UNIVERSIDAD POLITECNICA DE MADRID
ESCUELA TECNICA SUPERIOR DE INGENIEROS
INDUSTRIALES

**Desarrollo de sensores de fibra óptica
para su aplicación a la monitorización de
la integridad estructural en estructuras
aeronáuticas de material compuesto**

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2018

A mi padres, mi esposa y mis hijos.

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ABSTRACT

The main objective of this thesis is the technical development of optical fibers sensors technologies, in particular fiber Bragg grating sensors and distributed fiber based on Rayleigh backscattering frequency, and the demonstration of their applicability in structural health monitoring applications for aeronautical composites structures in a suitable selection of scenarios.

The development strategy is eminently practical. It is started primarily with the study of the monitoring needs in composite structures and the identification and concretion of the requirements. These requirements covers the fundamental aspects in relation to the performance, accuracy, reliability or sensor resistance but also the compatible integration, durability or mitigation of any impacts with relation to the global process, -production, assembly and in-service life. Secondly, the study of the sensor technologies with capability to match with the previous requirements, FBG sensors and distributed sensing fiber, the gradual analysis to determine capabilities and limitations and modifications proposals to fulfill the requirements. Thirdly, the definition and development of the tests at different scales, -Lab, panel, component and complete a/c- that enable to assess and demonstrate these capabilities and limitations, as well as any other necessary aspects for the acceptance of the technologies in the application scenario. Once the tests have been carried out, the analysis and discussion of the results take place and conclude with the drafting of the conclusions and future actions.

The application of the mentioned strategy is the base of the content of this document and is organized into seven chapters:

- The first chapter is basically an introduction of the structural health monitoring concept, the relation between the classical approach – nondestructive inspection methods to control the structural quality of the parts in the different stages of the product life-, and the connection with the global concept of structural health management. This chapter introduces briefly some of the most important and promising technologies today in development for structural health monitoring (SHM) applications and specially the two optical fiber sensor technologies that are developed in this thesis. Also, this first chapter describes in a conceptual way the general architecture of any SHM systems and the key aspects have to be considered on the development process of SHM technologies with regard to a Multidiscipline that encompasses Structures and Sensors.
- The second chapter is expressly dedicated to the presentation and description of the physical principles behind the two optical fiber sensors technologies developed in this thesis. The scope is not to provide a rigorous analysis of the physical principles of the technologies, which can be found in the special references at the end of this chapter, but to know how these technologies work up to the adequate level to understand their main capabilities and limitations from performance and engineering point of view.
- The third chapter is essentially devoted to the presentation of the possible use case scenarios, and the identification of the major drivers for the use of the two optical fiber sensor technologies presented in the second chapter. At the end of the

chapter is also found the main technical reasons justifying the integration of their technologies into the selected scenarios and the implementation process proposal in order to minimize any impact in the different stages of the structure: Manufacturing & Final Assembly Line (FAL), Operation and Maintenance.

- The fourth chapter is entirely dedicated to the development of each the requirements applicable to the application scenarios identified in the third chapter. This compilation constitutes an essential task for the correct development of the technologies. The requirements were identified and organized according to the following criteria: strain monitoring application, damage monitoring, installation in structural test platforms, data management end user, operation in the aircraft, maintenance and operators. The main sources and references for the preparation of this chapter were obviously, on the one hand aeronautical standards related to operational conditions of the aircraft, and, on the other hand, the fruit of the knowledge acquired through the professional experience.
- The fifth chapter is entitled as leading aspects within the technology development of the optical fiber sensor technologies. It is divided in four sections each one dealing with essential topics in these technologies: a) the main elements of the optical fiber technologies: fibers, cables, connectors and interrogators, b) the installation process and the breakdown of the main steps, c) the temperature compensation methods in those scenarios where is necessary to do it, and e) the conectorisation of fibers when they are embedded inside the composite materials.
- The sixth chapter is completely dedicated to the experimental area of the thesis and although it constitutes the most hard-working part of this document, it would run the risk to be misaligned with the needs without all the preparatory work done in the previous chapters. The tests presented and developed are considered by the author as possible examples of the validation tests in the development phase of these technologies. The first group of tests describes the durability tests relating the resistance of the technology and integration process against normal operational conditions. The procedure and methodology for these tests are presented in five representative immersion test mediums: skydrol, kerosene, cleaning agent and water. The second group of tests that are reported refers to the temperature compensation concept when measuring strain with optical fiber sensors and acting simultaneously strain and temperature. In the third place, a simple test performed in electromagnetic lab is described to demonstrate the non-interference of Electromagnetic Field (EMI) on measurement process with optical fiber sensors. The test consisted of applying a controlled electrical discharge simulating a lightning strike and meantime measuring the strain and temperature with bonded optical fiber sensors. In the fourth place are detailed lab tests on selected coupons with integrated distributed fibers in order to evaluate the strain range of the technologies in mechanical tests. In the fifth place it is depicted a structural test on a metallic panel instrumented with distributed optical fiber and classical strain gages as reference. In the sixth place, a large composite structural tests, instrumented and monitored during static and fatigue conditions is described. In the seventh place, composite structural test panels containing a bonded repair patch and tested in static and dynamic conditions are described. In the eighth place an structural tests panel instrumented with embedded and bonded fibers is disclosed.

The embedded fibers were installed in the production phase and the ingress-egress issue was solved by special connectors designed and manufactured for this particular purpose. The last section of this chapter is dedicated to the preparation and set up of an optical fiber installation based on FBG sensors for load monitoring in flight tests.

- Finally, the last chapter of this thesis, the seventh one, highlights the final and most important conclusions, the scientific and technological achievements and recommendation of future research activities.

In summary, the methodology followed and results of the tests constitute a new evidence demonstrating the capability and unique advantages of the optical fiber sensors for structural monitoring in aeronautical structures. Undoubtedly, the time for the systematic use of these technologies is closer, firstly in aeronautical structural test platforms and then, once consensus of the benefit is reached, in serial a/c, in the latter case not only for SHM purposes but even for other applications such as for example temperature monitoring.

ACRONYMS

AE: Acoustic Emission
AMM: Aircraft Maintenance Manual
APC: Angle Physical Contact
ATL: Automatic Tape Layer
AU: Acousto Ultrasonic
AUPE: Automatic Pulse Echo
AUTT: Automatic Through Transmission
BITE: Built-in Self-Test
BOTDR: Brillouin Optical Time Domain Reflectometry
BVID: Barely Visible Impact Damage
CBM: Condition Based Maintenance
CFRP: Carbon Fiber Reinforced Plastic
CTE: Coefficient of Thermal Expansion
CVM: Comparative Vacuum Monitoring
DTSS: Distributed Temperature and strain sensors
ET: Eddy Current
FAL: Final Assembly Line
FC: Ferrule Connector
FEA: Finite Element Analysis
FUT: Fiber Under Test
FBG: Fiber Bragg Grating
FOS: Fiber Optic Sensors
HTP: Horizontal Tail Plane
ITU: International Telecommunication Union
LH: Left side
LL: Limit Load
MMF: Multimode Fiber
MRB: Maintenance Review Board
MSG: Maintenance Steering Group
MUPE: Manual Ultrasonic Pulse Echo
MUX: Multiplexer
NACA: National Advisory Committee for Aeronautics
NDT: Non-destructive Testing
OFS: Optical fiber sensors
OFDR: Optical Frequency Domain Reflectometry
OLM: Operational Load Monitoring
OoA: Out Of Autoclave
PM: Polarization Maintaining
PoD: Probability of Detection
RH: Right Side
SHM: Structural Health Monitoring
SHMA: Structural Health Monitoring Management
SMF: Single Mode Fiber

SRO: Stringer Run Out
SWI: Swept Wavelength Interferometry
TCM: Thickness Control Material
TRL: Technology Readiness Level
UL: Ultimate Load
UT: Ultrasonic Testing
VTP: Vertical Tail Plane
XR: X-Ray
WCP: Wavelength Center Peak
WS: Wavelength Shift
WDM: Wavelength Division Multiplexing

INTRODUCCION

OBJECTIVES OF THE DOCTORAL THESIS.

The main objective of this thesis is the technical development of optical fibers sensors technologies, in particular fiber Bragg grating sensors and distributed fiber based on Rayleigh backscattering frequency, and the demonstration of their applicability in structural health monitoring applications for aeronautical composites structures in a suitable selection of scenarios.

As for the complementary objectives:

- The selection process of the application scenarios for these abovementioned technologies and the identification of the most important requirements.
- The preparation, execution and result analysis of the experimental tests based on the previous identified requirements.
- The discussion of the maturity of the technologies from the Lab to the Aircraft going by structural tests - and correlating the results with selected reference technologies.
- And the last but not least, the establishment of a technical configuration proposal for the different elements that compose the technologies and the implementation procedures being compatible with the sequential phases of the product - Manufacturing, Assembly and In-service life.

METHODOLOGY FOLLOWED IN THE DEVELOPMENT OF THIS THESIS.

The work done has been organized into seven chapters:

The first chapter is basically an introduction of the structural health monitoring concept, the relation between the classical approach – nondestructive inspection methods to control the structural quality of the parts in the different stages of the product life-, and the connection with the global concept of structural health management. This chapter introduces briefly some of the most important and promising technologies today in development for structural health monitoring (SHM) applications and specially the two optical fiber sensor technologies that are developed in this thesis. Also, this first chapter describes in a conceptual way the general architecture of any SHM systems and the key aspects have to be considered on the development process of SHM technologies with regard to a Multidiscipline that encompasses Structures and Sensors.

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The fifth chapter is entitled as leading aspects in the technology development of the optical fiber sensor technologies. It is divided in four sections each one dealing with essential topics in these technologies: a) the main elements of the optical fiber technologies: fibers, cables, connectors and interrogators, b) the installation process and the breakdown of the main steps, c) the temperature compensation methods in those scenarios where is necessary to do it, and e) the conectorisation of fibers when they are embedded inside the composite materials.

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fibers were installed in the production phase and the ingress-egress issue was solved by special connectors designed and manufactured for this particular purpose. The last section of this chapter is dedicated to the preparation and set up of an optical fiber installation based on FBG sensors for load monitoring in flight tests.

Finally, the last chapter of this thesis, the seventh one, highlights the final and most important conclusions, the scientific and technological achievements and recommendation of future research activities.

1. CHAPTER 1. STRUCTURAL HEALTH MONITORING AND OPTICAL FIBER SENSORS.

1.1 GENERAL CONCEPT OF STRUCTURAL HEALTH MONITORING.

Structural Health Monitoring (SHM) is a discipline that can be considered inside the Mechanical Engineering, linking the world of mechanical Structures and electronic Systems, and consisting of the integration of sensor devices into the structural components in order to provide continuous information related to the mechanical behaviour of the structure in operational conditions [1, 2, 3, 4, 5, 6, 7, 8].

It can be also considered as an advanced concept of the Non-Destructive Testing (NDT) technologies to ensure in the next future the integrity of aircraft structures during operational life. The basic approach for SHM is to become NDT an integral functionality of the structures. The main features distinguishing SHM as compared to conventional NDT would be the following:

- For NDT:
 - The access to the area to be inspected has to be available.
 - The NDT system is brought to the inspection area at the time of the inspection and removed afterwards.
 - The inspection itself has to be performed by a qualified and certified NDT inspectors.
 - The inspection requires to be carried out the aircraft downtime.

- For SHM:
 - The sensors remain permanently applied to the structure, whereas other devices such as the interrogation unit may be either on-board or off-board.
 - These sensors are interrogated periodically at established regular periodic times and hence enabling new inspection/maintenance structure approaches.
 - The measurements from the sensors can be read out directly such as the case for example of mechanical strain, temperature, humidity, etc. or in an indirectly way such as load or damage in the structures.
 - Once the sensors are installed, the physical access to the inspection area is not absolutely necessary so that for instance the inspection of inaccessible areas prone to damage can be also done without accessing to the area.

Based on the previous statements, the main potential benefits of SHM technologies as compared to NDT would be:

- The possible reduction of maintenance costs as a result of permanent monitoring from the sensors, without the need to physically access to the inspection area by the NDT inspectors.
- The increasing aircraft availability due to the reduction of the inspection time and the application of on-Condition Maintenance approach (Condition Based Maintenance: CBM). Instead of heavy maintenance scheduled tasks at a certain time interval, a flexible maintenance program would be planned on individual aircraft level. The maintenance tasks would be based essentially on the actual condition of each aircraft's structures rather than on fixed time periods based on the average performance of an entire fleet. It can be estimated that this approach would save millions of dollars in revenue currently lost due to lengthy but manual inspections and aircraft downtime.
- The reduction of weight and fuel costs by challenging design criteria on the bases of structural data that would be available at arbitrary times by the SHM sensors.

Apart from this vision of applying SHM to in-service aircraft, the concept of SHM can be also applicable to the monitoring of the previous stages of the lifetime of the aircraft structures such as Manufacturing, Assembly or specially Structural Test phase. Each of these stages would require the monitoring parameters (temperature, pressure, strain, ...) related to the quality of the structure or process, as well as different approaches as regard to the integration process.

The perspective of the SHM that is developed in this thesis corresponds to the structural monitoring of the parts when working in operational conditions.

1.2 STRUCTURAL HEALTH MONITORING (SHM) & STRUCTURAL HEALTH MANAGEMENT (SHMA)

This section aims to make perfectly clear the main differences between both concepts-SHM and SHMA- and how they both are linked and work together.

Structural Health Monitoring system is basically the system as a whole comprising all those elements that are necessary to interrogate, acquire and process the structural material responses. There are fundamentally four tasks in any SHM system:

- a) Sensing process, by which the measurand (strain, force, environmental parameters, etc.) is sensed by the sensors and converted into a signal suitable for store, conditioning, etc.
- b) Data sampling from the outputs of the sensors.
- c) Data acquisition including digitalization or recording, and,
- d) Data processing or computation phase.

Structural Health Management is the process of determining the current status of the structure (diagnostic) based on the information provided by the sensors (SHM). For example if a damage is detected by SHM system, the structural health management system would assess how severe is the damage detected in order to know whether the structure continues holding with the sufficient structural properties to perform its desired

function (prognosis) and also even more making the appropriate decisions or recommendations about the mission or the maintenance actions based on structural health monitoring data [1,9].

From practical point of view both systems working together would aim to meet the following requirements:

1. The detection of pre-defined structural damage during operational conditions.
2. The damage characterisation in certain aspects such as location, sizing or damage type.

The previous requirements, 1) and 2) could be carried out on-line or off-line depending on the technology and detail conditions.

3. The statement of the current status of the structure from structural view point, its remaining strength and evaluation of possible consequences due to the damage detected.
4. Finally the decision-making that would lead basically to:
 - Decision A) – the operation can continue and specifying the operation conditions (normal operation, with limitations or temporally.)
 - Decision B) – the operation is stopped and the repair or replacement of the damage structure has to be carried out.

Structural health monitoring and management systems working together would contribute to the increase of the aircraft availability. The continuous monitoring and prognostic capability would enable to optimize the operative time of the aircraft and to avoid unexpected severe downtime due to maintenance issues in the last time.

