gears. Suitable gears will be designed to promote the failure for causes such as micro-pitting, pitting and scuffing rather than for the traditional tooth bending.
3. Health monitoring:
   - Analytical demonstration of the reliability of the chip detector positions. Currently, this is demonstrated on a statistical basis by the amount of chip detector responses and relevant issues found on transmission components (and vice-versa). Visual warning to the flight crew is provided when one metal particle of sufficient size or a sufficient cumulative quantity of particles, bridge the axial gap of the magnetic plug soaked in the oil flow.
   - Analysis of the health monitoring vibrations, to correlate signal response and failure diagnosis. The main focus is on the MR Mast duplex bearing and on the epicyclical gears.

3.1.5 – Laser cutting (Leonardo Aircraft Division)

Laser cutting process of sheet metal alloy is considered with great interest by the manufacturers, because it allows to obtain:

Efficiency and Velocity in production
Flexibility of cutting
Accuracy in cutting

For primary aeronautical components, the current state of the process requires the elimination or rework of the so-called Heat Affected Zone (HAZ). This kind of rework requires time and costs, giving to Laser Cutting a low and restricted field of application in aeronautics.

Leonardo Company will investigate the effect of HAZ on fatigue behaviour to evaluate the possibility to apply laser cutting without eliminating the HAZ zone. A fatigue test campaign is planned, aimed at determining the effect of the HAZ on the fatigue behaviour of selected Aluminium, Titanium and Steel alloys. The list of the selected materials follows:

- Ti-6Al-4V
- 2024-T3
- T50
- A321
- 6061-T4
- 17-7PH Ann
- INCONEL 625 A
- T60 A

About 200 specimens have been fabricated. Fatigue tests are in progress.

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 Operations GmbH 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 performed to extend the experimental database with other results from different situations: 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 has been concluded; the experiments on open hole specimens have been 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 tips, a marking load block (typically 50,000 cycles at R=0.9) has been interspersed in the constant amplitude R=0.1 sequence. Fig. 12 shows a fracture surface.

A numerical strategy has been presented in detail in a paper at the Symposium in Nagoya, [2], 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. In the last two years, attention has been focused on the management of the crack growth analysis of a 3-D defect in absence of residual stresses. The solution of this problem is preliminary to the study of 3-D cracks growth in three-dimensional residual stress fields; some results will be presented in a paper at the Symposium, [3].

3.3 - Corrosion and fatigue

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

Corrosion issues are continuously increasing, also as a consequence of longer operative lives. Moreover, the number of LHD helicopters currently in service has become relevant and the effort for Continued Airworthiness is becoming an important task for the Fatigue Department.

The typical corrosion cases reported for helicopters are:

- pre-service corrosion due to the manufacturing process, like etching for surface treatment or bonding;
- in-service corrosion due to improper coupling of materials or protection;
- in-service corrosion due to aggressive environment.

Due to a few findings, also pointed out in previous National Reviews, Leonardo HD has decided to undertake the following mid-term actions against corrosion:

1) Reduction of the inspection interval;
2) Repair authorised with material removal according to specific instructions; in particular, a static stress analysis is performed, followed by fatigue tests for validation;
3) Change of materials: in this case, a fatigue analysis with new S/N curve is performed. The failure mode (and the S/N curve shape) will be accounted for.

Long-term actions against corrosion, undertaken by LHD, include the study of the correlation between corrosion and fracture mechanics data (crack growth from pits, life assessment for reuse or continued usage, validation of life and inspection intervals in service). Moreover, coupon tests will be performed in natural and accelerated aggressive environment (testing full scale corroded parts is expensive and potentially does not cover the worst case), generating a material database. LHD will improve its capability to manage service events with a suitable data base for fatigue with corrosion and probabilistic approaches, using the DARWIN software.

4. COMPOSITES AND FIBER METAL LAMINATES

4.1 – Numerical investigation on adhesive joints fatigue resistance (Univ. Bologna)

The need for lightweight structures in aeronautics is leading to a strong interest in adhesively bonded joints. However, the difficulties in analysing adhesive joints are a major obstacle to their use in practical applications. From the point of view of a damage tolerant design, current prediction capabilities of their fracture mechanisms lead to the necessity of designing heavy, sub-optimal structures.

The activities carried out in the Department of Industrial Engineering of the University of Bologna aim at contributing to the understanding of disbonding of adhesive joints, mostly from a numerical point of view.

The effect of adhesive thickness on fatigue crack growth in an epoxy film adhesive (FM94) was investigated, using a combination of experiments and numerical modelling. For the range of thicknesses analysed, an increased thickness led to an increased crack growth rate. It was found that the energy required per unit of crack growth did not depend on the adhesive thickness. In contrast, the energy available for crack growth does depend on the adhesive thickness.

The numerical analysis shows that the crack-tip stress is not sensitive to the adhesive thickness (Fig. 13 shows the maximum principal stresses for three different adhesive thicknesses), but that the amount of plastic energy dissipation scales with the cube of the thickness. The experimental results imply that this increase of plasticity has an anti-shielding effect, as the crack growth rate is increased.

Furthermore, a numerical model for disbonding propagation under mode II and mixed-mode loading conditions has been developed, taking into account the thickness of the adhesive.

Mode II disbonding poses several difficulties with experimental measurements, which motivated the development of a numerical model. It is expected that numerical results could provide useful information for proper experimental set-up. Additionally, stress and strain distributions can be computed and introduced into analytical models for fatigue disbonding analysis.

Disbonding growth is taken into account by introducing a Cohesive Zone Model (CZM), which is able to capture the process zone around the crack tip and to enforce an energy-based failure criterion. The model, which had originally been developed for DCB specimens under mode I, was then extended to consider more general loading conditions.

Fatigue in adhesively bonded joints is usually related to parameters from Linear Elastic Fracture Mechanics (LEFM), such as the stress intensity factor or the strain energy release rate. The computation of these parameters from experimental data in mode I is relatively easy. On the contrary, their evaluation under mode II is made difficult because of the different propagation mechanism. In fact, the closure of the crack and the contact between the crack surfaces, as well as the complex crack patterns that are found in tests hinder accurate measurements of the disbond length, introducing a large scatter in the data. The crack length predicted from the numerical model can be employed to estimate the disbond length in the real specimens and compute the energy release in the propagation process. This also provides useful information on the residual strength of the specimen and can be extended to geometries which are closer to in-service components.

Another approach to fatigue can be established by a correlation between the crack growth rate and the energy dissipation per cycle, in an attempt to improve the physical understanding of the fatigue phenomenon. A practical implementation requires an estimate of the dissipated energy, which could also encompass some plastic deformation. The cohesive model is a suitable way for estimating the energy under conditions like mixed-mode loading or when significant plasticity is present.

The model developed is a suitable option for the estimation of fracture mechanics parameters in cases in which complex geometry and loads prevent the application of analytical theories. The final goal is to include progressive degradation of the cohesive properties, thus directly modelling fatigue disbonding in the adhesive.

A paper will be presented at the Symposium on this topic, [4].

4.2 – Delamination onset resistance of composite material systems (Univ. Pisa)

In previous National Reviews, information was given on a collaboration between Leonardo Helicopter Division 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 in the last period has been focused on the assessment of new materials, that are proposed to LHD by the suppliers (typically, a change in fibre).

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 associated with a 5% stiffness reduction with respect to the initial value. Various material systems have been evaluated: two couples of carbon/epoxy systems (913C-HTA and 913C-HTS; 950-HTA and 950-HTS split tape), and a couple of glass/epoxy systems (913-AGY and 913-OCV).

The results of the first couple of materials are shown in Figs. 14 and 15, where a slightly better behaviour of the 913C-HTA material is observed with respect to the 913C-HTS.