1.3 STRUCTURAL HEALTH MONITORING TECHNOLOGIES AND OPTICAL FIBRE SENSORS.

There are today several emerging technologies with different level of maturity aiming to be implemented permanently into aircraft with structural health monitoring purposes [10, 11]. One of the main classification responds to the technology uses and the scope of the monitoring areas; global technologies monitoring relatively extensive areas and local technologies only focus on hot spot areas. These are some of the technologies with greater projection in aeronautical applications for the next years:

- a) Comparative vacuum monitoring (CVM). It is a relatively simple method for in-situ, real time monitoring of crack initiation and/or propagation in metallic structures. Today is also in development for composite damage detection. CVM is based on the measurement of the differential pressure between fine galleries containing a low vacuum alternating with galleries at atmosphere in a simple manifold (see figure below). When a crack is initiated in an area covered by these bonded sensors, a connection between both type of galleries is produced and a change on the differential pressure is detected (figure 1.1).

Figure 1.1. Comparative Vacuum Monitoring sensor.

- b) Acousto-ultrasonics (AU). It is a global ultrasonic technique based on the propagation of Lamb waves that employs two separated types of piezoelectric transducers, sender (or active) and receiver (or passive) to monitor the structure. The transducers are bonded to the structure in a way to cover the inspection of the interest area. Then the active sensors are excited and the passive sensors collect a reference signal that is the pattern of the structure in healthy condition. The monitoring process itself consists of repeating this emission & receiving process and compare the acquired data with the initial or reference pattern. In case of damage, the signal received by the passive transducers should contain the change event and by the proper processing will provide the significant information about the damage and its characterisation.
- c) Acoustic emission (AE). AE technology consists of the use of uniquely passive ultrasonic transducers (20Khz-1Mhz) to listen to the sounds of failure occurring in materials and structures. Crack initiation and growth in metallic structures due to fatigue, hydrogen embrittlement, stress corrosion or creep can be detected and located by the use of AE technology. AE technology is also finding application in the non-destructive testing of composite materials and structures made from composite materials for the detection of fiber breakage or matrix cracking.
- d) Eddy current sensor (ET). Eddy current sensors is a conventional non-destructive inspection method, commonly used in current maintenance operations. Their main application is to detect cracks in metallic parts. The probes are manually scanned over wide areas and the reading of an acquisition system allows to detect surface and sub-surface cracks. The SHM approach of this technology consists of the use of foil eddy current sensors to hot spot monitoring solutions. The copper winding is printed on a substrate that is bonded to the area to be monitored. They can be mounted on interfaces between structural parts or tailored to many different part shapes (around bolts, in corners, etc.). The connections can be also integrated in the sensors giving access to very remote places and providing periodic reading out of the structural integrity of the area.

- e) Fiber optic sensors (FOS) [12, 13, 14, 15]. FOS can be classified into different technologies in function of the modulation & demodulation technique used to measure the shifts in the light parameters such as intensity, phase, wavelength or polarization states. Inside the optical fibre sensors technologies, the most promising technologies that are developed in this document are, Fibre Bragg Grating (FBG) and Optical Frequency Domain Reflectometry (OFDR). The next table summarize briefly the main features of each two technologies.

Table 1.1. Fiber Optic technologies in the scope of this document.

Fiber Bragg grating	Distributed sensing optical fiber
FBG's previously written in the fiber	No sensors are written in the fiber and conventional telecom single mode (SM) fiber is used as sensing fiber
Discrete sensors on the fiber, from 3 to 20 mm gage length and spatial resolution depending on grating manufacturing capabilities.	Gage length and spatial resolution is configured by software
FBG wavelength center shifts linearly (in normal range operation conditions) with strain and/or temperature changes.	Sensor consists of the analysis of the optical back scattering reflection of the fibre. For a given fibre, the scatter amplitude is a random but static property that can be modelled as a long, weak FBG with a random period.
Measurements made via monitoring wavelength shift	In case of OFDR, the backscattering is processed in frequency domain.
High multiplexing capabilities but a certain limitation in the number of gratings per fiber.	The complete length of the fibre is sensed.

1.4 GENERAL ARCHITECTURE OF SHM SYSTEMS.

It can be said that any Structural Health Monitoring system with independence of the technology is composed of a serial of generic elements [15, 17, 18, 19, 20]. These elements are listed as follows:

- a) Sensors. The sensors are the sensitive devices in close contact with the structure to monitor, and converting the measurand into a signal suitable to be stored, conditioned, processed, etc. The type of sensor depends on the technology itself and the application scenario (detection of damage, strain monitoring, surface crack in metallic materials, ...) and it is composed of the transducer, the adhesive (if surface bonded) and the protection layers to resist conveniently the environmental conditions (sealant and top coat). The way to integrate the sensors in the structure is a key issue in the technology development since the installation has to be robust enough during the complete life time of the structure. We can distinguish three generic methods to integrate the sensors into the structure:
 - a. Surface bonded
 - b. Embedded inside the material

- c. Integrated between for examples two intermediate layers of the structure
- b) Cables and connectors. The mission of the cables and connectors is to communicate the sensors with the interrogator unit. Since they have also to resist the on-board environmental conditions, they have to be designed, manufactured, tested and qualified for that purpose.
- c) Interrogator unit and multiplexor. The interrogator unit is basically the hardware brain of the system that sample, condition and acquire the response of the sensors. It integrates usually a microprocessor to process and analyse the outputs of the sensors. The exact configuration depends on the particular technology and type of sensors. The interrogator can incorporate also multiplexors to expand the number of channels in the system and therefore to increase the number of sensors to monitor.

1.5 KEY ASPECTS ON THE DEVELOPMENT PROCESS OF SHM TECHNOLOGIES

As previously mentioned, the structural health monitoring of aeronautical structures is a discipline linking the Structures from mechanical point of view and the Sensors & System from instrumentation point of view. The development process of these technologies is a lengthy and complex team work that need to be at least defined and scheduled from the beginning taking into account a high number of requirements. The identification of the complexities and challenges related to these requirements help us to design and prepare the necessary development phases.

These are the main reasons justifying the complex and laborious development phases of SHM technologies:

- a) The large amount of requirements that need firstly be identified to later meet from structural and system viewpoint.
- b) The decision making based on SHM system involves directly to the safety of aircraft, therefore it is absolutely necessary the complete demonstration of the maturity and reliability of the technologies in front of all stakeholders: Manufacture aircraft, Operators and Certification Authorities [21].
- c) The necessary precise definition of the need, expected benefits, application and integration level. All these factors have a strong influence in the development process to be followed.

Based on the previous premises, it is absolutely necessary to stablish a systematic and objective procedure for the development of SHM technologies for aeronautical applications while taking into account the need to perform the development in the most costly and time effective way. These are the main steps in the process, some of them, developed in this document:

- a) Definition of the general application, motivations (first rough business case) and identification of the essential requirements. This first step serves to guide

into the next steps of the process. The next requirement families can be used to support in the identification process:

- Certification requirements coming from Aeronautical Regulations (Airworthiness standard, Advisory circulars, Airworthiness Directives, etc.)
 - Performance requirements of the technology such as damage detection capabilities, operational load monitoring, accuracy, resolution, reliability, repeatability, etc.
 - Durability requirements related to the onboard environmental conditions of the technology (temperature resistance, humidity, vibration, etc.)
 - Integration requirements related to the manufacturing, assembly or in-service life (integration method of the sensors, power supply, connectors, etc.)
 - Commercial/business requirements related to the cost and benefits of the technology for the end-user.
- b) Identification of the physical detection principle and selection of the technology to develop.
- c) Development of the complete technology architecture (sensor, cables, interrogator, integration as a whole, etc.) to reliably adapt and match with the essential requirements previously identified and avoiding unnecessary development steps:
- Understanding the physical concept of the technology.
 - Definition on how to use and to apply the sensors, interrogator unit and installation issues in general for structural health monitoring application.
 - Design and preparation of all separated elements of the SHM application scenario.
- d) Preparation and execution of the screening test campaigns. Verify and demonstrate the compliance with the requirements and maturity of the technology (laboratory and real environmental conditions).
- e) Review of the scenario, detailed definition of the final application and the specific requirements.
- f) Preparation and execution of the test campaign to verify and demonstrate, the compliance with the specific requirements.
- g) Assessing the results of the test campaign and evaluation of the maturity of SHM technologies with regard to given application scenarios in a quantitative and objective way.

- h) Identification and evaluation of any impacts, limitations, Mean Time Between Failures (MTBF) and compatibilities of the technology system in the different applicable steps of the product life; manufacturing, assembly and operational life.

The general and specific requirements can be ordered and organised by a pyramidal hierarchy in function of the level of complexity and proximity respect to the final application, and are numbered from TRL1 to TRL 9 (TRL: Technology readiness level) from the base to the vertex pyramid respectively. In the course of maturity assessment, the requirements from TRL 1 to TRL 3 shall provide the technologist actor an objective assessment on the potential performance of SHM technology in order to satisfy a given application scenario. The fulfilment of requirements from TRL 4 to TRL 6 shall provide objective evidence for the SHM technology regarding performance, durability, reparability, maintainability or integrability to the structure in on-board conditions. The achievement of TRL 6 is a key indicator for technology readiness. At this level it can be confirmed the enough capability of the technology development process so that Qualification Program takes over the further development.

The formal qualification and certification process will demonstrate the evidence that a technology will function within specified operational limits (specification) with an acceptable level of confidence. The qualification process will consolidate also the level of the responsibility of the technology inside the aircraft (DAL: Design Assurance Level). This latter process is out of the scope of this document although it can be anticipated that some of the tests presented here (in chapter seven) shall be quite similar to the required from Technology Qualification [22, 23].

2 CHAPTER 2. PHYSICAL PRINCIPLES OF THE STUDIED OPTICAL FIBER TECHNOLOGIES.

2.1 OPTICAL FIBER AND OPTICAL FIBER SENSORS.

An optical fiber is an electromagnetic waveguide composed of three parts; the core, the cladding, and the coating (figure 2.1).

- The core is a cylindrical rod of dielectric material generally made of glass with dopants (i.e. germanium, to increase index of refraction). The light propagates along the core of the fiber based on the total internal reflection principle. The angle at which total internal reflection occurs is called the critical angle of incidence. At any angle of incidence, greater than the critical angle, light is totally reflected back into the fiber core.
- The cladding layer is surrounding the core and made of a glass dielectric material with lower index of refraction than the core material. The fiber's index depends on the density of the dopants it contains. The cladding is essential for example to decrease the loss of light from core into the surrounding air or for protecting the core from contaminant, chemical or mechanical effects. Typically the cladding is 125 micron external diameter.
- The coating is the layer of material surrounding the coating and used to protect an optical fiber from physical damage. There are different possible materials for the fiber coatings as referred in chapter 5 .

Figure 2.1. Constitution of the optical fiber.

Optical fibers are divided into two groups, the single mode and multimode. Multimode fibers are the type of fiber commonly used for communication proposes. Single mode fibers are the type of fiber used for sensing applications with fiber Bragg or distributed sensing. The recommended geometrical, optical, transmission and mechanical parameters of this fiber can be found in ITU-T Recommendation G652 (ITU-International Telecommunication Union).

Fundamentally, any fibre-optic sensor technology works by modulating one or more properties of a propagating light wave, including intensity, phase, polarisation, and frequency, in response to the environmental parameter being measured (strain, temperature, vibration, humidity, etc.).

Next it is described more in detail the principle of the two technologies developed in this thesis.

2.1.1 FIBER BRAGG GRATING SENSOR.

A Bragg grating sensor is a local sensor for typically the measurement of strain and/or temperature sensing written in the core of the optical fiber. Basically it consists of a permanent periodic perturbation of the refractive index along a short length, typically from 3-20 mm, fabricated onto bare photo-sensitivity fiber by the exposition to laser ultraviolet light (excimer laser with wavelength of 240-250 nm). Two intense ultraviolet beams are angled to form an interference pattern with the desired periodicity producing the redistribution of the dopants according to the periodic law (figure 2.2 a). Another common method to produce grating on the fiber is by illuminating the fiber with a UV laser through a phase mask. This mask is a binary grating with a groove profile and depth optimized to diffract most of the incident UV laser energy into the plus and minus first diffraction orders while minimizing energy in the zero and higher orders [24, 25, 26, 27, 28, 29, 30].

Figure 2.2. a) Production of FBG sensors and **b)** Fiber Bragg grating sensor principle (From Wikipedia 2017)

Once the grating is manufactured in the fiber, when the light from a broad band source interacts with the grating, a single wavelength, called the Bragg wavelength, is reflected back whereas the rest of the signal is transmitted (figure 2.2 b). The central wavelength of the reflected component (λ_R) satisfies the Bragg condition:

$$\lambda_R = 2n_{\text{eff}}\Lambda \quad (2.1)$$

with n_{eff} the effective index of refraction and Λ the period of the index of refraction variation of the FBG.

The period and index of refraction of the fiber are intrinsically sensitive to environmental parameters such as temperature and strain (to a lesser extent also sensitive to pressure, and humidity, this latter case if the fiber coating is hydroscopic [31, 32]). The wavelength center (WC) shifts linearly, under typical temperature range, when strain and/or temperature are applied. Therefore the monitoring of the reflected wavelength shift is the essence of FBG as a SHM sensor.

The change of wavelength of an FBG due to strain and temperature can be approximately described by equation 2.1 [33, 34]:

$$\Delta\lambda(\epsilon, T)/\lambda_0 = (1 - p_\epsilon)\epsilon + (\alpha + \xi)\Delta T \quad (2.2)$$

where $\Delta\lambda$ is the wavelength shift and λ_0 is the initial wavelength. The first part of expression describes the impact of strain on the wavelength shift, where p_ϵ is the strain-optic coefficient, and ϵ is the strain experienced by the grating. The second part of the expression describes the impact of temperature on the wavelength shift, where α is the thermal expansion coefficient describing the expansion of the grating with the temperature, and ξ is the thermo-optic coefficient describing the change in refractive index with temperature. In general, the temperature sensitivity of a grating occurs principally as a result of the temperature dependence of the refractive index in the fiber material and, to a lesser extent, to the thermal expansion in the material which changes the grating period spacing.

In the main telecommunications transmission frequency, C-band 1550-nm window, the equation can be simplified to:

$$\Delta\lambda(\epsilon, T) = S_\epsilon \epsilon + S_T \Delta T \quad (2.3)$$

S_ϵ is the wavelength/strain sensitivity and with approximate value of 1.2 pm/ μ strain
 S_T is the wavelength/temperature sensitivity of roughly 10 pm/ $^\circ$ C.

These values are somewhat dependent on the dopant species and concentration in the core of the fiber, but also to a lesser extent the composition of the cladding and coating. Variations of 5-10% between standard telecom fibers can be common. A calibration test in front of a reference technology is the most adequate to determine adequately the temperature and strain coefficients.

Several gratings can be written along a single optical fiber in an intermittent way to obtain a quasi-distributed sensing system and improving multiplexing capabilities of the technology.

Concerning the measurement set up of an FBG system, basically can be simplified in the following elements (figure 2.3):

- Interrogator unit that consists of firstly an optical source, typically a tunable laser, that continuously “interrogates” the reflection spectrum of the FBG sensors on the fiber. Secondly an optical detector to detect and modulate the WC shift and finally the signal processing hardware and software. Because of the wavelength nature of FBG, sensor measurements remain accurate even with light intensity losses/attenuations due to bending or transmission.
- Multiplexed FBG sensors written in the fiber and in the location of the areas to be monitored.
- Single mode transmitted optical fiber and connectors to communicate the interrogator unit with the sensors.

Figure 2.3. Generic set up of FBG instrumentation system.

2.1.2 DISTRIBUTED FIBER SENSING (DSST: DISTRIBUTED SENSING STRAIN AND TEMPERATURE)

A distributed fibre optic sensing system presents a unique feature that has no match with conventional sensing techniques and turn out unbeatable, the whole optical length fibre can be sensing. The physical principle is based on when an electromagnetic wave is launched into an optical fibre, the photons of the light are redistributed by various mechanisms (Rayleigh, Brillouin or Raman) in the form of scattering (figure 2.4). If physical parameters such as strain or temperature changes, the scattered signal in the fibre will be modulated. The scanning and signal processing of the backscattering comparing with reference fibre conditions will provide the information of the continuous changes along the complete fibre [35].

Figure 2.4. Mechanism of backscattering in optical fiber (Composite Structures, Elsevier, January 2016).

The measurement of Rayleigh, Raman or Brillouin scattering distinguish among the different distributed sensing methods currently available and their main features: spatial resolution, distance range, measurement time, data processing and system cost. The table 2.1 notes the gross differences between distributed sensing technologies: Brillouin (BOTDR), Raman or Rayleigh [36].

Table 2.1. Distributed Optical fiber sensing methods.

OPTICAL FIBER DISTRIBUTED SENSING METHODS			
	BOTDR	Raman OTDR	Rayleigh OFDR
Spatial resolution	~1 m	~1m	~1 mm (depending on sensing range)
Fiber length or sensing length	20–50 km	1- 30 km	~10-70 m
Measurement time	1–5 min	< 3 min	For static applications: 3-6 s For dynamic applications: up to 100 Hz (tradeoffs in acquisition rate, sensing length, and spatial resolution)
Temperature and strain	Yes	No (only temperature)	Yes
Temperature accuracy	2–3 °C	1°C- 3 °C	0.5 °C
Strain accuracy	60 μ	No	1 μ
Dynamic measurement	No	No	Yes

The work developed in this thesis is focused on the analysis of the Rayleigh backscattering technology by optical frequency domain reflectometry (OFDR). This technique highlights because its high spatial resolution -in the range of millimetres-, well above the other two techniques based on backscattering analysis. The limiting factor of Brillouin or Raman is the extremely low intensity of the scatter that makes very difficult to increase their resolution. On the contrary Rayleigh scattering is quite limited in terms of range of fibre length in comparison with the other two back scatter mechanisms [37, 38, 39, 40].

The Rayleigh backscatter in optical fibers is caused by the elastic interaction of the photons with the random fluctuations in the core index of refraction profile along the fiber length. This scatter varies from segment to segment in the fiber but the profile along the fiber is highly repeatable and can be considered as a unique static property for a given fiber (see in figure 2.5 [35, 36] the repeatability and consistency of three consecutive scans of the same fiber). It represents a characteristic fingerprint for each specific fiber. The fiber can then be modelled as a continuous weak and long FBG with a random period. Therefore changes in the local period of the Rayleigh scatter caused by an external stimulus produce changes in the locally reflected spectrum.

The system used in this development utilizes a swept-wavelength coherent interferometry (SWI) to interrogate fiber optic sensors and measure the Rayleigh backscatter (amplitude and phase) as a function of position in the optical fiber. The SWI collects the backscatter optical power, U , in the spectral frequency domain, $U(u)$. The detectors collect the light backscattered from the FUT as the laser spectral frequency is tuned through a range of frequencies. $U(u)$ data is processed with a Fourier Transform to generate the backscatter optical power as a function of time delay, $U(\tau)$. Then backscattered amplitude $U(\tau)$ is scaled as a function of $U(x)$.

Figure 2.5. Repeatability and consistency of Rayleigh backscattering from three consecutive scans of the same fiber length (Luna Technologies Courtesy)

For a specific fiber segment j , backscattering spectrum is denoted as $U_j(v)$. When physical parameter changes in the sensing fiber, a measurable change on the backscattered light along the optical fiber sensor is created, $U_j(v)$ shifts to $U_j(v-\Delta v_j)$. By cross correlation operation comparing the backscattered light of the sensing fiber under test (FUT) in two states, one initial state - a reference $U_j(v)$ -, and second state when physical changes are applied $U_j(v-\Delta v_j)$, it is possible to determine the physical state of the fiber at the time of measurement. The two backscattered profiles are correlated point to point (segment to segment) to determine the spectral shift of the backscatter along the length of the sensing fiber.

This shift is analogous to the spectral shift produced in a Bragg grating:

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta v}{v} = K_T \Delta T + K_\epsilon \Delta\epsilon \quad (2.4)$$

Values for K_T and K_ϵ are somewhat dependent on the dopant species and concentration in the core of the fiber, but also to a lesser extent on the composition of the cladding and coating. Variations of 5-10% between standard telecom fibers can be common. Default values for most germane-silicate core fibers: $K_T = 6.45 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ and $K_\epsilon = 0.780$. Assuming a scan center wavelength of 1550 nm and the presence of only strain or temperature, the following conversion factors can be used: $\Delta\epsilon = (-6.67 \mu\epsilon/\text{GHz})\Delta v$ and $\Delta T = (-0.634 \text{ }^\circ\text{C}/\text{GHz})\Delta v$.

As mentioned, the scatter profiles of the two states are compared along the entire fiber length in increments of gauge length Δx (windows of analysis), set in the Data Processing step configuration of the technology. Each interval Δx represents an individual sensing element and defines the width of the data block that will be used to cross correlate spectral shift. Each segment Δx represents an individual sensing element. To make a distributed measurement, it is necessary to measure the shift in the cross-correlation peak for each

segment along the FUT. This is done by software sliding the analysis window over each section of the fiber in increments defined also by the user.

The next figure 2.6 is a scheme summarizing graphically the complete process:

Figure 2.6. Scheme of the measurement process followed by a distributed optical fiber sensing based on Rayleigh backscattering (TRL. C. Miguel)

3 CHAPTER 3. STRUCTURAL HEALTH MONITORING SCENARIOS FOR OPTICAL FIBER TECHNOLOGIES (FBG AND DSST).

3.1 MATERIALS, STRUCTURES AND MAIN SCENARIOS.

Structural Health monitoring approach can be developed for any structure independently of the material; metallic, polymers, ceramics or composite. The work reported in this thesis mostly refers to applications in composite structures that in turn are completely representatives or even real aeronautical structures.

The main features of the structural materials used in the manufacturing of the samples and specimens involved in this thesis are:

- Carbon fiber reinforced plastic (CFRP) based on carbon fibre reinforced thermosetting epoxy prepreg.
- High performance unidirectional tape 180°C – curing class
- Intermediate modulus fibre
- Thickness per ply (mm^2): 0.13-0.26
- Resin content (% weight): 32 -38
- Prepreg areal weight (g/m^2): 200 – 400
- Fiber areal weight (g/m^2): 130 -270

Further to the structures, the most important characteristics are:

- Monolithic and stiffened flat and curved CFRP structures made of tape, fabric or combinations materials.
- Structures can be stiffened by different types of stringers: L's, omegas, or T's and different endings (linear, elliptic, flat and double angle)
- The sizes of the structure can be divided into large, medium or small parts:
 - o Large parts such as upper & lower skin of wing, Horizontal tail plane (HTP), vertical tail plane (VTP) or fuselage parts.
 - o Medium part such as ribs or spars.
 - o Small parts such as fittings, clips.
- The structures can include flanges, ramps, radius, bonding line, stringers, reinforced areas, ...
- The bonding lines can be performed by co-bonded, co-cured, or secondary bonding process.

Concerning the application scenarios, four direct cases have been identified, in which the implementation and use of structural health monitoring technologies based on optical fiber would provide substantial benefits from engineering point of view[41, 42, 43, 44, 45]. These four scenarios are briefly described in the following.

3.1.1 STRAIN MONITORING SCENARIO.

Strain is a measurement of the deformation of a body/structure when subjected to external force system. It is the natural response of a material when is stretched or compressed, bended or torsion, and directly related to the stress inside the material. The measurement of the strain forms part of the experimental stress analysis discipline, where the process to determine the stress is based on the experimental measurement of the deformation. Therefore the measurement of the strain in the real structure is an experimental method to verify the level of the stress that is currently holding the structure and how close is it from the admissible limit.

The strain monitoring scenario for aeronautical structures is an scenario applicable in two phases of the aircraft product: structural tests platforms (on ground tests or the flight test programs) and during operation of in-service aircraft.

- a) In the structural tests platforms scenario (figure 3.1) the reason of the strain monitoring are basically related to the validation of the theoretical models (FEA: finite element analysis) that in general provide very good results for standard configurations such as isotropic material or regular geometries but however precise of the need of experimental results for the correction-validation of more complicated cases. These are some of the criteria followed for the location of the punctual strain sensors usually installed in structural tests platforms:
- Positions in which FEA model has to be verified or validated. This continuous improvement of the analytical model by strain monitoring instrumentation would lead to a more accurate sizing of the real structure.
 - Location of the strain sensors can be also defined in order to cross-checks between structural tests, flight test a/c and FEA.
 - Locations defined as critical load path in order to set up a general surveillance of the structure by strain gauge measurements.
 - Positions close to artificial damages or natural damage (once the test has started) in order to investigate load redistribution in adjacent load paths.
 - Positions in areas where there is unpredicted or unexpected behavior (i.e. structural repairs).

Figure 3.1. Example of structural test platform scenario (Airbus Proprietary)

- b) In in-service aircrafts (figure 3.2), the pure strain monitoring of selected areas can be used as a method to improve the understanding of the load patches in the real structure or even as an inspection method to detect possible anomalies as consequence of failures in adjacent elements (note that today it is not possible except in especial situations to detect the damage just based on strain measurement). The strain sensors are located in strategic positions of the parts, even with hard accessibility, and monitored during the in-service operation of the aircraft.

The classical sensors for strain monitoring in aeronautical industry are electrical strain gages. They were developed more than 50 years ago, they own well-established scientific principles and obviously are considered well-proven strain sensors. They are simple to install and utilize. Nevertheless, the technology also have weak points, as for example: strain gauges need three cables per sensor what increase enormously the density and volume of wiring in applications requiring hundreds of sensors, risk of disbond or drift in long term fatigue applications and the inherent ignition risk in inflammable or explosive environments.

Figure 3.2. In-service aircraft scenario (Airbus Proprietary)

Optical fiber sensors for strain monitoring constitute an emerging methods that aim to demonstrate comparable performance to strain gauges and even also superior features for example in relation to multiplexing capabilities, installation time or as passive sensors in areas susceptible to ignition risk. A more detail analysis about the motivations for the use of optical fibers is done further on in this same chapter.

3.1.2 OPERATIONAL LOAD MONITORING (OLM)

This scenario refers to the monitoring of the loads in a structure under its normal operating environment in order to know more in detail the real behavior of the structural parts as well as its severity in real environment (figure 3.3). This scenario can be investigated with different purposes:

- a) When the aircraft's role has changed within the lifetime of the aircraft and the stresses and strains in the structure are significantly different as initially studied. Some of the reasons of these changes can be the mission of the aircraft changed, flight envelope expanded, increased weights or increased engine thrust.
- b) For the support on the determination of the remaining life of an aircraft and therefore if feasible the lifetime extension [46]. The life of aircrafts are often referred to the flight hours or number of flights, but in fact is not just a matter of flight hours but also it is necessary to know about the load spectrum inside flight hours. The load monitoring in real conditions is enormously useful for the analysis of the extended life providing a measure of the aging or real usage of the aircraft.
- c) For detection of overload monitoring, that consists of the experimental detection of overload in the structure to ensure the aircraft is not operated beyond an acceptable level of risk.

The way loads are currently monitored in aircraft is either by implementing electrical classical strain gauges at well-selected locations or by using the flight parameters monitored on the aircraft and then by certain algorithms deduced the loads [47]. As already mentioned, some of the limitations in using electrical strain gauges for strain monitoring are related to their relatively high amount of wiring (three wires are required for each sensor), difficulty for ensuring proper surface bonded installation during the complete flight mission and drift issues related to the aging. The use of optical fibers in this application aim to enhance these latter weak points.

Figure 3.3. Operational Load monitoring scenario (Airbus Proprietary)

3.1.3 STRINGER DEBONDING SCENARIO

This scenario consists of the in-service inspection of adhesive lines (bonded/co-bonded/co-cured) in special composite structure configurations such as the stringer run-outs tips (SRO) (figure 3.4). This type of damage is considered critical from design point of view since can reduce enormously the load capability below ultimate load (UL).

The SHM data would enable operators to identify the initiation of damage in situ - debonding appearing in the run-out area between skin and stringer - without the expense or time required to take the structure out of service. Ideally, the technology will also determine the damage type, location and size as well as the structure's health prognosis.

Today the in-service inspection of CFRP structures is chiefly carried out by visual inspections or classical NDI. These in-service inspection tasks are performed according to scheduled and unscheduled inspection programs always requiring the landing of the a/c and the corresponding time consuming by qualified NDI inspectors. The inspection of adhesives lines to detect stringer disbond is repeatedly called in AMMs (Aircraft Maintenance Manual instructions) after the occurrence of certain unscheduled events such as: hard landing, bird strike, flying in excessive turbulence or after tire burst.

The use of SHM technologies, in this case optical fiber sensors integrated into the stringer/skin adhesive lines, would replace this classical inspection program by on-condition maintenance with the consequence benefits in terms of maintenance cost and aircraft down-time. Apart from this change from inspection point of view, the use of permanent sensors monitoring the stringer run out tips could address to the relaxing of the current composite design criteria (weigh reduction without detrimental of the composite structural performance) and therefore to enable the design with lower residual strength values by the fact that SHM would indicate us when a disbond happen and its size.

Figure 3.4. Stringer debonding detection scenario (Airbus Proprietary)

The main potentials of optical fibre sensors in this application would be the use of an indirect but simple method to detect the disbond and also the ability for large monitoring extensions with distributed fibre. The principle of detection would be based on the direct

measure of strain profile changes and after simple but robust processing the inspection of the adhesive line. The detection concept would not need of temperature compensation. The technology could be integrated in Production providing among other issues, the fibre installation is compatible with the stringer/skin manufacturing process.

3.1.4 SCENARIO OF THE INSPECTION OF BONDED COMPOSITE REPAIR.

Bonded composite repair is a repair method for the structure consisting of the removing of the damage areas of the material and replace them by new composite layers previous interposition of an adhesive layer between the pre-cured (parent material) and fresh layers (repair material). This repair process can be done in two stages:

Figure 3.5. Bonded composite repair scenario (Airbus Proprietary).