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

Within the framework of the CleanSky2 "Regional Aircraft" Innovative Aircraft Demonstrator Platform (IADP), an experimental activity has been performed at the Department of Civil and Industrial Engineering – Aerospace Division of the University of Pisa for the assessment of the interlaminar fracture toughness properties and the impact damage resistance of two composite material systems. Two materials systems have been selected for the Liquid Resin Infusion (LRI) plus Out of Autoclave (OoA) curing that are investigated in the IADP, with two deposition processes: an Automated Fiber Placement TX1100 IMS65 – EP2400 and a Hand Lay-Up IMS65 – EP2400. The AFP coupons were manufactured by Novotech, a PMI based in Apulia. In addition to traditional mechanical characterization tests, it is worth mentioning that the two materials were assessed also for what concerns the interlaminar fracture toughness in mode I, mode II and in two mixed mode conditions (ratio G2/Gtot equal to 0.33 and 0.67) using the Mixed Mode Bending set-up. Moreover, impacts were inflicted on quasi iso-tropic specimens for evaluating the Compression After Impact resistance; three thichnesses were investigated, and for each thickness a total of 15 coupons were used.

Fig. 16 shows a comparison between the graphs Force-Time recorded during the impacts of the same situation for the two material systems: no particular difference can be observed, while in fig. 17 the ultrasonic C-scan, performed by the University of Naples "Federico II", which collaborated to the research, shows that the damage in the HLU material is lower. This event is confirmed in table I, where the compressive strength evaluated in the CAI test shows slightly superior percentages with respect to the "intact" value for the HLU technology.

5. COMPONENT AND FULL-SCALE TESTING

5.1 – Development of the Airbus A220/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.

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 (concluded in the period covered by the present Review, during which other significant changes occurred to the program, that became Airbus A220). The differences in spectrum loading require the performance of two separate tests.

Three design lives have been applied (180000 flights) to the “metallic” HT test article; in the first two lives, the fatigue behaviour was evaluated, while in the last one (from 120000 to 180000 flights) artificial cracks were introduced on the test article to verify crack growth behaviour and residual strength capacity.

The Horizontal Tail Fatigue and Damage Tolerance testing has been completed successfully at Pomigliano Plant: no unstable growth of artificial cracks has been detected. Two residual strength tests have been completed, one on the Trailing Edge Ribs and the other on the Horizontal Stabilizer Trim Actuator Secondary Load Path, giving successful results.

The tear down inspection of the test articles is to be started.

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 components, characterized by high costs for their maintenance or replacement, have seen an extension in their fatigue life, as a consequence of the completion of long experimental activities.

In 2018 certification has been obtained for a new AW109S variant, named AW109S-Trakker, with skid landing gear, that allows to save costs and to improve payload; rescue hoist kit approval is closing (March 2019).

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

In the last two years, a number of improvements have been introduced on the three helicopters of the family (AW169 is the smallest and AW189 is the largest). Such improvements are often the consequence of the end of the certification test, with a clearance extended to a longer life for replacement. These extensions have a positive effect in terms of 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 (similar information was given in the previous review, but relevant to other items):

a) AW139

- Certification of the Human External Cargo (HEC) hook system is the major improvement in the last two years. This system, shown schematically in fig. 18, has been qualified according to EASA Certification Specification 29, amendment 4 and the applicable paragraph was 29.571. The various elements that compose the chain have been analysed in terms of safety using various criteria, according to the peculiar characteristics of the element itself. The main groups are: main cargo hook, secondary cargo hook, long line assembly (Y-shaped) and hook release means. The HEC kit will be installed complemented by a polycon (or equivalent) intercommunication system and a cargo hook camera. The total length of the long line is from 20 to 90 m, with increasing steps of 10 m. The maximum weight is 800 Kg (i.e. 8 persons). Fig. 18 shows how the various details have been qualified (Safe Life SL or Damage Tolerant DT or Multiple Load Path MLP solutions) and table II reports the outcome of the fatigue analysis.

b) AW169

- Airframe life extension to 20.000 Fh to be finalised.
- MR Interblade Fluidelastic Damper extended to 15.000 Fh;

- MR and TR Blade life extension concluded, 60.000 landings (start-stop cycles) equivalent to 15-20 thousand flight-hours.

c) AW189

- Airframe life extended to 15.000 Fh.
- MR Blade: improved acceptance criteria for manufacturing discrepancies and life improvements for FIPS (Full Ice Protection System) MR blade.
- TR blade calendar life extension

7. REFERENCES

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[2] L. Boni, D. Fanteria, L. Lazzeri, D. Furfari: “Numerical prediction of fatigue crack propagation in cold-expanded holes”, 29th ICAF Symposium, Nagoya, 7-9 June 2017.

[3] L. Boni, D. Fanteria, D. Furfari, L. Lazzeri: “Fatigue crack growth in pin-loaded cold worked holes”, paper to be presented at the 30th ICAF Symposium, Krakow, 5-7 June 2019.

[4] N. Zavatta, E. Troiani: “A numerical approach to the disbonding mechanisms of adhesive joints”, paper to be presented at the 30th ICAF Symposium, Krakow, 5-7 June 2019.

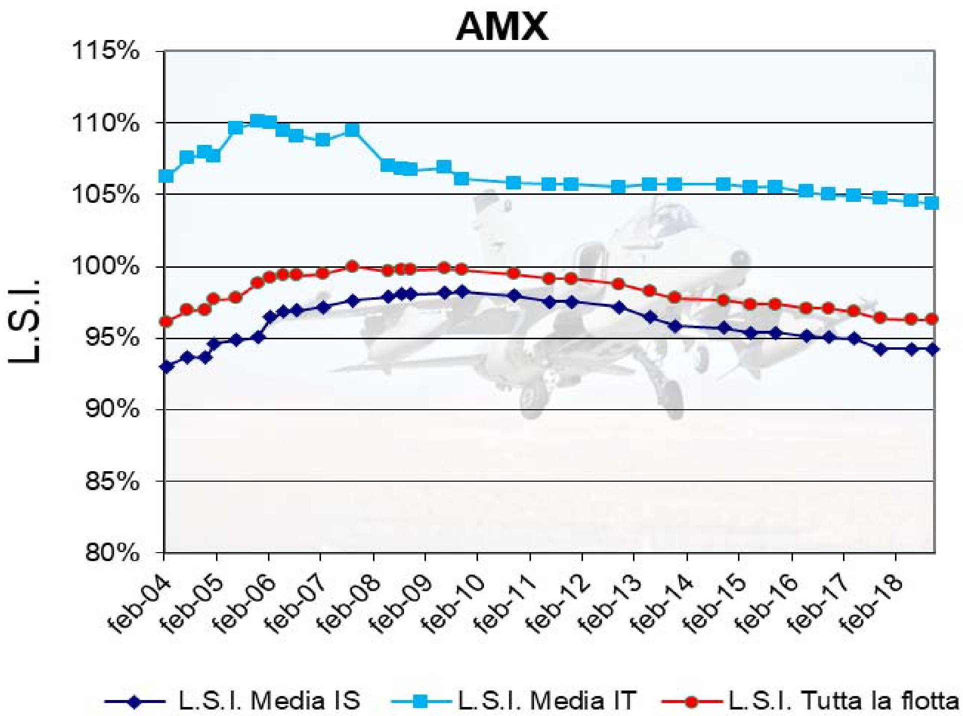


Fig. 1 – Trend of the global Load Severity Index for the AM-X fleet.
(IS: Strike aircraft; IT: Trainer aircraft)

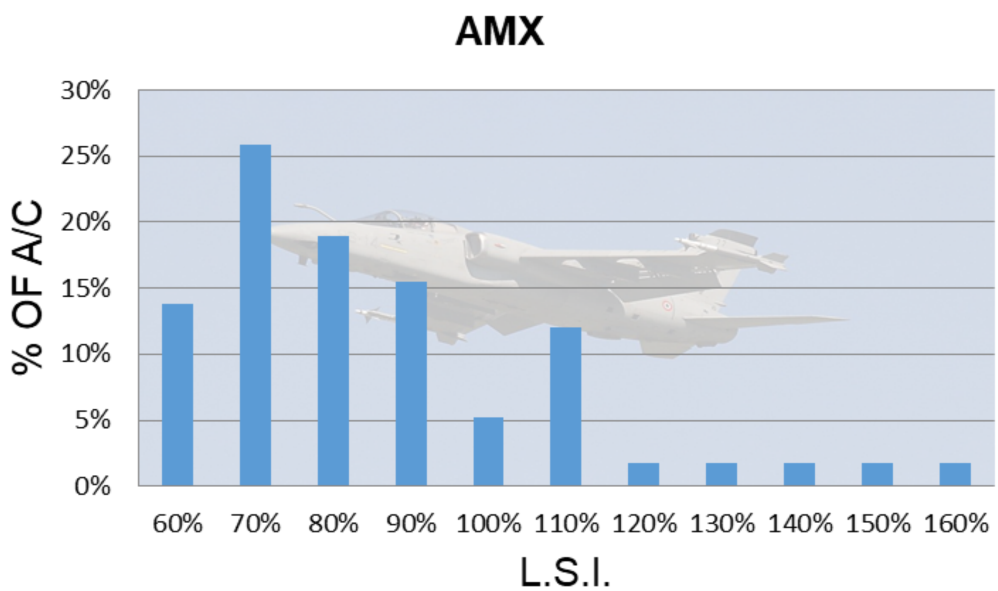


Fig. 2 - Load Severity Index distribution in the AM-X fleet.