- a) Production, when the structure is inside this stage and susceptible to be repaired by a composite patch. The curing process is done inside a typical composite manufacturing autoclave with conditions of pressure, vacuum and temperature according to a pre-established cycle. The post repair inspection can be done in a similar way how is performed for conventional structures in production time (AUTT or AUPE: automatic trough transmission or pulse echo).
- b) In-service, when the structure is under in-service operations and suffers a damage (i.e. accidental impact) that after the inspection and analysis requires a repair process to restore the proper load capability. This process has many times to be necessarily carried out in Out of Autoclave (OoA) conditions, with no pressure and just vacuum and heat. The lack of pressure can leave in many occasions the

structure with lower compact level that makes quite difficult the inspection of the repair material and bonded line through conventional ultrasonic techniques. This inspection gap of the repair patched is in fact one of the reasons why bonded repair patches are not so extensively used for primary composite structures in a/c.

The use of SHM sensors, and specially optical fiber sensors, in this scenario (particularly for in-service stage) is promoted by the possibility to integrate the sensors during repair process inside the adhesive line. These sensors would be housed and protected by the material itself providing the functional capability to detect adhesive disbond. The optical fiber sensors would be periodically sampled during operations and would trigger maintenance actions (detailed non-destructive inspection) when a debonding is detected during in-service operations.

The SHM technologies applied into this scenario would support in general to the extension of bonded repair instead of bolted repairs and will contribute to minimise the risk of weak bonds.

3.2 IDENTIFICATION OF THE MAJOR DRIVERS FOR THE USE OF OPTICAL FIBER TECHNOLOGIES AS SHM TECHNOLOGIES IN COMPOSITE STRUCTURES.

Once presented the possible scenarios for the use of optical fiber sensors in composites structures, it is necessary to identify the major drivers for the implementation of these technologies and their corresponding benefits. The following is the author proposal list of the possible drivers and benefits for the scenarios proposed -strain and load monitoring, adhesive, line inspection (stringer debonding) and composite repair inspections- because of the use of optical fiber sensors.

- a) On-board monitoring system providing real operational data related to the structural integrity during flight:
 - Supporting a better control of the a/c fleet.
 - Support for the aircraft life extension in front of the Authorities.
 - Integration of SHM systems in the composites would be a demonstration of new technological leap working with intelligent structures.
- b) Improvement for strain monitoring in structural and flight tests platforms.
 - More cost effective strain instrumentation system.
 - Lower installation time.
 - Additional monitoring capabilities (strain profile, embedded sensors, residual strain accounted, etc.)
- c) Permanent inspection during in-service operation of adhesive lines (immediate detection of disbond).
 - The design benefits would be focused on weight reduction and would be based on the possibility to modify the current composite design criteria from non-growth to growth (fatigue in composite). This new criteria would evolve

to thinner structures having less conservative criteria (instead of designing up to UL some structures can be designed up to LL), with lower residual strength at the expense of the implementation of a reliable SHM monitoring system able to monitor and detect damage in composite structures.

- The Maintenance benefits would be addressed to the cost reduction into the maintenance program. For schedule inspections would not be foresee very important savings since schedule inspections (preventive actions) in composite structures CFRP suppose today a very low effort. Nevertheless for unscheduled inspections (corrective actions) the use of SHM technologies would suppose the following advantages:
 - Immediate actions to restore load capability when accidental damage is detected in in-service.
 - Reduction of time for unscheduled inspections
 - Permanent inspection of hidden areas
 - Support in the certification in special events such as tire impact or tail strike.

d) Inspection solution for adhesive line of OoA bonded composite repair patches

- Extension of the use of bonded repair patches instead of bolted repair and their corresponding benefits.

e) Development of innovative structures with functional properties (smart structures).

- The design and use of smart structures at industrial level require from very high skills and maximum technological level and could be used strategically as commercial purposes to demonstrate technological superiority against competitors.

3.3 TECHNICAL REASONS FOR THE USE OF OPTICAL FIBER SENSORS IN COMPOSITE STRUCTURES WITH STRUCTURAL HEALTH MONITORING PURPOSES.

Within the field of instrumentation engineering, the sensors based on fiber optics are gaining ground on the conventional instrumentation, coming to represent, for certain specific applications, an almost unique solution.

These are today the main advantages of optical fiber sensors (fiber Bragg grating or distributed sensing fiber) over conventional sensors for the scenarios previously proposed. Most of these features will be evaluated in the experimental part:

- Optical fiber sensors are sensitive to several external factors (i.e. strain and temperature). On the one hand this is quite positive but on the other hand could be negative if the decouple of both parameters affecting simultaneously is not done properly.

- Low weight of the fiber. When comparing electrical strain sensors with optical fiber sensors we reduce the weight not just because the significantly lower number of cables but also because the lower density of the glass fiber versus the conductive material (copper).
- Small profile of the sensors (from 60-200 microns diameter) that confers the possibility to embed the fiber in composite materials with low intrusiveness.
- Embedded sensors are the best approach to protect the sensors from the environment.
- Time installation. When compared with electrical strain sensors, and providing the number of punctual sensors is higher than 10 (by own experience), the time installation is lower not just clearly for distributed fiber but also even for FBG sensors.
- Competitive cost. The cost of optical sensors when compare with electrical strain gages results higher or lower depending on the number of measurement points. Optical fiber sensors becomes more cost-effective as many sensor points are needed.
- High multiplexing capability. It is related to the capability of optical fiber sensors to have several sensors in an unique channel. This is an important advantage over classical electrical strain gages. This feature help actually also to mitigate the complexity of the installations with high number of wirers.
- Good spatial resolution. Distributed sensing fiber based on optical frequency domain reflectometry (OFDR) is today unrivaled in terms of density of sensors for spatially distributed measurements. It presents enormous improvement over any existing sensing solutions.
- Strain rosettes can be also created with optical fibers although today is still a manual process (some exceptions with FBG) and tend to be larger than conventional ones due to the minimum radius of the fiber.
- Good fatigue resistance very specially when the sensors are embedded into the composite structure. Similar results are very difficult to be obtained with conventional strain gauges.
- Excellent durability under on-board environmental conditions when the sensors are conveniently protected.
- Sensors have demonstrated long life and low drift what is very interesting for long duration structural tests. The complete reflective spectrum is very stable over the time.
- Measurements are immune to electromagnetic interferences (EMI) and lightning strikes. EMI induces false information on electric sensors difficult to discriminate.

- Since no electrical signal is carried on the fiber, optical fibers are passive and safe sensors producing no ignition risk in inflammable or explosive environments.
- Absolute measurements. FBG is a sensor encoded directly into wavelength. The output does not depend on the amplitude light level; losses in the connecting fibers and couplers, or recalibration or re-initialization of the system, and this confers an inherent feature for self-referencing. This is an important issue when it is necessary to measure the evolution of parameter over a very long term period.

3.4 IMPACT ASSESSMENT ABOUT THE INTEGRATION OF OPTICAL FIBER SENSORS IN AERONAUTICAL STRUCTURES.

This section is a prediction exercise of the possible impacts of the technology in the different stages of the aeronautical structures: Manufacturing & Final Assembly Line (FAL), operation and maintenance.

a) Manufacturing & FAL

If the fibers are installed in manufacturing process is necessary:

- Preparation and qualification of the installation process of the fibers, sensors and connectors in Production.
- Ensure the adopted ingress-egress solution is compatible with the trimming process of the structures.
- The operators have the enough skills to work and handle the optical fiber sensors.
- Note that the embedded fibers are not detected by Production NDI (automatic pulse echo: AUPE), excepting the inspection is performed by XR. The embedded connectors would definitely be detected by AUPE.

If the fibers are installed in FAL is necessary:

- Preparation and qualification of the installation process of the fibers, sensors and connectors in Production.
- The operators have the sufficient skills to work and handle the optical fiber sensors.

b) Operation:

- No impact would be expected in principle regarding a/c operation in flight (CS-25).
- To minimize the risk of impact in the implementation and operation, the process would have to be gradual from lower to higher responsibility. This is a proposal for the implementation in three gradual and consecutive generations:

1. First generation:

- Integration of SHM sensors in the a/c (optical fiber connectors compiled into the avionic bay).
- Off-board SHM system, bringing the IU to the avionic bay when a/c operation stops.
- No modification in composite design criteria, and just demonstration of the robustness of the installation in in-service conditions as well as benefits in unscheduled inspections.

2. Second generation:

- Integration of SHM technologies in the a/c.
- First modifications in composite design criteria .
- Redundancy of the working operation: Off-board (as previous generation) and on-board, to demonstrate in-service operations and benefits.

3. Third generation:

- Integration of SHM technologies in the a/c
 - Composite structures design under growth criteria
 - On-board.
- Preparation of operational procedure for the system (on-board and/or off-board) and definition of application interval.
 - Additional system involves adding weight for equipment and fiber and connectors weight (negligible)
 - Preparation of the maintenance instruction of the system (quick and automatic self-diagnostic procedure before measurements, ...)
 - Minimum training for a/c operators: connection of the system, retrieval of the data, pass or fail decisions, ...

c) Repair and maintenance process

- Requirement of installing the sensors with no impact on repair and maintenance process.
- Optical fiber sensors (bonded or embedded) and corresponding fiber routes have to be properly identified in the drawings of the structures similar to any other airborne system.
- No especial maintenance tasks are planned for keeping functionality of SHM system (sensors, fibers or system). Only a very short procedure covering few and simple tasks before each acquisition.
- Special training for those operators acquiring SHM from the IU.

- In case of repair of the structure in locations with embedded bonded sensors, the repair has to include the restoring of the SHM functionality. The solution to this point requires the study case by case.

4 CHAPTER 4. DEVELOPMENT OF THE REQUIREMENTS APPLICABLE TO THE APPLICATION SCENARIOS.

This chapter is entirely dedicated to the development of the requirements applicable to the application scenarios identified in the third chapter. This compilation constitutes an essential task for the correct development of the technologies. The requirements have been identified and organized from practical point of view according to the following criteria:

- a) Strain monitoring application
- b) Damage monitoring
- c) Installation in structural test platforms
- d) Data management end user
- e) Operation in the aircraft
- f) Maintenance system point of view
- g) Operators working with optical fiber sensors

The main sources for the preparation of this chapter can be found in the References, at the end of the document [48, 49, 50, 51, 52, 53, 54, 55, 56, 57]. On the other hand many others requirements exposed here did not have previously been collected but they are fruit of the author's experience and also from numerous discussions with the different stakeholders inside Aircraft and Instrumentation Community.

4.1 REQUIREMENTS FOR A STRAIN MONITORING SYSTEM

The next table is a summary of the most important requirements identified for these technologies when used within strain monitoring system.

Table 4.1. Requirements compilation for a strain monitoring system.

STRAIN MONITORING REQUIREMENTS
Strain range: ± 10000 microstrain
Strain resolution: minimum of 2 microstrain
Strain accuracy: 0.5-2%
Operational temperature range: -60°C to 130 °C
Compensation of temperature effect
Variable gage length
High spatial resolution
Stable sensitivity, linearity, repeatability
Negligible transversal sensitivity
Need to determine main strain directions
Enough fatigue resistance (defined case by case)
Static and dynamic measurements
Sampling rate: from few Hz to kHz
Reaction time of the sensors <1 ms
Synchronization with other systems (load system)
Long term stability measurements
Low drift
Sensor position accuracy
Sensor alignment error
Appropriate strain transfer
Chemical and mechanical resistance (defined case by case)
Easy, quick and cost effective installation
Low mass (sensor set: sensor, adhesive, protection, cables)
No influence to EMI
Low ignition risk (explosion safety)
Competitive price (sensor+read out)
Repeatability and traceability of the sensors
Maturity and Standardization
Reparability

4.2 REQUIREMENTS FOR DAMAGE MONITORING SYSTEM (STRINGER DEBONDING).

The next table summarizes the main requirements applying to the optical fiber sensor technology for the detection of stringer debonding in structural test or in-service operations:

Table 4.2. Requirements compilation for damage monitoring system.

DAMAGE MONITORING REQUIREMENTS
Damage detection. Detection threshold a certain area (mm^2)
Detection reliability (PoD:90/95)
Damage location (X, Y, Z)
Damage identification (disbond, delamination)
Damage size (mm^2)
Damage assessment (residual strength)
No influence of external parameters (i.e. temperature)
Resistance to environmental conditions (temperature variation, vibrations, etc.)
Sensors (OFS) fully integrated or adapted to the structure to be monitored
Minimum impact of the installation of the OFS in Manufacturing Plants or /and FAL
No impact of the technology on a/c operational
Self-diagnostic principle of the SHM systems
In case of finding damage requiring repair, the technology has to continue being operative
Minimum training for a/c operators: connection of the system, retrieval of the data, pass or fail decisions, ...

4.3 REQUIREMENTS FOR INSTALLATION IN STRUCTURAL TEST PLATFORMS.

Since the requirement values for structural tests can be very different from one test to another, in this section are collected the set of requirements are necessary to work when preparing sensor installation in structural test platforms. They are summarized as a table.

Table 4.3. Requirements compilation for structural test platforms.

STRUCTURAL TEST PLATFORMS	
REQUIREMENT	BRIEF DESCRIPTION
Areas & Locations to be monitored	Define the number of sensors, number or channels, use or not MUX, etc.
Sensor density	Define the number of sensors to monitor a reference area of one square meter
Sensor area	Define the area covered by the sensor to monitor a reference area of one square meter
Sensor & cable positions compatible with NDT	Sensors and cables cannot impact the performance of classical NDT program
Technology application procedure	Compatibility of technology surface preparation prior to bonding and protection of the sensors & cables compatible with the test
Operational mode of the test	Capability of the technology to operate in the test mode (static, dynamic)
Environmental conditions in structural test (temperature, vibrations, etc.)	Compatibility of the technology with these conditions
Power supply in the tests	Compatibility of the technology with electrical power conditions in the test location
Dimensions of the equipment	Compatibility of the technology system with available space
Distance between equipment location (room control) and test specimen	Compatibility of the technology network with the location, safety constrains in the test
Technology installation time	Compatibility of the technology with the available time according to structural test schedule
Measurement procedure	Compatibility of the technology measurement procedure with the structural test
Display vs load	Capability of the technology to plot technology output versus load
Data display	Compatibility of the technology with what required in the structural test
Store and access to the data	Compatibility of the technology with what required in the structural test
Restoring procedure in case of troubles	Compatibility of the technology with what required in the structural test

4.4 REQUIREMENTS FOR THE SHM SYSTEM FROM DATA MANAGEMENT USER POINT OF VIEW.

These requirements were identified in the development process of these two technologies especially when applying them in mechanical and structural test platforms. Some of the most important are listed in the table below:

Table 4.4. Requirements compilation from data management.

DATA MANAGEMENT REQUIREMENTS
Ability to adjust the sensitivity factor (strain, temperature)for each sensor.
Ability to expand the number of channels.
Ability to adjust acquisition speed in function of the requirements of the test: static or dynamic (from a few Hz to several kHz).
Ability to synchronize measurement with other different system through external trigger signal.
The display of the information of the sensors shall be configurable for the user.
The user will define the head title of each plot with the possibility to modify the type of line, color or any other features of the graph.
The user shall be able to introduce predictions for the different plots so that they could be used as comparative during the test acquisition.
The system (software) will enable the acquisition of another analogic signals (temperature, load, strain, pressure, etc.) and these signal will be able to combine with the output of the optical fiber sensors.
The axis of the plot shall be: <ul style="list-style-type: none"> o Output of the sensors versus time o Output of the sensors versus another analog signal as for example load.
The system (software) shall enable the mathematical operation among the different sensors outputs or segment when the sensors or segment are in the same or different channels. This make special sense for instance in applications requiring temperature compensation.
The software will enable the configuration of special alarms, thresholds, warning during the acquisition, etc.
The data saving process will be configurable by the user: all the raw data, individual files (as many as plots), different files for different channels, etc.
The data must be recorded on a permanent medium. When onboard system the data will be saved in the a/c and after the flight, the data shall be transferred to a ground station.