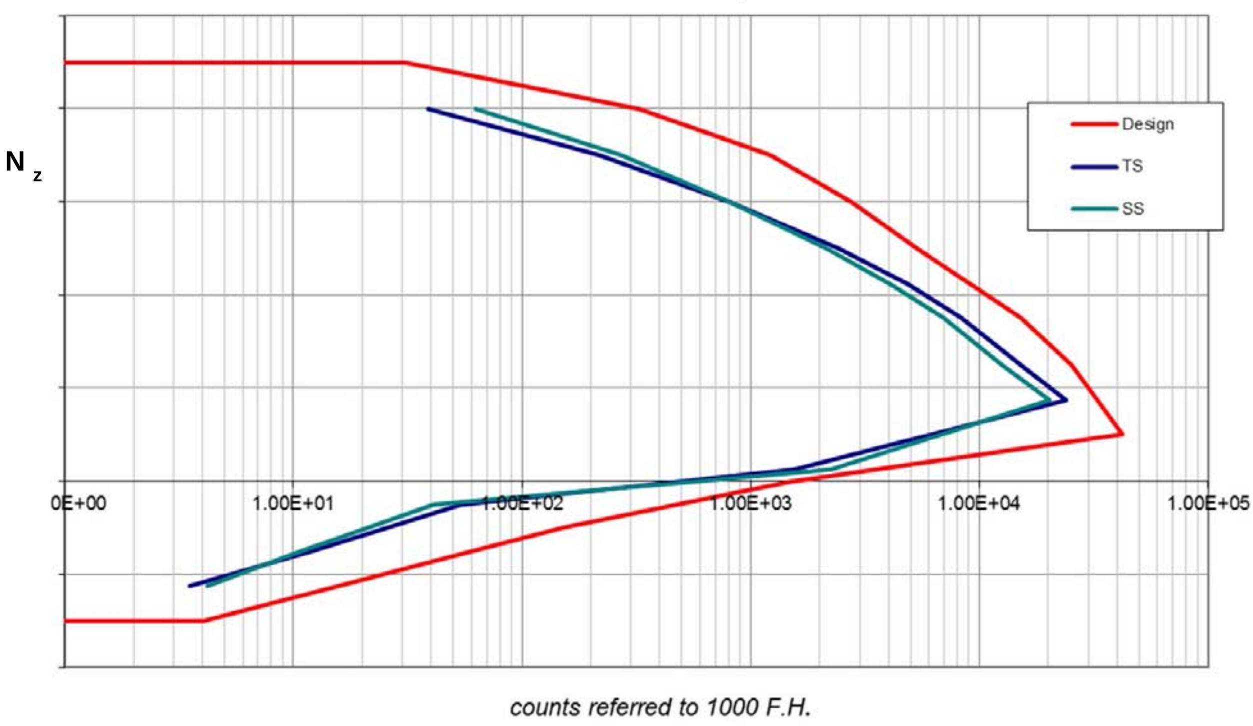


Fig. 3 – IAF Eurofighter Typhoon usage spectrum vs. design spectrum.

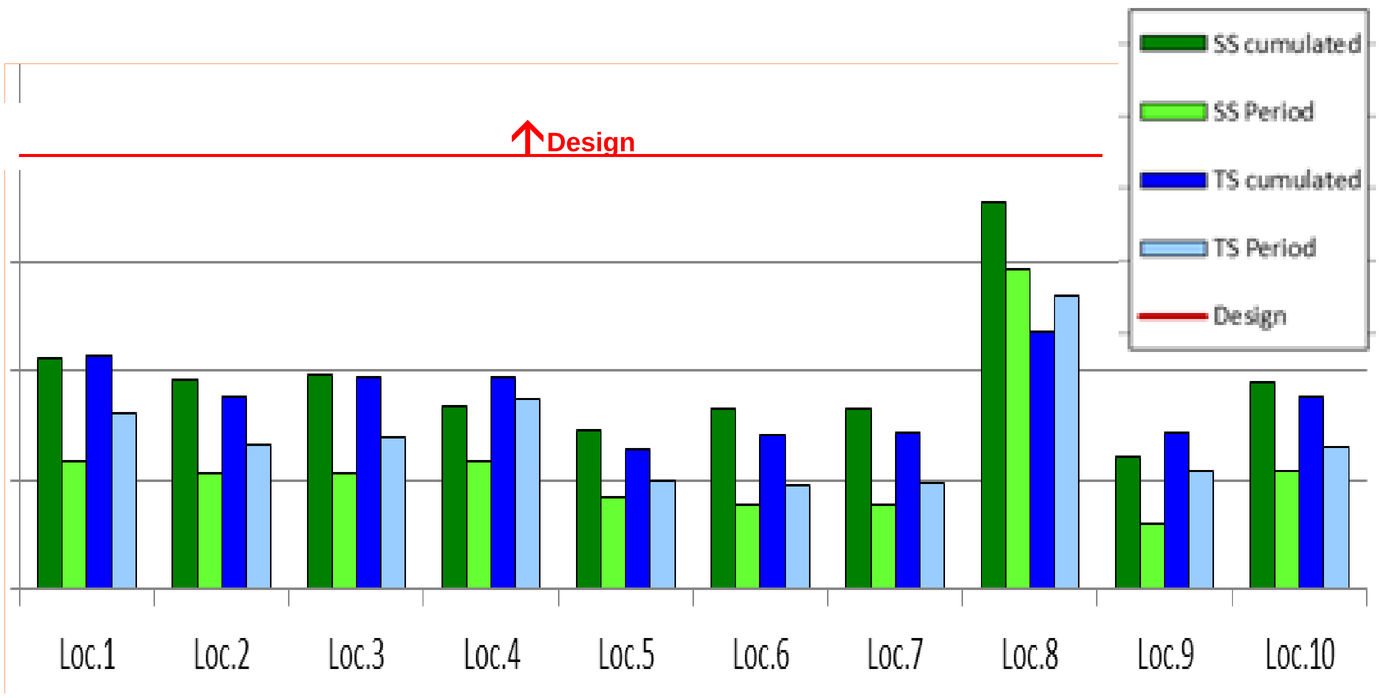


Fig. 4 - Fatigue Indexes values for IAF Typhoon aircraft.
(For location definition, see previous editions of National Review).