4.5 REQUIREMENT FOR THE SYSTEM FROM OPERATIONAL POINT OF VIEW.

Most of these requirements are based on international standard RTCA DO 160-Environmental Conditions and Test Procedures for Airborne Equipment-. The next table is an extraction of this standard. Details of the test procedure of each test can be found in this international reference. The categories selected for each test depends on the level of the responsibility of the system (DAL). As explained in the chapter 3, for a first generation of the system this level is relatively low but overtime this level will be higher and therefore requiring more severe conditions.

Table 4.5. Requirements compilation for operational viewpoint.

DURABILITY REQUIREMENTS	CRITERIA
Temperature	DO 160 D section 4 cat A2.
Temperature variation	DO 160 D section 5 cat C.
Altitude	DO 160 D section 4 cat A2.
Humidity	DO 160 D section 6 cat A.
Acceleration	DO 160 D section 7 cat A.
Operational and crash safety shock	DO 160 D section 7 cat B.
Vibration	DO 160 D section 8 cat S.
Waterproofness	DO 160 D section 10 cat Y.
Resistance to fluid ingress	DO 160 D section 11 cat F.
Sand and Dust	DO 160 D section 12 and cat D.
Magnetic effect	DO 160 D section 15.
Emission of Radiofrequency energy	RTCA/DO160D – Section 21Cat. M
Radio frequency susceptibility	DO160D Section 20 - Cat T
Flammability/smoke/toxicity	DO 160 D section 26 cat C.
Fire	DO 160 D section 26 cat A.
Explosion Hazard	Explosion resistance: DO 160 D section 9 cat A.
Voltage spikes	DO 160 D section 17 cat A.
Materials requirements	ABD100.1.6
Interrogation unit dimensions	ARINC 600 4U.
MTBF IU	800000 hours
Power supply for IU and MUX	28 VDC

4.6 REQUIREMENT FROM MAINTENANCE POINT OF VIEW.

One of the most important requirement from maintenance view point is the capability of the system of Built-in self- test (BITE) . This in fact not only apply to the IU but also for the sensors (FBG sensors and distributed fiber) . Both, FBG system and distributed fiber system, will require the self-diagnostic principle for the system and the installation that will be applied as a set of tasks at the beginning of the test. Examples of these task are:

- Calibration of the system, alignment devices and the checking of the most important functionalities of the system.
- Checking of the installation and detection of wrong issues such us macro/micro bending, wrong connectors, lack of cleanness, break of the fibers, etc.
- Special functionality to check the proper adhesion of the sensors to the structure by a systematic routine comparing the current response of the sensors with a healthy reference.

Apart from that the aim is to keep their required maintenance tasks (inspection/servicing/test/calibration) to the minimum.

When the equipment on-board, a detailed planning will need to be prepared according to Maintenance Review Board (MRB) process and the Maintenance Steering Group (MSG) analysis procedures to comply with certification standards.

4.7 NEED OF TRAINING PEOPLE WHEN WORKING WITH OPTICAL FIBER IN THE A/C.

In order to mitigate the risk of break the optical fiber during the installation and also to ensure the proper use of the technology, it seem absolutely imperative the need of the training and qualification of the people working with optical fiber in the a/c, not only for communication applications on commercial aircrafts but also for structural health monitoring purposes. The current philosophy for European aircraft manufacturers is to train electrical harness manufacturing operators and strain gauges installers in the processes required for the implementation of optical fiber for communication and structural health monitoring purposes respectively [58].

5 CHAPTER 5. LEADING ASPECTS IN THE TECHNOLOGY DEVELOPMENT OF OPTICAL FIBERS FOR STRUCTURAL HEALTH MONITORING PURPOSES.

5.1 ARCHITECTURE OF THE TECHNOLOGIES.

In general terms it can be said that a structural health monitoring system based on optical fiber sensors is composed of the following elements:

- Sensing optical fibers or sensor regions in the fiber
- Optical fiber cables
- Optical fiber connectors
- Interrogator unit
- Multiplexer
- Computer and software

The features of each of the elements can be different when referring to FBG sensors or distributed sensing fiber (DTSS: Optical fiber distributed temperature and strain sensors). As follows, it will be described briefly these elements indicating the main particularities for each technology.

5.1.1 FIBERS AND OPTICAL FIBER SENSORS.

The optical fiber is one of the essential element of the technology. As described in the chapter 2 it is basically the light transmitting medium based on total internal reflection principle. It is physically comprised of core, cladding and coating:

- Core is the central region of an optical fiber through which light is transmitted.
- Cladding is the material surrounding the core of an optical fiber that has a lower index of refraction in order to steer the light in the core.
- Coating is the material put on a fiber during the drawing process to protect it from the environment.

The optical fiber has essentially two functions, on the one hand, to serve as communication line between the interrogator unit and the different sensing points. On the other hand, the optical fiber contains the sensing lengths sensitive to the external parameters (temperature and strain). These sensing areas can require the previous written on discrete locations, in the case of FBG technology, or that the standard fiber over the complete length work as sensing length based on backscattering reflection, case of distributed fiber. The sensing length of the fiber for strain monitoring applications have to be surface bonded or embedded inside the composite. The integration process has to ensure the proper strain transference from the host material to the fiber sensing, during the in-service conditions and over the lifetime of the structure.

The optical fiber for any of these two sensing technologies is single mode optical fiber (SMF) instead of multimode fiber (MMF) (figure 5.1), with core/cladding size typically in the order 9/125 micron. The reasons for that are basically the high dispersion and attenuation of the multimode fiber in comparison with single mode fiber. International Standard ITU-T

G.652 compile the main requirements of single mode optical fiber and ITU-G657 for the case of low bending fibers.

Figure 5.1. Multimode and single mode optical fiber (From cables-solutions.com)

The coating of the fiber is a significant characteristic in the optical fiber for strain and temperature sensing monitoring applications. The elastic modulus of the coating and its adhesion to the cladding are related to the proper strain transference from the material to the core [59, 60]. From practical point of view (figure 5.2) the longer the bonded length, the stiffer the coating and the adhesion to the cladding, the more adequate the strain is transferred to the optical fiber. Note that the mechanical properties of the coating depends on the temperature and hence it is necessary to consider the possible property variation over the temperature range.

Figure 5.2. Strain transference dependence.

Other important aspect related to the fiber coating is the ease to remove and recoat it due to the need of splicing. In general, the better the coating for strain transfer, the worse the coating for stripping, hence it is a tradeoff solution.

Finally the coating thickness and the cladding provide the diameter of the fiber, and this parameter has to be evaluated in the special applications wherein the fiber is embedded inside the composite. Excessive fiber diameter in relation to the thickness of the part can address to the degradation of some mechanical properties such as compression strength.

Concerning the FBG sensors, the table 5.3 refers to the main FBG features with influence in the performance of the sensors.

Table 5.1. Main FBG features.

FEATURES	UNIT
Number of gratings in array	n
Distance between consecutive FBGs on the array	mm
Center wavelength and Wavelength tolerance	nm
Reflectivity peak and Reflectivity average	%
Side-lobe level ratio	dB
Grating Length (l)	mm
Width peak or width FBG spectral	nm
FBG SNR	dB
Polarization dependence	pm
Type of inscription process	With/without coating, during drawing[1]
Recoat diameter and length	Micros and mm
Type of coating process	during drawing process, recoated,
Fiber type	material, bend loss, diameters, coating material, ...
FBG manufacturing process	holographic interference, phase mask
Tensile load	N
Coating uniformity	microns
Identification, marking of the FBGs in the fiber	e.g. markers on fiber
Total length array	mm
Splice less FBG chain	Y/N
Connecting requirement, Pigtail length	type of connector (i.e. FC/APC), m
FBG strain sensitivity (S) and Strain gauge factor (k)	$\mu\epsilon/\text{pm}$
Temperature sensitivity	$^{\circ}\text{C}/\text{pm}$
FBG sensor strain range (tension and compression)	$\pm\mu\epsilon$
Temperature range and annealing process	$^{\circ}\text{C}$, Y/N
Minimum operating radius of curvature	mm
Fatigue resistance	cycles
Stability behavior	pm/time unit
Hysteresis	pm
Humidity range	%humidity
Expected FBG service life.	years
Batch	date of manufacturing

5.1.2 OPTICAL FIBER CABLE.

The optical fiber cable constitutes the external structure protecting the optical fiber. It is constructed by adding to the fiber the strength member and jacketing. The strength member is the part of a fiber optic cable composed of Kevlar aramid yarn, steel strands, or fiberglass filaments that increase the tensile strength of the cable. The jacketing, that can be made of different polymer materials, is surrounding the strength member and provide the environmental protection and optical insulation of the fibers. The specific materials of the structure cable provide the features of the cable to resist the hostile environmental conditions such as thermal shock, humidity, vibrations, flammability, smoke and gas emission or resistance to fluids (EN 3745).

Figure 5.3. Optical fiber cable (Airbus Proprietary)

The next table is an example of some typical requirements for optical fiber cable to be installed into aircraft.

Mass	4 g/m max.
Operating temperature	-55 °C to +125 °C
Attenuation at 850 nm (+20 °C)	< 4 dB/km
Attenuation at 1300 nm (+20 °C)	< 2 dB/km
Numerical aperture	0,275 ± 0,015
Minimum bend radius (+20 °C)	- Installation: 20 mm (10 x cable outside diameter) - Long term: 20 mm (10 x cable outside diameter) - Storage: 40 mm (20 x cable outside diameter)
Tensile rupture strength	> 200 N
Stripping tools	AIPS 07-11-002

Figure 5.4. Example of requirements for airborne optical fiber cable (Airbus Proprietary).

Concerning to the number of fibers in the cable, the cable can be formed for only one fiber –single way cable- or many fibers protected and contained within a single jacket or buffer tube -bundle or multi way cable (see figure below from GORE).

Figure 5.5. Example of multiway optical fiber cable (From Gore.com)

In the particular case of optical fiber embedded in the composite material, the bare fiber is implemented inside the composite pre-preg during the manufacturing process and after the curing process the fiber is left inside without any cable protection since this protection is directly done by the composite material itself. This issue is discussed with more detail in the section 5 of this chapter

5.1.3 OPTICAL FIBER CONNECTORS.

It is the mechanical device used to perform the optical alignment and join two fibers together.

In the case of FBG and distributed fiber for lab and structural test applications, the connector commonly used is FC/APC (convex polish shape with angle $8 \pm 0.2^\circ$) essentially because the optical performance (insertion loss typically $\leq 0.20\text{dB}$ and max. $< 0.50\text{dB}$ and return loss typically $\geq 65\text{dB}$ and min. $> 60\text{dB}$, life time - 1000 plugging & unplugging, protection to contamination and cleanness.

For flight tests application the connector normally used is MIL38999 series. This type of connector is qualified in front many aeronautical standards and fulfil typical requirements for in-service operation such as corrosion, temperature, moisture or vibration resistance, hermetic or durability among many others (EN 3745, ARINC 802-1).

For the case of optical fiber sensors inside the composite structures and using embedded connectors refer to the section 4 of this chapter for more details and proposals.

Figure 5.6. Example of optical fiber serial connector MIL 38999 (From Airbus Standard).

5.1.4 INTERROGATOR UNIT.

The interrogator unit in the architecture of an SHM system based on optical fiber is the opto-electronic device used to interrogate either the reflections coming from each FBG sensors or the backscattering from the normal single mode optical fibre. In both technologies the measurements are performed with an only single-ended fiber configuration.

a) Fibre Bragg grating interrogator.

Two interrogator units were used for FBG technology in this thesis. They use a tunable laser and are based on wavelength division multiplexing (WDM) technique. This technique provides the ability to interrogate multiple sensors, each grating written at a unique wavelength, along a single fiber over long distances. The wavelength interpretation is performed by zero-crossing algorithm. The equipment enables, by the software, the configuration of an unique wavelength windows for each FBG sensor within the complete wavelength range. Special care must be maintained to avoid overlapping of distinct FBG's spectra. The number of sensors to incorporate within a single fiber depends majorly on the wavelength range of operation of each sensor (temperature and strain) and the total available wavelength range of the interrogator. There is no restriction from interrogator viewpoint on how closely the FBGs can be spaced along the fiber. Once FBGs are configured, the next steps are to create the expressions for the sensors and to define the sampling and saving parameters.

One of the equipment used in this Thesis is designed for low speed applications (up to 10 Hz) but with the advantages of providing very high accuracy and stability (2.5 pm) and the option to monitor the FBG spectrum. The second equipment used in the Thesis is designed for dynamic applications (up to 1 kHz) at expenses to have lower accuracy and stability (5 pm) than the static version.

b) Distributed fiber interrogator.

Two interrogator units were used for distributed sensing technology. They use a swept-wavelength interferometer (SWI) to measure the Rayleigh backscatters as a function of position in the optical fiber.

The first one is a ultra-high resolution optical backscatter reflectometer for static measurements. The user starts defining the sensing fiber length (sensing range) and the processing parameters (gauge length and sensor spacing) and begins performing a measurement for reference state. Afterwards, a second measurement is performed once a strain or temperature perturbation is applied to the fiber sensing under test (FUT). The cross comparison between both measurements enables to determine the relative change in the physical parameter.

The second system is able to work in different modes. Each mode balances tradeoffs in acquisition rate, sensing length, and sensor spacing. Once selected the mode, it is necessary to create the sensors, then to define and select the sensing length in the fiber sensors, next to configure the acquisition parameters (name file, sampling, trigger acquisition) and finally select the tare (reference) for the measurement. This second equipment provide the physical parameters versus time on real time.

5.1.5 MULTIPLEXER.

It is an optoelectronic device used to expand the number of channels (sensing fibers) that the interrogator can manage. Internally the device comprise serial of switches that enable to expand from 1 to 4, 8 or 16 channels and therefore the expansion of the number of monitoring fibers, more FBG sensor or more meters of sensing fiber.

Two multiplexers are used in this thesis, the first one for FBG interrogator that enables to expand from 4 to 16 channels, and the second one for distributed fiber that expand from 1 to 8 channels.

5.1.6 COMPUTER AND END-USER SOFTWARE.

They constitute the interface between the technology and the end-user. The software and main functions are specific for the technology - FBG or distributed fiber -and manufacturer and any case the configuration and maximum benefit require always from knowing the installation process, being familiar with the measurement principles and technology limitations, and the particular test objectives.

5.2 INTEGRATION OF OPTICAL FIBER SENSORS. PLANNING AND DESIGN OF THE INSTALLATION.

These are the main steps that were followed for the design of an optical fiber installation for structural health monitoring purposes:

- a) Identification and definition of the sensor locations and measurement directions.
- b) Notice from the beginning the strain range, environmental conditions and whether or not it is necessary to compensate the temperature effects.
- c) Make decision about the optical fiber technology to use; discrete sensors – FBG- or distributed fiber – OFDR.
- d) Make the decision of the procedure to install the sensors: embedded sensors or bonded surface.
- e) Adhesive selection in case of bonded surface sensors.
- f) identification of all installation constraints from global point of view. These are some examples to be considered:
 - The scenario; manufacturing, FAL or in-service.
 - The physical constrains (accessibility, shape of surface, etc.)
 - The complex fiber routes in case of applications consisting of monitoring few locations dispersed in a large extension areas.
 - The drilling operations in the structure (repair by riveting, placing finger plates) that could damage the installed fibre.
 - The locations of embedded optical fibre and optical fibre connector. They should be placed in locations defined by Stress and Operations.
 - The ingress-egress when embedding the optical fiber.
- g) First estimation of the optical budget.
- h) Definition of the main features of each individual component; optical fiber, optical fiber cable, connectors and systems.
- i) Selection of all the components in the installation. In case of FBG, prepare specification to manufacture sensor arrays: type of gratings, sensor length, wavelength centres, distances between sensors, etc.
- j) Acquisition of the installation materials.
- k) Installation of the sensors:
 - Embedded sensors in Manufacturing.
 - Bonded sensors in FAL.
- l) Protection of the sensor adequately in function of the area (fuselage, fuel tank, internal boxes, etc.)
- m) Checking of the installation and sensors performance.
- n) Set up of the installation.

The next scheme (figure 5.7) is a summary of the complete process:

Figure 5.7. Summary of the main steps for the design and installation of sensing optical fiber system.

5.3 TEMPERATURE COMPENSATION WITH OPTICAL FIBER SENSORS.

Optical fiber sensors, FBG and distributed fiber sensing based on Rayleigh frequency, response to strain but also to temperature. When both parameters are acting simultaneously the output of the sensor is a combination of the two factors ($\Delta\lambda_{total}$). Only the wavelength shift contribution associated to stress (ϵ_s : mechanically induced strain) are important from structural point of view, therefore the other part of wavelength shift – thermal output ($\Delta\lambda_{TO}$)- has to be subtracted from the complete signal.

$$\Delta\lambda_{Total} = \Delta\lambda_{\epsilon} + \Delta\lambda_{TO} \quad (5.1)$$

$$\Delta\lambda_{\epsilon} = \Delta\lambda_{Total} - \Delta\lambda_{TO} \quad (5.2)$$

There are several methods for determining the thermal output of the optical sensors. Some of the them, are briefly explained as follows [61, 62, 63, 64].

Method A: Using CTE and measuring temperature change.

Thermal output may be estimated if the Coefficient Thermal Expansion (CTE) of the substrate material and gage constants are known. This method requires the temperature change measurement using a conventional temperature sensor (thermocouple or an optical temperature sensor). Equation below contains the terms to be considered.

$$\Delta\lambda_{TO} = (\alpha_{mat} - \alpha_{fib}) \Delta T S_{\epsilon} + S_T \Delta T \quad (5.3)$$

The first term is the relative difference in coefficients of thermal expansion between the gage fiber and the material on which it is mounted. The second term refers to the index of refraction of the Bragg grating as a function of the temperature dn/dT . Note that the thermal response of a bare fiber is dominated by the dn/dT effect (accounts for ~95% of the observed shift).

Once thermal output is estimated, this can be used in the equation 5.2 to compensate the temperature.

$$\Delta\lambda_{\epsilon} = \Delta\lambda_{Total} - [S_T \Delta T + (\alpha_{mat} - \alpha_{fib}) \Delta T S_{\epsilon}] \quad (5.4)$$

Method B: Auto compensated optical fiber sensors.

The concept consists of a self-compensating sensor set. This sensor includes the proper configuration in the set in such a way that when temperature changes the effect of the temperature in the sensor is compensated due to thermal effect in the set, that is mean, compression of the set when positive temperature changes and expansion of the set when negative. The set is designed to work properly for a range of temperature and when mounted on a test specimen having a specific thermal expansion coefficient (CTE). If the sensor is mounted on a test specimen having a different CTE, then a correction factor should be applied to reduce the thermal effects.

Method C: Previous experimental measurement of thermal output.

This method requires the previous measurement of the thermal response of the optical sensor mounted on the material, what it could not be always feasible. The test article would need to be placed with a mounted optical sensor in an environmental chamber. The chamber is then ramped through the temperature range of interest while recording the temperature and the sensor output. This previous test would create a table of the thermal output versus temperature that would enable to correct posteriorly the wavelength shift to get only the mechanically induced strain.

Method D: Temperature compensation using a dummy

This method involves the use of a second dummy test sample, identical to the specimen under test (material, CTE and sensor configuration), to compensate the temperature. This dummy test sample should be mounted free of stress and located as close as possible to the active specimen under test so that both samples experience the same temperature. In this configuration, the dummy sample will respond to temperature and provide the direct measurement of the thermal output.

$$\Delta\lambda_{TO} = \Delta\lambda_{dummy\ sample} = S_T \Delta T + (\alpha_{mat} - \alpha_{fib}) \Delta T S_\varepsilon \quad (5.5)$$

On the other hand the specimen will be affected by temperature and load.

$$\Delta\lambda_{specimen} = S_T \Delta T + [(\alpha_m - \alpha_f) \Delta T S_\varepsilon \beta + S_\varepsilon \varepsilon] \quad (5.6)$$

In the equation 6, β is a coefficient denoting the movement constraint of the sample.

With this configuration if we subtract the output of the dummy to the output of the specimen, the wavelength shift due to stresses will be obtained and therefore when divided by the strain coefficient, the strain due to stress (ε_s) will be calculated (eq. 5.7).

$$\varepsilon_s = \frac{\Delta\lambda_{specimen} - \Delta\lambda_{dummy\ sample}}{S_\varepsilon} \quad (5.7)$$

Method E: Two fibers with different responses to temperature and strain.

This method consists of locating adjacently two fibers with different responses to temperature and strain. The method requires the measurement of the two wavelength shifts of both fibers having different linear response coefficients to strain ($K_{\varepsilon1}$, $K_{\varepsilon2}$) and temperature (K_{T1} , K_{T2}).

$$\begin{bmatrix} \frac{\Delta\lambda_1}{\lambda_1} \\ \frac{\Delta\lambda_2}{\lambda_2} \end{bmatrix} = \begin{bmatrix} K_{\varepsilon1} & K_{T1} \\ K_{\varepsilon2} & K_{T2} \end{bmatrix} \begin{bmatrix} \varepsilon \\ \Delta T \end{bmatrix} \quad (5.8)$$

The resultant matrix is then inverted to calculate deformation and temperature from the two wavelength shifts. The resulting discrimination between temperature and strain is highly dependent on the ratio of the strain coefficients and the ratio of the temperature coefficients; if the ratios are equal the determinant is zero and the calculation will fail. The simultaneous strain and temperature resolution will only approach the independent measurement resolution if the determinant is relatively large.

Method F: Use of Polarization-Maintaining (PM) optical fiber [61].

Another method is to measure the spectral shifts of the two polarization modes from an FBG sensor written on a PM fiber. In PM fiber the strain coefficients for the two polarization modes are similar, but the temperature coefficients differ slightly. As the results a new matrix can be composed and the procedure would be similar as explained in the method E, equation 5.8.

5.4 CONECTORISATION OF EMBEDDED FIBRES. INGRESS-EGRESS SOLUTIONS.

5.4.1 BACKGROUND

The integration of the optical fibers into composites structures by embedding them inside the lay-up is not only actually one of the most attractive solution contributing to smart composite materials but also the optimum approach that insure the maximum protection and integrity of the fibers inside the structural parts against the ambient. Nevertheless this intended integration level remain still as a challenge [65, 66, 67, 68] since there are no today industrial mature solutions fulfilling with all main necessary requirements:

- a) Robust and resistant ingress-egress optical fiber method, that is mean, mature solutions with absence of vulnerability in the transition point that enables the optical connection of the embedded fiber inside the composite with an external interrogator unit.
- b) Reliable optical connection devices providing the proper light injection into the fiber and fulfilling the insertion requirements given by the technology (FBGs or backscattering).
- c) Solution compatible with the composite production process in terms of resistance to curing conditions (pressure, temperature and vacuum) and working together without impact on the composite manufacturing tasks and times (trimming, transport, etc.).
- d) Solution covering the reparability/replacement criteria of the technology in case of break of the optical fiber.
- e) Solution compatible with the structural and environmental requirements of the parts; the functional performance cannot conflict with the structural properties of the part (un-intrusiveness by miniaturized size) and the in-service operational

life. The introduction of the embedded fiber and connector cannot compromise the structural integrity of the part.

- f) And the last but not least, the solution has to be simple and industrialisable, thus not only suitable for laboratory environments but also easily scalable for mass/volume production ensuring the survival and repeatable quality.

In this section, the topic of fiber embedded in composite parts during manufacturing process is dealt with as a whole. Firstly the identification of the main requirements, constraints and tasks to perform when embedding optical fiber into/onto composite parts. Secondly two approaches for ingress-egress of the fiber inside the material are presented and described. Results of the first approach in an industrial environment are presented in the chapter 6- experimental results.

5.4.2 MAIN TASKS WHEN EMBEDDING OPTICAL FIBER IN COMPOSITE MATERIALS.

Essentially two tasks can be distinguished when embedding optical fiber in composite materials, firstly the group of tasks addressed to prepare and integrate the fiber inside the layers of the composite –host material- and secondly the previous preparation/design solution for the fiber ingress-egress to ensure the proper protection and connection.

5.4.2.1 EMBEDDING THE FIBER.

Selection of the fiber

Initially the first step to consider is the selection of the type of fiber to be embedded, and taking special attention to the coating of the fiber. The coating of the fiber determine the resistance to temperature and the handling. Polyimides, special acrylates and special polymeric materials are some of the current coatings used when embedded fiber in composites. Normal acrylates are generally discouraged due to lower temperature resistance, low modulus and worse adherence to the resins.

Intrusiveness of the fiber inside the material

Next important issue when embedding optical fiber is related to the possible intrusiveness of the fiber inside the material. The intrusiveness of the optical fiber inside the composite material can be defined as the lack of homogeneity inside the composite material in the vicinity of the embedded optical fiber that can cause the local bending on the reinforcement carbon fiber or the accumulation of resin close to the fiber. If no special cares during optical fiber embedding process are taken into account, this intrusiveness effects can clearly degrade the structural properties of the composite material and therefore to weaken the strength of the material.

Figure 5.8. Possible accumulation of the resin around the optical fiber

The next features comprise some of the key aspects concerning the intrusiveness of the fiber inside the composite materials that should be considered before any implementation:

- The diameter of the fiber. Fiber optic has an small profile to be in principle considered as embedded inside the material. However if we compare this diameter with the lower dimension of the carbon reinforce fiber is clear that fiber optic cannot be introduce in any way. A general rule is smaller the diameter lesser intrusive. The costs to pay for thinner fibers are in relation to the higher precaution to take care at the moment of laying up the fiber or the higher price if the fiber is out of current communication standards.
- The relative direction between the reinforcement carbon fiber and the optical fiber. The general rule to follow is that both fibers – reinforcement and sensing- should run in parallel to facilitate the embedment process of the optical fiber into the resin material. Maximum distortion of the fiber inside the material will be produced when both fibers are perpendicular to each other. This latter configuration produce an excess of resin surrounding the fiber that can promote delamination and therefore reduction of fatigue resistance especially with compression loads.
- Location of the fiber inside the thickness of the material. There are important items to consider concerning the location of the optical fiber inside the thickness:
 - a. The embedded fiber is the optimum approach to protect them against external agents. As deeper the fiber into the thickness as better the protection.
 - b. The intrusiveness decrease when the fiber is located closer to the surface, especially for lower thickness parts.
 - c. Adapted **ingress-egress solution** for the position of the fiber. As we shall see later, the connector solution is different in function of the position of the fiber: surface or inside.
 - d. Fiber position inside the laminate could be impacted by geometrical constraints or boundary conditions of the parts.

Therefore, the decision concerning the final position of the fiber inside the thickness laminate will require a compromise solution taking into account each of the above mentioned items and weight each one conveniently. For low thickness, approaches considering the fiber close to the surface should be initially the most convenient; whereas for thick thickness since the effect of the fiber inside became more negligible the fiber position could be more innermost the material if convenient.

Preparation of the length and routing.

The preparation of the length and routing has to be done in accordance with the conditions and requirements of the parts, such as the area of the structure, the location of the drills, number of sensors and connections and overall avoiding the intrusiveness of the fiber inside the material.

The fiber optic laying requires simple but very careful handling to avoid at all costs the break of the fiber. This is actually the time in the installation process requiring the maximum attention and care. The operation can be feasibly carried out manually or automatically depending essentially of the accessibility to the area, volume production and degree of automation.

There is no need of special surface preparation or treatment when optical fiber is placed on the pre-preg composite material, simply the cleanness of the fiber surface.

The positioning of the fiber inside the manufacturing process could require performing some previous reference marks on the metallic tools and/or the fiber itself in order to ease the adequate location and alignment of the fibers and sensor segments.

The placement of the optical fiber sensors during layup process should be done taking into account the required measurement direction and to avoid any movement of the fiber once placed and when the additional plies are lay-up.

The preparations of the connection edge or edges of the fiber are key issues (devoted hereafter).

Finally to mention that the number of fibers is not limited to one but multiple fibers can be embedded in one part. Obviously the above criteria should be applied in proportion to the number of fibers embedded and whenever authorized from Stress to ensure no impact at all on the strength of the structure.

5.4.2.2 INGRESS-EGRESS.

5.4.2.2.1 CONCEPT AND REQUIREMENTS

The ingress-egress of the optical fiber inside composite material parts is the transition area between the composite (comprising inside the embedded optical fiber) and the external fiber optic to be connected to the external interrogator unit. This transition area can be in

principle located in the edge of the structure or top of the surface, depending essentially of the boundary conditions of the part and the manufacturing constraints [69,70].

A summary of the main requirements applying to ingress-egress solutions follows. Actually the requirements are not only applying to the materials of the solution but also the performance of the concept itself.

- a) **Material resistance**. This refers to the proper selection for the materials of the connection device to fulfill with the following criteria:
 - Resistance to complete range of temperature. Composite curing conditions establishes the maximum temperature, around 180-220 °C and applied for up to 5-6 hours. In-service conditions mark the lowest temperature to resist, up to -60 °C.
 - Compatible thermal expansion during and after the curing process of the composite structure. Materials of the connectors must be thermally compatible with the composite material. In turn, the dimensions of the elements of the connection device and the type of fitting between them must be such that, after curing of the structure, the integrity of the entire device and its functional properties must remain intact.
 - Environmental resistance. The resistance to the aeronautical environment in terms of humidity, pressure, corrosive environments, vibrations, etc. The possibility of formation of galvanic couples that promotes the corrosion is a factor to be minimized by also the proper selection of the materials.
- b) **Streamlined outer shape**. This criteria aims to avoid, while embedded and during curing, the formation of porosities and holes around the embedded connection device which obviously would impact significantly the mechanical strength of the composite material in this area.
- c) **Tightness or sealing**. This concept is extremely important not only for the in-service life of the connection device, but especially during the process of curing the composite structure itself. Due to the existing conditions of temperature and pressure in the curing process, the resin reaches a degree of fluency so that, if no appropriate measures are taken, the proposed solution will not be viable due to the contamination of the resin inside the connector, thus damaging the optical contacts contained therein. Accordingly, in the process of installing the device in the composite structure, either in or out on an edge

surface, measures should be taken with the purpose of preventing the flow of resin into the optical contacts.