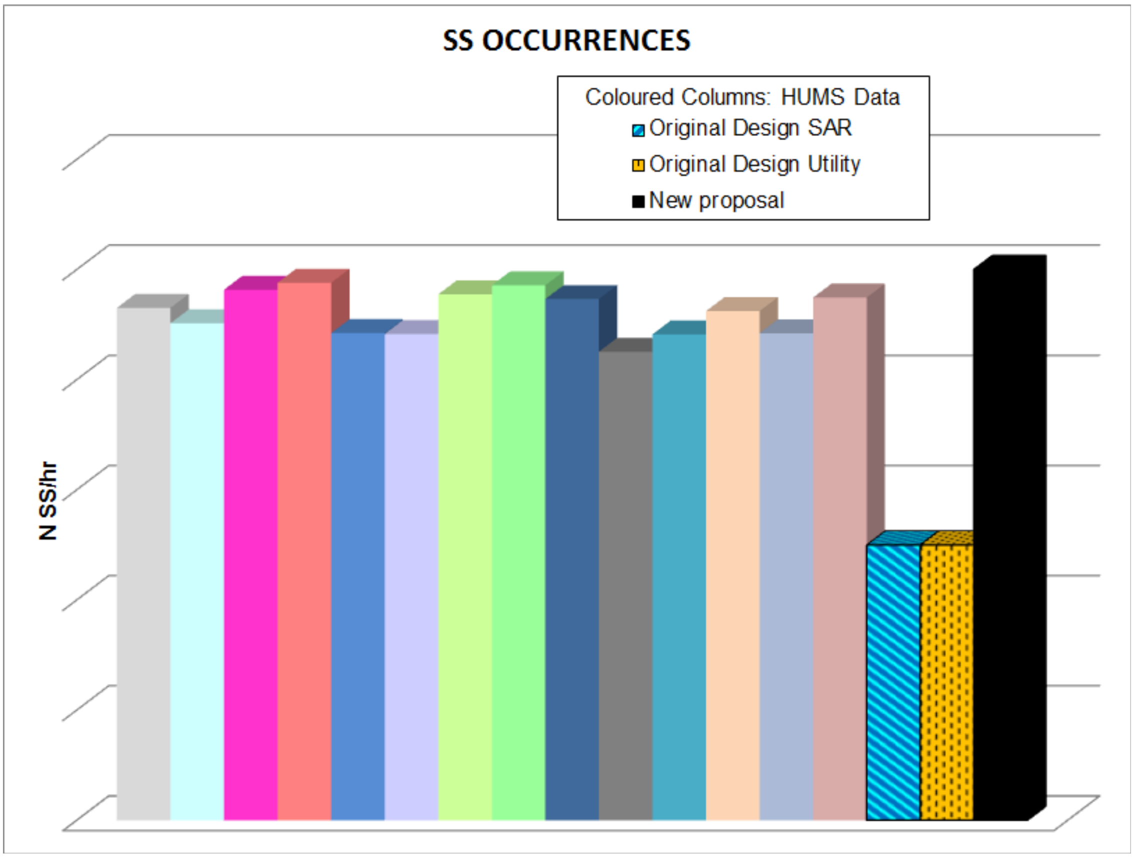


Fig. 5 - Analysis of HUMS data from a EH101 fleet: distribution of the number of Start-Stop cycles per hour.

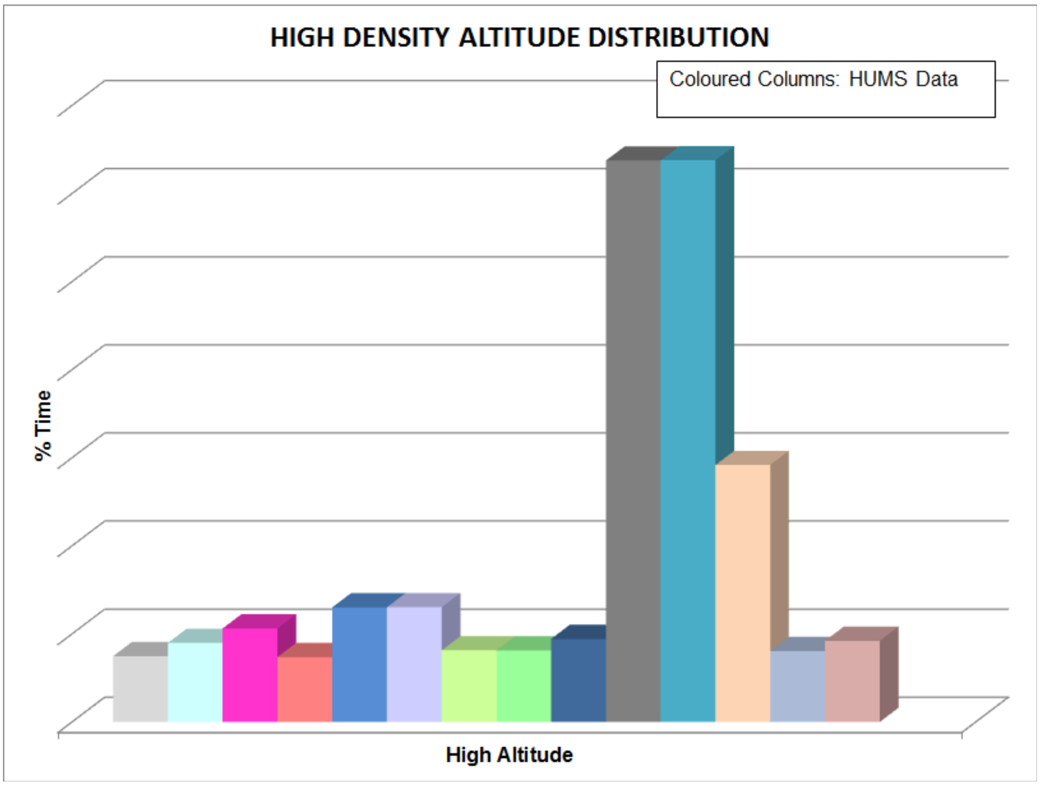


Fig. 6 - Analysis of HUMS data from a EH101 fleet: distribution of the altitude of the sortie.

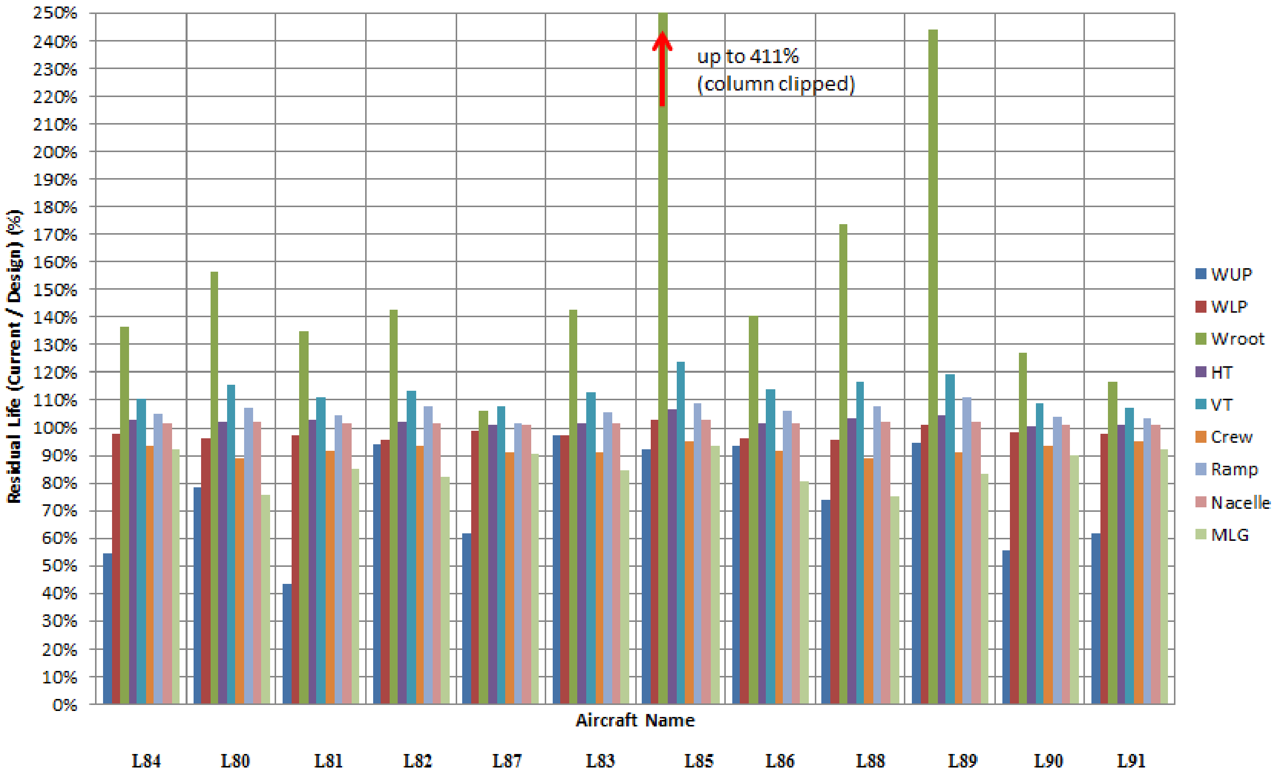


Fig. 7 – Residual life, as a percentage of original design life, of the control points in different C-27J aeroplanes.

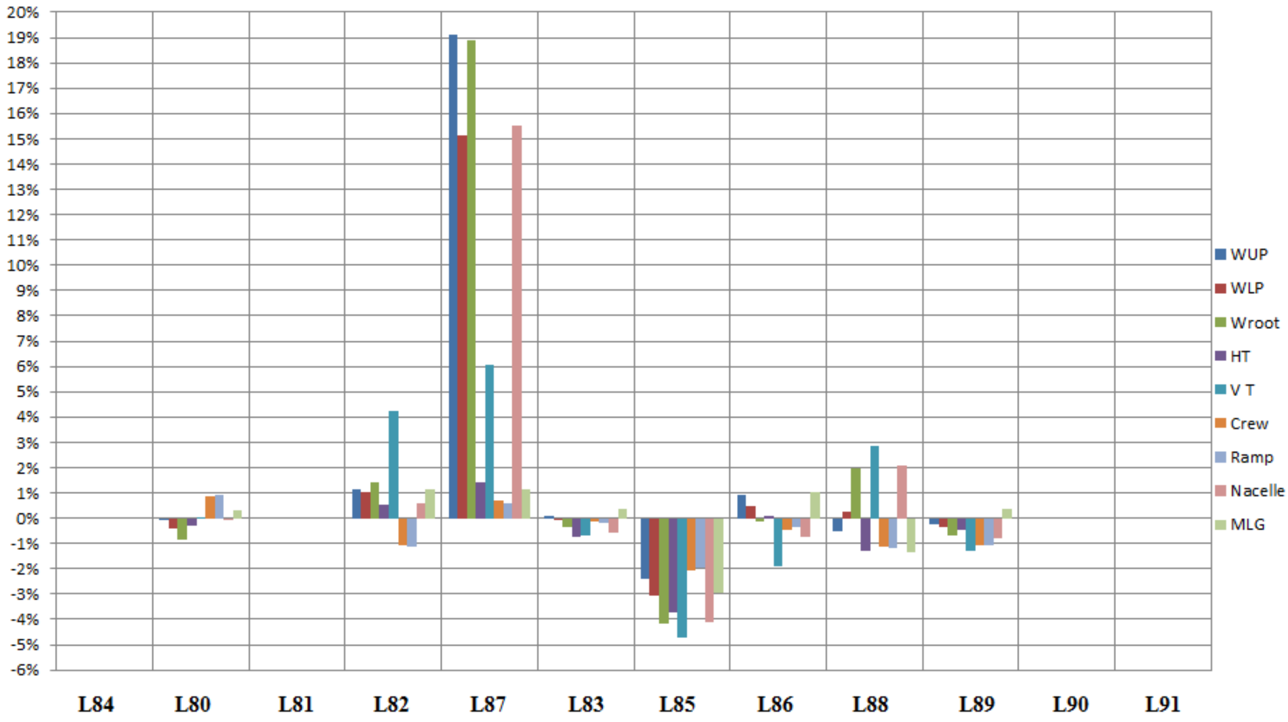


Fig. 8 - LSI variation in the last period of monitoring for a number of C-27J aircraft.

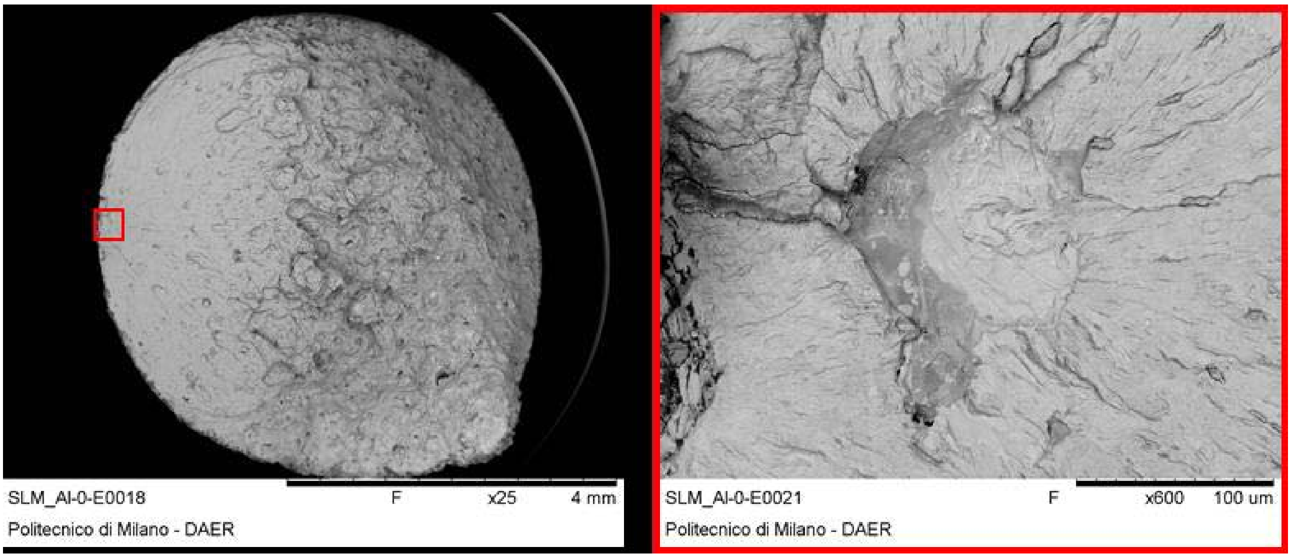
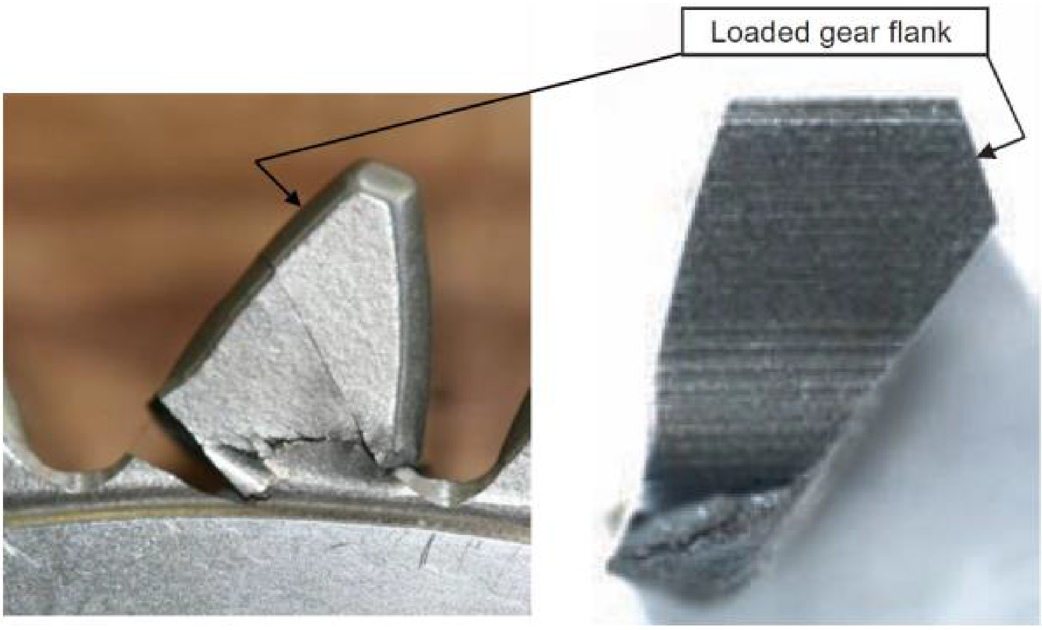
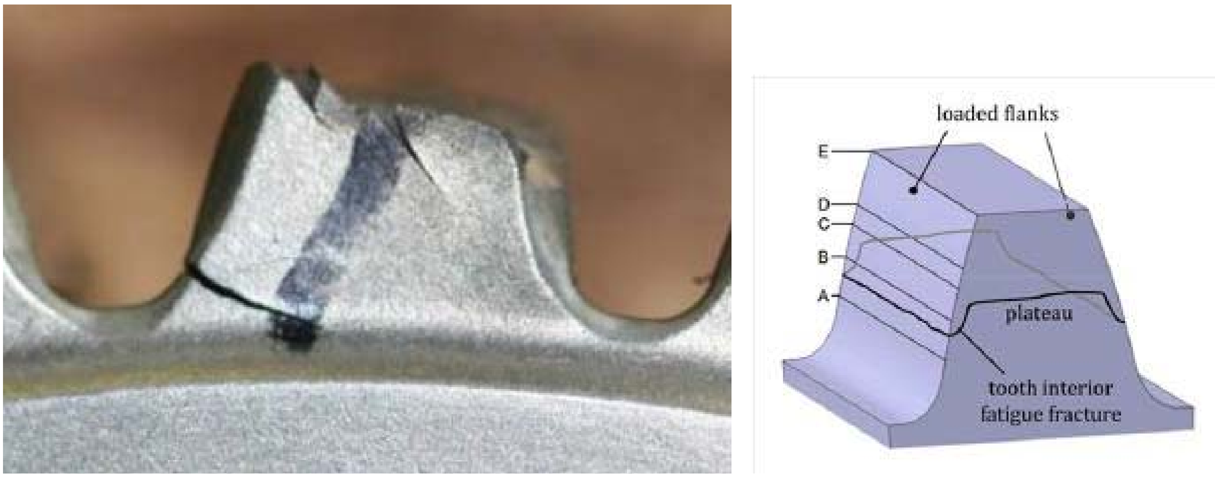