- d) **Minimum size of the device.** Given that the main applications of these sensors are structural monitoring components (composite structures), it is obvious that the own inclusion of the device must not lead to deterioration of the mechanical properties of these elements (structures composite). In this regard, the dimensions of the connecting device and of the elements forming it will be the smallest as possible, and variable depending on the thickness of the material structure to be monitored, especially in the case that the fiber exits in the edge of the composite structure. This is actually one of the shortcomings of the commercial solutions today; connectors are too large to be embedded inside the material compromising the structural integrity of the part in this area.
- e) **Need of trimming process & compatibility with manufacturing and assembly operations.** During the curing process of composite structures, the excess of resin flows toward the edges producing not only a decrease in thickness but also altering the dimensions of the part. This effect introduces the need for trimming the part which consists of cutting the edges of the structure to its nominal dimensions. In the case of composite parts comprising embedded fiber that coming out by the edges, the mentioned fiber would be incompatible with the trimming process since this cutting process would produce the destruction of the fiber in the transition area and thus the continuity from sensors embedded in the structure and the external monitoring unit. The installation of the connecting device and its penetration depth should be such that subsequent work will allow edging of composite structures without damaging the integrity of the connecting device and ensuring the proper finish of the edge of the composite part for subsequent assembly. Notice that if the solution involve cut the connector, since connector and part are made from different materials this operation could clearly impact in the current trimming composite process since it would be difficult to ensure the clean cutting avoiding break or deformation of the embedded device and the right finish of the edge.

Finally regarding this point, the last but not least, the connector device and integration methodology must ensure the minimum risks of breakage of the fiber during the manufacturing steps and assembly while allowing performing the trimming of the edges of the structure without damaging or break the mentioned fiber exit. If the connector or fiber are eventually broken would result in an important waste of material and man-hours.

- f) **Connecting and disconnecting.** Device with capability of connection and disconnection of the fiber by a quick and simple way.
- g) **Other criteria common to classical optical fiber connectors:**
 - Optical performance (Insertion loss, return loss, etc.)
 - Repetitively.
 - Robust locking mechanism
 - Minimum number of plugging & unplugging
 - Durability (mechanical and thermal resistance)
 - Mechanical and thermal resistance (crash, impact and vibration, ...)

There have been some publications and patents in the last years presenting different proposals to try to solve the complete problem but none of them has been industrialized basically because some of the requirements described were not met properly [71]. In view of the technical complexity and the diversity of the cases, the solution will not be unique but a portfolio of various solutions and the selection of the most adequate according to the part, manufacturing and assembly constraints, and operational conditions.

5.4.2.2.2 PROPOSED SOLUTIONS.

Two original solutions are described for the ingress-egress of optical fiber inside composite parts. Both of them have been demonstrated in the lab and the first one was also demonstrated in production environment as described in the chapter 5. The first solution (A) consists of a miniaturized connector to be integrated inside the thickness material or on the surface. The second solution (B) constitutes a solution for surface connector when strict insertion features are required. Both solutions are either patented or in process [69, 70].

1. SOLUTION A.

A connection device for optical fiber embedded inside the composite structure. The device is totally or partially embedded within the layers of the composite structure to be monitored, during the manufacturing process of the structure, in a zone previously selected.

The embedded area can be through the edge of the structure or the surface of the structure allowing the connection and disconnection of the embedded fiber, while preventing breakage problems.

In the event that the fiber, and thus the device, exits through the surface of the composite structure, the connection device is located in a proper composite area with previous sequence of escalation so that they are compensated and avoiding residual

stresses after curing the structure and also the presence of defects or excess resin in the vicinity. The device is then protected by a series of additional layers.

This connection device can be adapted for single fiber or multiple fibers -more than one optical fiber to be connected. Both solutions are conceptually identical; the only differences are in the form of confrontation between the fiber and the size of the external compartment.

The connecting device comprises the following elements:

1. A first connecting element (1) embedded in the composite material, either on the edge or on the surface of structure and located inside a resistant compartment. This first element comprise inside precisely positioned a tubular element (2) (ferrule) manufactured under highly rigid and tight tolerances. This tubular element that can be polished at different angles according to the insertion loss requirements, comprises internally a concentric bore where the embedded optical fiber is located and externally is connected to a sleeve guide (3) for directing and centering with the optical fiber core coming from external interrogator unit. There is an internal thread on the external compartment that is used to be properly joined with second connection element.
2. A protective element(4) that make the first connecting element perfectly sealed and resin tight during the manufacture process, and thus preventing the intrusion of resin in said first connection element. This protection is withdrawn once the structure is cured. This protective element is designed and installed during the manufacturing process avoiding adherence to its outer surface so that once cured the structure this protection can be easily removed from the first connecting element.
3. A second connection element (5) that is fit by external thread to the first connection element after removing the previous protective element once the structure of composite material goes in-service operations. This element comprise accurately hosted inside a ferrule coupled to fiber optical from external system and a chain of springs to ensure proper adjustment of the optical faces.
4. Finally a mechanical protection joined to the second connecting element, and whose purpose is to protect mechanically the first and second connection element in a way that any mechanical effort (vibration, shock, etc.) be absorbed by this protective element.

Figure 5.9 Proposal (A) for optical fiber connection for embedded fibers (Airbus Proprietary).

2. SOLUTION B.

A connection device for optical fibre embedded inside the composite structure or close to the surface layers. The device is positioned onto the composite surface conveniently protected by a serial of additional pre-preg layers. The optical fiber can be on the top of the surface or inside the composite laminate. In this last case the fibre has to go through the layers when reaching the surface connector.

The connection device can be adapted for a single fiber or multiple fibers. Both solutions are conceptually identical.

The connection device comprises the following elements:

a) Components of the connector solidary to the composite parts.

1. A precise cylindrical ferrule joined axially and firmly to a metallic regular prism (1). These pieces own a concentric bore where the optical fiber from composite material is ending up. The optical face of this ferrule constitutes the end of the fiber located inside the composite material and therefore is to be conveniently polished according to a predetermined angle to match with the insertion requirements from interrogator technology system.
2. A nozzle-shaped metallic tube (2) with an inner machined prism wherein precisely is allocated the set ferrule-metallic prism-fiber. This piece has also mechanized two

external threads and an inner cotter housing to ensure the proper alignment of the previous ferrule with an external ferrule located in the external part of the connector.

3. A solid base (3) constituting the external part of the connector and to be placed onto the surface composite part where connector is allowed. This base as mentioned previously is covered and protected with additional composite layers during installation/manufacturing process. This base has mechanized a through hole divided into sections; firstly a threaded interior bore in order to fit the previously depicted nozzle-shaped metallic cylinder. This first bore finish in a second thinner concentric hole through which the embedded optical fiber goes into the connector devices.

b) External parts of the connector.

1. External alignment device (4) working as male part of the connector and to be introduced into the nozzle-shaped cylinder to facilitate the coupling procedure and alignment at a pre-determined angle. This accurate small component consists of a tube with an inner regular mechanized to allocate an external ferrule. This part has also externally machined a cotter enabling a unique assembly position with nozzle-shaped metallic tube solidary to composite parts, in order to align the two ferrules. Furthermore an external thread is used to fit with a new metallic tube working as closure piece.
2. External ferrule (5) firmly joined to a metallic prism and coupled to fiber optical from external interrogator unit.
3. Chain of springs (6) pushing the two ferrules to ensure proper contact pressure between the optical faces.
4. Closure piece (7) involving the entire external alignment devices and closing the connector through a threaded screw.

Figure 5.10 Proposal (B) for optical fiber connection for embedded fibers.(Airbus Proprietary).

6 CHAPTER 6. EXPERIMENTAL PART

INTRODUCTION.

This chapter constitutes the experimental part of the thesis. The definition of each of the tests detailed as follows are based on the scenarios and requirements developed in the previous chapters. The tests presented are considered as clear examples of the type of validation tests for these technologies in the development phase. The qualification tests aiming to demonstrate the repeatability and reliability of the technologies in front of the requirements of a specific standard would be out of the scope of this thesis.

The presentation of the tests is not done in importance order since all of them include essential aspects in the technology development of optical fibers for SHM purposes. Rather the tests are organized closely to the classical pyramidal test hierarchy, that means as many simple and cheap tests as possible to determine essential aspects such as performance or resistance to ambient, and then decrease the number of tests but in turn increasing their complexity, costs and proximity to the real conditions. It is important to note that the tests presented here are not the only ones performed during the development phase but many others have not been included majorly to simplify the work.

The first type of tests describes the durability tests relating the resistance of the technology and the integration process against the normal operational conditions. The procedure and methodology for these tests are presented in five representative immersion test mediums: skydrol, kerosene, cleaning agent and water. The second type of tests that are reported refers to the temperature compensation concept when measuring strain with optical fiber sensors and acting simultaneously strain and temperature. In the third place, a simple test performed in an electromagnetic lab is described to demonstrate the non-interference of Electromagnetic Field (EMI) on the measurement process with optical fiber sensors. The test consisted of applying a controlled electrical discharge simulating a lightning strike and meantime measuring the strain and temperature with bonded optical fiber sensors. In the fourth place are detailed lab tests on selected coupons with integrated distributed fibers in order to evaluate the strain range of the technologies in mechanical tests. In the fifth place it is depicted a structural test on a metallic panel instrumented with distributed optical fiber and classical strain gages as reference. In the sixth place, a large composite structural tests, instrumented and monitored during static and fatigue conditions is described. In the seventh place, composite structural test panels containing a bonded repair patch and tested in static and dynamic conditions are described. In the eighth place an structural tests panel instrumented with embedded and bonded fibers is disclosed. The embedded fibers were installed in the production phase and the ingress-egress issue was solved by special connectors designed and manufactured for this particular purpose. The last section of this chapter is dedicated to the preparation and set up of an optical fiber installation based on FBG sensors for load monitoring in flight tests.

6.1 DURABILITY TESTS

6.1.1 CONCEPT AND OBJECTIVES OF THE TESTS

The durability tests constitute an essential step in the development of structural health monitoring technologies since one of the most important group of requirements are due to their permanent sensors application on the aircraft structures and their performance during the operational life.

It is a mandatory kind of test that have to be done in order to demonstrate the maturity level of the technology. The tests applies not only to the bonded sensors scenario but also to any other device of the system (connector, cables, etc.) working and exposed to environmental working conditions.

These types of tests are carried out primarily with two objectives, firstly to validate the prediction of the behavior of the technologies in the long term, and secondly to demonstrate the robustness of application procedure and the performance of the technology, during the complete life of the technology in the structure.

The durability tests campaign is carried out on representative samples under selected load/environmental conditions also representative of the real conditions over the time. In some cases the conditions can even be more severe than the real ones with the purpose to accelerate the effect of the ambient on the sample/sensor and hence reduce the time for the conclusions of the tests.

The main characteristics identifying these tests are:

- a) The exposure medium: water, skydrol, fuel, etc.
- b) The environmental parameters: temperature, pressure, humidity, etc.
- c) The mechanical loads and spectrum: static, fatigue, etc.
- d) The duration of the tests: hours, days, etc.

After the exposure medium, the application procedure of the technology is considered acceptable providing after the test conditions the performance of the sensors integrated on the sample remains unaltered and meeting as the beginning with the sensor specification. In this test campaign this criteria was demonstrated by performing functional cycle tests after the immersion tests and by the latter comparison of the optical fiber sensors outputs (working as strain sensors) with electrical foils installed just after the immersion tests.

6.1.2 METHODOLOGY OF THE TESTS.

The methodology followed in the preparation of these tests consisted of:

- a) Identification of the environmental conditions. This task is done based on the real conditions wherein the real parts are working. In essence the most important aspect is to identify those external agents related to the ambient that could affect negatively the performance of the permanent sensors bonded on the structure over the time. The test ambient has to be identified in function of medium, severity,

temperature and application time to reproduce conveniently in the climatic chamber the controlled conditions.

- b) Preparation of the samples. The preparation of the samples is divided in the following subtasks:
1. Design of the samples. In case of composite samples, it basically consists of the selection of the composite material representative to the real parts, stacking, thickness, number of samples, dimension of each sample and surface condition.
 2. Manufacturing of the panel.
 3. Non-destructive inspection of the panel.
 4. Cutting and extraction of the samples.
 5. Surface bonding of the sensors on the samples. The sensors are bonded on the samples in accordance to the selected procedure (see chapter 5) and with a pigtail to be able to interrogate them later on during the functional tests.
 6. Application of sealant and further special protection (top coat). Due to the external agents (chemical and mechanical), the only application of adhesive can be not enough to protect the sensor and adhesion. Additional layers such as sealant or coatings properly selected are commonly applied to ensure the resistance of the sensor to the ambient over the time.
- c) Preparation and set up of the environmental conditions. This process is majority done in a climatic chamber, with possibility to control temperature variation, time and exposure medium. Once the setup of the exposure medium is done, an additional key feature for these tests is the selection of the climatic chamber with possibility to extract the cables and connectors from the sensors so that their evolution can be monitored through the acquisition unit outside and close to the chamber (see picture 6.1.1). This permanent monitoring along the test enables to study more in detail the influence of the ambient and detect any drift effect of the sensors.

Figure 6.1.1. Example of environmental test (TRL. C. Miguel).

- d) Environmental tests. The samples are introduced in the climatic chamber for specific conditions and time. Periodic interrogation of the sensors is performed to study the effect of the test conditions on the performance of the technology, for example for the water immersion test the acquisitions were done at 24h, 48 h, 72 h, 168 h, 192 h, 336 h, 360 h, 384 h and 408 h.
- e) Mechanical test on the samples and finding of the tests. Once exposure time is completed it is necessary to determine and conclude whether sensors and the followed application procedure was enough mature to resist the simulated environmental conditions. This is done by the following process:
1. Cleaning of the samples after the immersion tests.
 2. Application of a reference technology on the samples, measuring the same parameter than optical fiber sensor primarily applied. In the case of strain optical fiber sensors, classical electrical strain gages were bonded in the same or the other side of the coupon.
 3. Functional tests consisting of cyclic loading on the samples and comparison between the reference technology and the technology under tests. These cycles are representative of the normal aircraft flights and applied during repetitive times. During these mechanical tests, the optical fiber sensors (subjected previously to environmental conditions) and strain gages are interrogated so that after the cyclic tests we can study and cross-correlate both measurement outputs. If the comparison of the test produce similar measurements, then the test conclusion would be positive and hence the resistance of the sensor and application procedure to the environmental conditions is fulfilled. If, on the contrary, the optical fiber sensors do not follow the reference sensors, it would mean the deterioration of the sensor

Figure 6.1.2 Load spectrum applied after the environmental test.

under test or joint procedure and therefore new application procedure or protection will have to be designed and tested.