Fig. 9 – Fracture surface of a fatigue sample (Al alloy produced by SLM) tested in tension-tension fatigue.

(a) Root Failure (RF)



(b) Tooth Flank Failure (TFF)



(c) Tooth Interior Fatigue Failure (TIFF)

Fig. 10 – Various types of tooth fatigue failures.

Fig. 11 – Dedicated planetary rig, for testing planet gear bearings.

Fig. 12 - Evolution of the crack front in Cold Expanded pin loaded hole, as evidenced by marker loads.

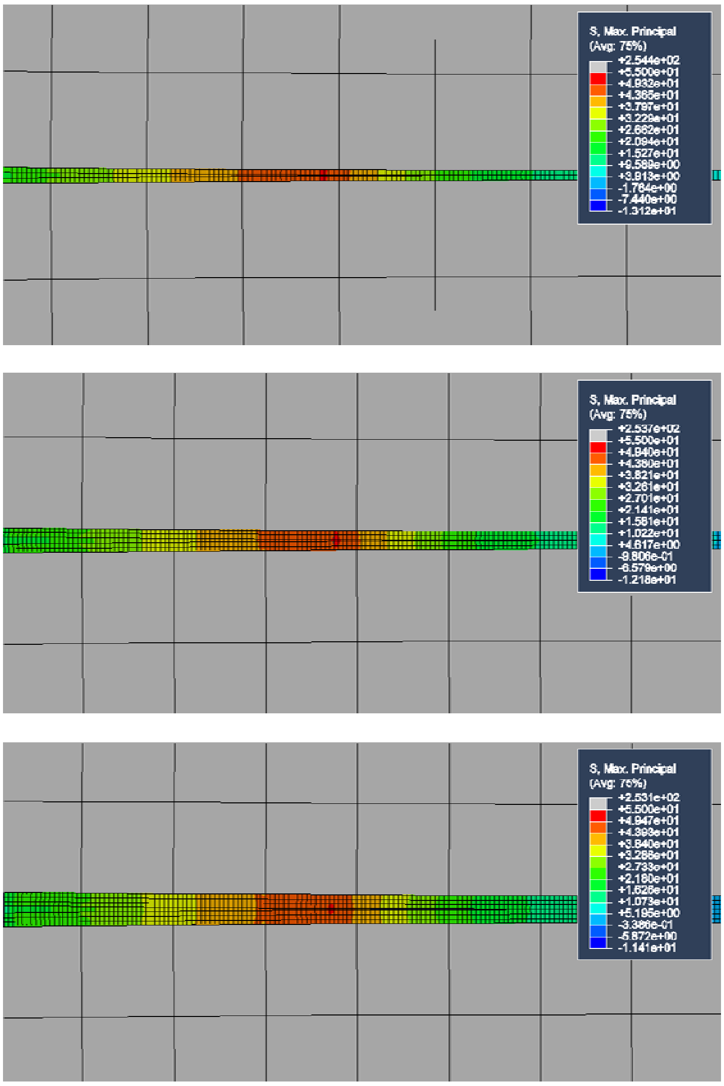


Fig. 13 - Comparison of maximum principal stress distribution for three different adhesive thicknesses.

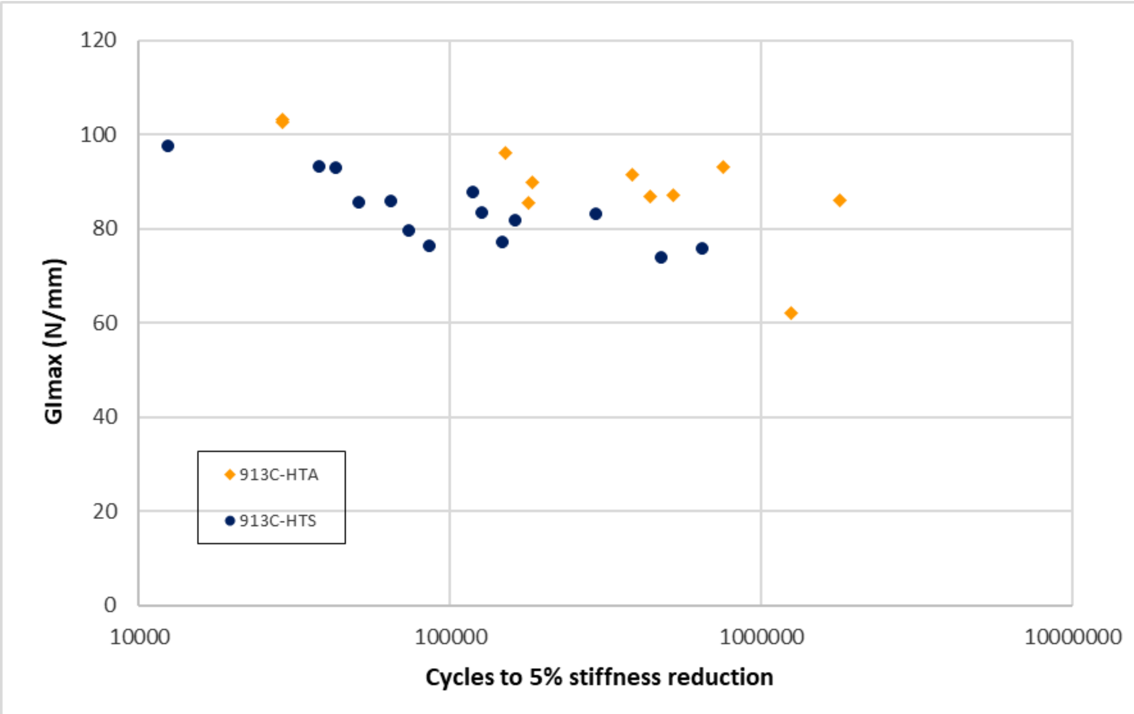


Fig. 14 - Fatigue tests results of delamination growth onset in DCB specimens (R=0.1; GI evaluated with the Williams-Kinloch formulation).

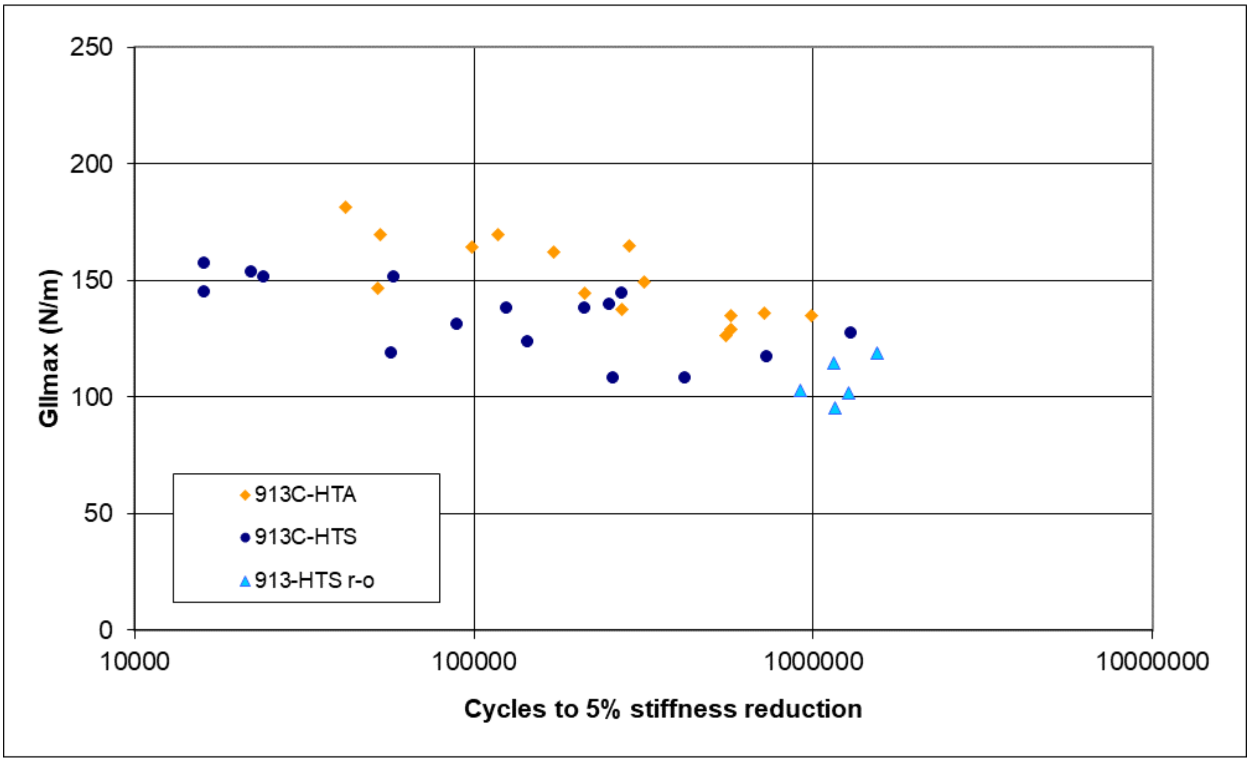


Fig. 15 – Fatigue tests results of delamination growth onset in ENF specimens (R=0.1; GII evaluated with the Compliance Calibration approach).

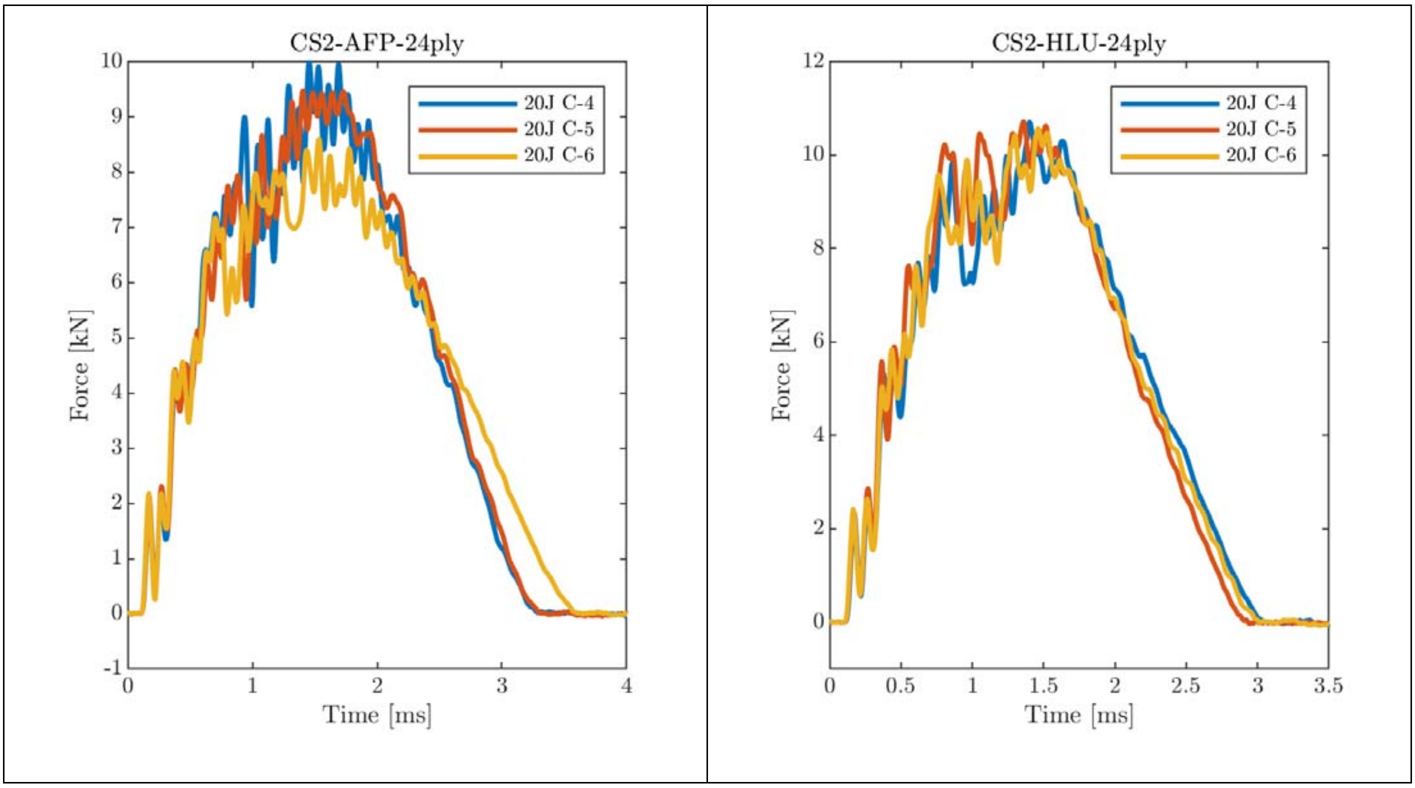


Fig. 16 – Force-time evolution in a series of 20 J impacts on the two material systems examined.

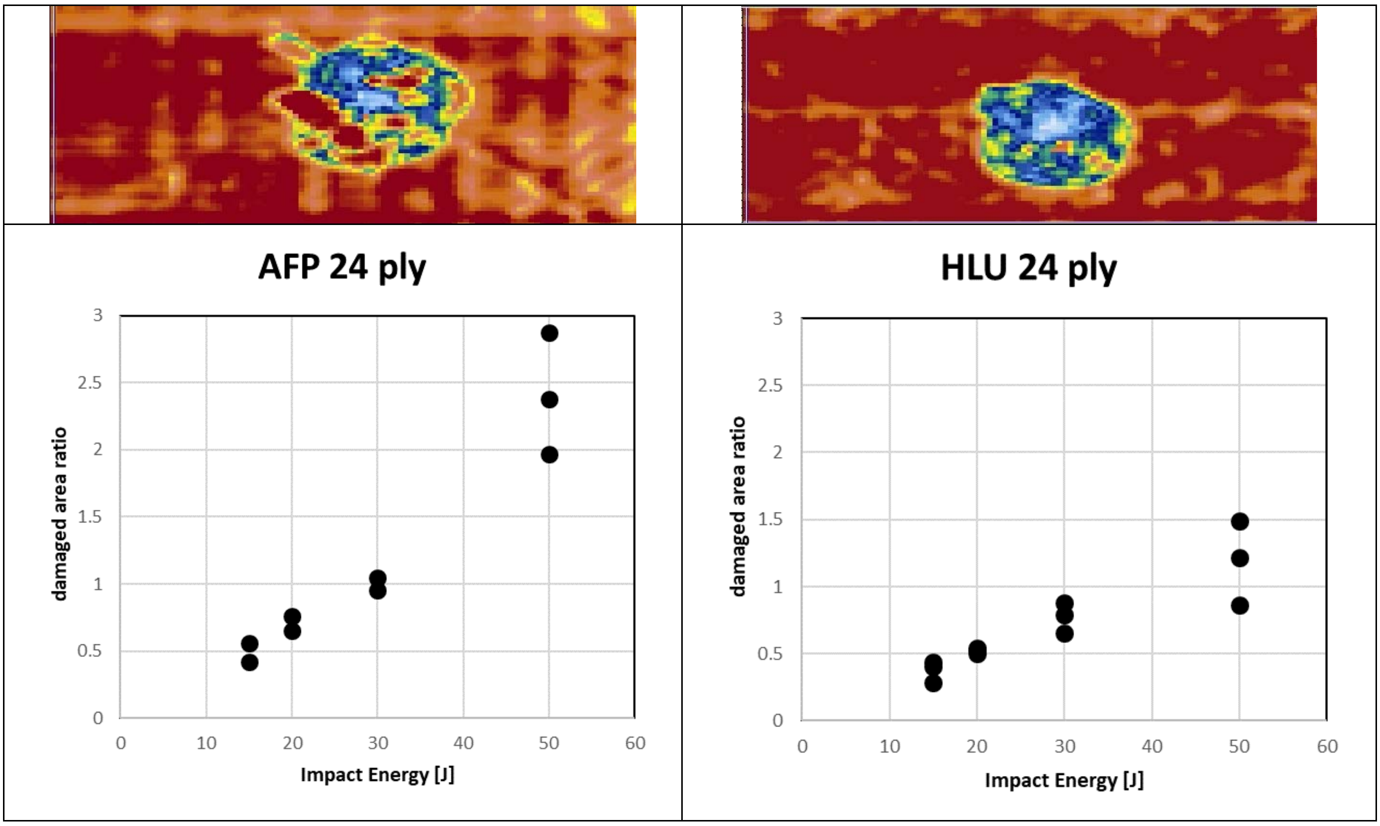


Fig. 17 – Non-dimensional damaged area detected by means of Ultrasonic C-scan, as a function of impact energy.

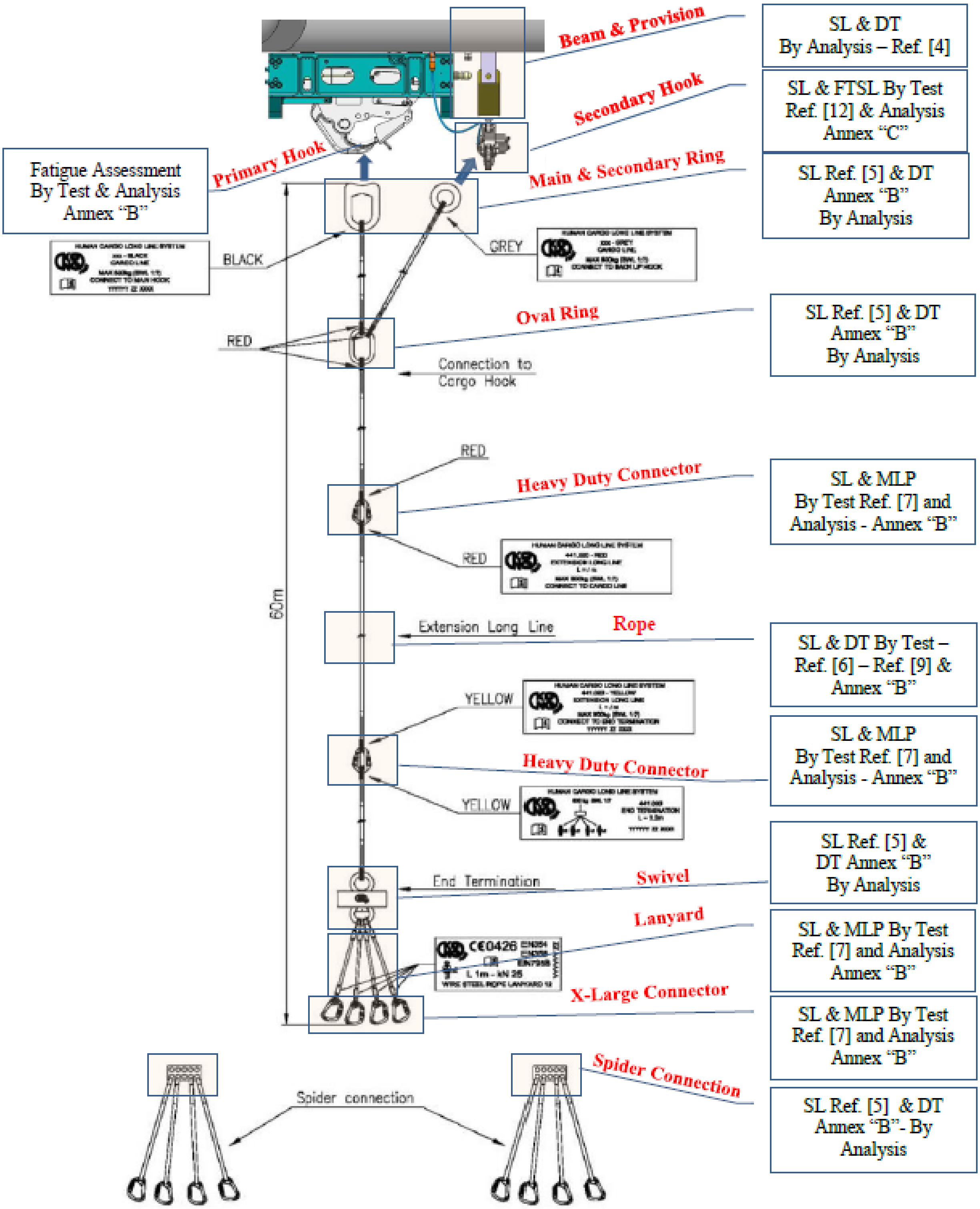


Fig. 18 – Outline of the qualification of the various components of the Human External Cargo kit for the AW139 helicopter.

Energy levels	AFP 24 plies	HLU 24 plies
15J	74%	74%
20J	66%	68%
30J	57%	61%
50J(cut-off)	48%	53%

Table I – Comparison of the percentage of the original compressive strength retained in the two material systems examined after low velocity impact with a CAI test.

Component	P/N	Safe Life	FTSL / MLP [FH]	Inspection Interval [FH]
Beam Structure Assy	3G2592A02731	19485 FH	/	No Growth
Dual Cargo Structural Provision	3G5311A28111	>40000 FH	/	No Growth
Secondary Hook	6F2592V00251	21030 FH	477 FH (2)	/
Main Hook Ring	Long Line 6F2592V01151	40486 [Ext. Load Cycles]	/	No Growth
Secondary Hook Ring (3)		Unlimited	/	No Growth
Oval Steel Ring		17736 [Ext. Load Cycles]	/	No Growth
Heavy Duty Connector		Unlimited	2896 [Ext. Load Cycles] (1) (4)	/
Swivel		Unlimited	/	No Growth
Lanyards		37806 [Ext. Load Cycles]	500 [Ext. Load Cycles] (1) (4)	/
X-Large Connector		Unlimited	2896 [Ext. Load Cycles] (1) (4)	/
Spider Connection Plate		Unlimited	/	No Growth
Rope		/	1500 [Ext. Load Cycles]	1500 [Ext. Load Cycles]

Table II – Results of the analyses performed on the critical elements of the HEC kit for AW139.