The next scheme summaries all the steps of the process.

Figure 6.1.3 Summary of the process followed for the durability tests (TRL. C. Miguel).

6.1.3 DESCRIPTION OF THE TEST SPECIMENS AND INSTRUMENTATION

The test specimens consist of 280 x 32 x 3 mm composite coupons that were extracted from a 600 x 650 mm composite panel previously manufactured. The complete panel was firstly manufactured, then inspected by UT reflectance plate and finally since not relevant indications were found, the different samples were extracted. Next the samples were grouped by kind of environmental test. Finally the sensors were surface bonded and protected on each of the samples.

The next pictures summaries the preparation process of the samples.

Figure 6.1.4 Preparation process of the test samples (TRL: C. Miguel).

6.1.4 INSTRUMENTATION ON THE TEST SPECIMEN

The instrumentation in the samples was surface bonded in two stages. In the first stage - before immersion test- the optical fiber sensors- FBG- were installed. In the second stage, after the immersion test, an electrical foil gage was installed on each sample (see figure 6.1.5). This electrical strain sensor was installed into the sample with the only objective of being used as reference technology for FBG during the functional cyclic mechanical tests performed after the immersion test and therefore with the purpose to demonstrate the performance of the optical sensors after the exposition to the environment.

Figure 6.1.5 Instrumentation during the functional tests (Airbus Proprietary)..

6.1.5 DESCRIPTION OF THE TESTS DONE

Since the total number of tests to be performed in order to qualify the different locations in the aircraft is clearly out of the scope, this document discloses only five immersion tests. These tests were selected as the most common fluids susceptible to be in contact with some structural parts in the aircraft. The temperature and test duration were chosen based on aeronautical standards dedicated to the qualification of airborne systems (RTCDA DO 160). These fluids are:

- a) Skydrol 500B-4, as a common fire resistant aviation hydraulic fluid.
- b) Kerosene, as a commonly used fuel to power jet engines of aircraft.

- c) Dylestone DLS, as a cleaning solvent use regularly for maintenance operations in the aircraft such as degreasing, tripper, etc.
- d) Water, as the most probable fluid can reach many areas of the aircraft due to rain, ice, etc.

The next table, 6.1.1, summarizes the conditions of the tests for these four fluids and the samples used in each of the tests.

Table 6.1.1 Immersion tests.

Name of the test	Environmental conditions	Duration of the test (h)	Number & designation of samples
Skydrol	Immersion in Skydrol 70 °C	1200	5 samples Samples 59, 65, 66, 67, 68, 69
Diestone DLS (Cleaning agent)	Immersion in (Dylestone Room temperature	168	5 samples Samples 5, 31, 33, 70, 71
Water	Immersion in water 70°C	408	5 samples Samples 34, 41, 42, 43, 44, 45
kerosene	Immersion in kerosene 40°C	168	4 samples Samples 46, 47, 48 and 49

6.1.6 MAIN RESULTS OF THE TESTS

The main results of these tests basically entail:

- a) The follow-up of the spectrum of the FBG sensors along the immersion time. This was done by a regular acquisitions performed in different steps along the exposure time and consisting of the connection and acquisition of the spectrum of the FBG sensors installed in each sample. Then these spectrums were plotted together for each sample and the center wavelength peak (WC) followed and compared from the beginning to the end of the test so that it can be evaluated any possible drift of the WC.
- b) Strain measurement plots. These plots correspond to the functional cyclic test done on each of the sample just right after the environmental tests. These graphs plot together the output of the FBG sensor and the foil strain gage installed after the immersion test. These tests are the functional trials determining whether or not the bonded sensor procedure and protection are adequate for the application.

In order to simplify the reporting of these tests, the next information will be presented for each test:

- a) Pictorial summary including the samples at the moment of the immersion test, the samples after the immersion time and one sample in the functional test.
- b) A plot collecting the FBG spectrum of one representative sample along the immersion test and one graph of WC peak versus time to evaluate the drift of the sensor.
- c) A table collecting the evolution of the wavelength center surface bonded on each of the sample used in the different immersion tests.
- d) Cycle strain measurement plot of one representative sample, correlating FBG and strain gage outputs.

6.1.6.1 SKYDROL IMMERSION TEST RESULTS

Figure 6.1.6. Pictorial summary of skydrol immersion test (Airbus Proprietary).

Table 6.1.2. Skydrol immersion test. Evolution and drift.

Skydrol immersion- Evolution and drift (1200 h)				
Sample	Initial center wavelength	Final center wavelength	wavelength variation during test (pm)	Maximum & minimum temperature during the test (°C)
D59	1531,287	1531,150	137	67,1-76,2
D65	1551,325	1551,125	200	
D66	1546,238	1546,125	113	
D67	1541,312	1541,15	162	
D68	1551,312	1551,113	199

Figure 6.1.7. Evolution of the CW peak during skydrol immersion test.

Figure 6.1.8. Functional test after skydrol immersion.

6.1.6.2 WATER IMMERSION TEST RESULTS

Figure 6.1.9. Pictorial summary of the water immersion (Airbus Proprietary).

Table 6.1.3. Water immersion test. Evolution and drift.

Water immersion- Evolution and drift (408 h)				
Sample	Initial center wavelength	Final center wavelength	wavelength variation during test (pm)	Maximum & minimum temperature during the test (°C)
D34	1537,613	1537,475	150	68,1-73,6
D41	1541,137	1541,05	87	
D42	1537,963	1537,925	63	
D43	1535,300	1535,213	87	
D44	1558,175	1558,113	74	
D45	1531,850	1531,963	113

Figure 6.1.10. Evolution of the CW peak during water immersion test.

Figure 6.1.11. Functional test after water immersion.

6.1.6.3 DYLESTONE IMMERSION TEST RESULTS

Figure 6.1.12. Pictorial summary of the Dylestone immersion (Airbus Proprietary)

Table 6.1.4. Dylestone immersion test. Evolution and drift

Dylestone immersion- Evolution and drift (168 h)				
Sample	Initial center wavelength	Final center wavelength	wavelength variation during test (pm)	Max. & Min. temperature during the test (°C)
D5	1552,350	1552,353	38	23,0 -26,6
D70	1570,762	1570,764	37	
D71	1538,538	1538,537	41	
D31	1531,437	1531,433	52	
D33	1555,913	1555,916	62

Figure 6.1.13. Evolution of the CW peak during water Dylestone immersion test.

Figure 6.1.14. Functional test after Dylestone immersion

6.1.6.4 KEROSENE IMMERSION TEST RESULTS

Figure 6.1.15. Pictorial summary of the kerosene immersion test (Airbus Proprietary)

Table 6.1.5. Kerosene immersion test. Evolution and drift

Kerosene immersion- Evolution and drift (168h)				
Sample	Initial center wavelength	Final center wavelength	wavelength variation during test (pm)	Maximum & minimum temperature during the test (°C)
D46	1537,595	1537,600	24	39,0 -43,0
D47	1534,905	1534,923	32	
D48	1557,812	1557,792	52	
D49	1531,659	1531,650	58

Figure 6.1.16. Evolution of the CW peak during water kerosene immersion test.

Figure 6.1.17. Functional test after kerosene immersion

6.1.7 MAIN CONCLUSIONS OF THE DURABILITY TESTS DONE

After the analysis of the results, these are the main conclusions of these tests:

1. The methodology used has enabled to evaluate the adequacy of the application procedure as well as the assessment of the drift of the sensors and the final effect of the mediums by the functional tests.
2. The functional cyclic loads after the immersion tests have demonstrated the resistance of the all optical fiber sensors and the appropriated installation procedure. This is a consequence of the plots after the tests showing the good correlation between the optical fiber sensors and the strain gages, whenever within 2%.
3. The follow up of the FBG spectrums have demonstrated very low drift of the wavelength center. As it can be seen in the tables of the tests, table 6.1.2 to 6.1.5, the variation of the wavelength from the beginning to the end of the test were smaller than 100 pm for those immersion tests lasting less than 200 h and lower than 200 pm for skydrol test lasting more than 1000 h. This is an important issue for the permanent sensors on structural health monitoring applications.
4. These conclusions are really useful to estimate the possible error in long term measurements and also to establish when periodically would be convenient to reset the reference of the sensors in cases this effect need to be corrected.
5. These conclusions cannot in principle be assured for all FBG sensor in the market today. It is important to mention that the FBG used in this test campaign were, firstly and previously to the durability test, visually inspected before, during and after a tensile simple test with the purpose to detect micro cracks on the grating optical fiber surface. Secondly, the FBG sensors were then stabilized by a pre-annealing process at a temperature exceeding the in-service temperature (in the immersion test).
6. This test campaign was focused on bonded sensors since they are much more susceptible to be affected by the environmental effect. In the case of embedded sensors in composite structures, the own material protects the sensor and the areas susceptible to be deteriorated by the ambient would be essentially the ingress egress area and the optical fiber cables. The demonstration of the durability requirements for the transition of the fiber and the cables would require similar immersion tests but with different functional trials such as optical fiber connector performance and pull out test among others.
7. This durability tests campaign was done using only FBG as optical fiber sensors. Since the application and protection of the FBG sensors is very similar to distributed optical fiber, saving the scale issue, the main conclusions said should be also extrapolated to distributed optical fiber. For this technology, an additional conclusion that could be considered is in relation to the stability of the

backscattering of the fiber over the life time. For distributed fiber (based on Rayleigh) the sensor reference would be a snapshot of the backscatter of the fiber at a single point in time. The scatter profile is in turn due to the inherent index variations along the fiber during the fiber draw process. In a similar way to the fixed index changes created into Fiber Bragg Grating sensors, there are the index changes created inherently during the draw process. Therefore, in the same way that it is not expected the change of FBG grating over time, we would not expect the fiber's inherent index variation to change with time (unless fiber is stored in extreme conditions, like at temperatures near glass transition aprox. 1000C)[37].

6.2 TEMPERATURE COMPENSATION TESTS WITH DISTRIBUTED FIBER

6.2.1 OBJECTIVES OF THE TESTS

The main objective of these tests is the demonstration - in those scenarios where strain and temperature are affecting simultaneously- on how the temperature can be compensated so that its effect can be decoupled from the effect of the strain and therefore only strain related to mechanical stress are reported by optical fiber sensors. The measurements are carried using distributed sensing fiber and FBG sensors.

As explained in the chapter 5 , there are several approaches that can be in principle applied to do this task, and the best option would depend, among other factors, on the measurement accuracy we need. In these tests the method of the dummy sample is followed, wherein apart from the test specimen subjected to load, there is an extra sample (dummy), identical to the specimen under test (material, CTE and sensor configuration) but only subjected to temperature change. Thus the working procedure will consist of acquiring simultaneously the sensor outputs from both samples –dummy and specimen- and then to subtract the first to the second one respectively.

6.2.2 DESCRIPTION OF THE TESTS SAMPLES

a) Dimensions of the CFRP coupons:

100 x 280 mm and 3 mm thickness (figure 6.2.1)

b) Taps:

80 x 50 x 1.5 mm

Figure 6.2.1. Coupons for temperature compensation tests.

c) Number of samples and instrumentation:

Two set of samples, A and B, composed of two samples (1 and 2) each set, are tested. The coupon 1 of both sets was subjected to load and temperature and the coupon 2 was subjected only to the temperature effect.

The set A comprises two samples with surface bonded distributed optical fibers as described in figure 6.2.2. Apart from the distributed sensing fiber, one FBG sensor was also bonded on each sample in identical position. In addition a thermocouple (type K) was fitted close to each sample to measure its temperature.

The set B comprises also two samples, one sample with embedded optical fiber and the second one with bonded optical fiber. Apart from the distributed fiber, one electrical strain gauge was surface bonded on each sample in identical position. In addition a thermocouple (type K) was fitted close to the sample to measure the temperature. The figure 6.2.2 shows the fiber route and location of FBG and S/G on the set of samples A and B.

Figure 6.2.2. Set of samples A and B.

The next tables 6.2.1 and 6.2.2 provide the location of the fiber distances on the samples for the two sets. The "touch to catch" process was done on the discrete points of the samples.

Table 6.2.1. Set sample A.

Set sample A			
Sample	Point number	Distance on distributed fiber (m)	Comparison
2 (bond. Fiber)	1	2,818	
2 (bond. Fiber)	2	2,857	
2 (bond. Fiber)	3	2,901	
2 (bond. Fiber)	4	2,969	
2 (bond. Fiber)	5	3,011	FBG 2
2 (bond. Fiber)	6	3,058	
2 (bond. Fiber)	7	3,118	
2 (bond. Fiber)	8	3,173	
2 (bond. Fiber)	9	3,215	
1 (bond. Fiber)	10	4,231	
1 (bond. Fiber)	11	4,281	
1 (bond. Fiber)	12	4,333	
1 (bond. Fiber)	13	4,388	
1 (bond. Fiber)	14	4,448	FBG 1
1 (bond. Fiber)	15	4,482	
1 (bond. Fiber)	16	4,560	
1 (bond. Fiber)	17	4,602	
1 (bond. Fiber)	18	4,654	

Table 6.2.2. Set sample B.

Set sample B			
Sample	Point number	Distance on distributed fiber (m)	Comparison
2 (bond. Fiber)	1	2,270	
2 (bond. Fiber)	2	2,323	
2 (bond. Fiber)	3	2,353	
2 (bond. Fiber)	4	2,433	
2 (bond. Fiber)	5	2,478	FBG 2
2 (bond. Fiber)	6	2,535	
2 (bond. Fiber)	7	2,581	
2 (bond. Fiber)	8	2,637	
2 (bond. Fiber)	9	2,679	
1 (emb. fiber)	10	3,620	
1 (emb. fiber)	11	3,670	
1 (emb. fiber)	12	3,730	
1 (emb. fiber)	13	3,795	
1 (emb. fiber)	14	3,844	S/G 1
1 (emb. fiber)	15	3,901	
1 (emb. fiber)	16	3,966	
1 (emb. fiber)	17	4,010	S/G 2
1 (emb. fiber)	18	4,050	

6.2.3 TEST MATRIX

The tests carried out can be classified in two groups:

- Ramp load tests where the load ramp goes from 0 to 140 kN, in 20 kN steps.
- Cyclic load tests where the load varies cyclically from 0 to 75 kN at a frequency of 1 Hz.

In turn, these two groups of tests were performed at different stabilized temperatures: room temperature (around 25 °C), 45° C, 65°C and -35 °C.

All the tests done are summarized in the table 6.2.3, where is also indicated the sampling rate for each acquisition device (distributed fiber, FBG and thermocouple).

Table 6.2.2 Test Matrix.

Test day	Number of test	Set of samples	Temperature range (°C)	Load range (kN)	Distributed fiber sampling (Hz)	FBG sampling (Hz)	TC sampling (Hz)
day 1	Test 1	A	RT	0-140 (step 20 kN)	1	1	1
day 1	Test 2	A	RT	1-75 (cycles)	23,8	23,8	1
day 1	Test 3	A	RT	1-75 (cycles)	23,8	23,8	1
day 2	Test 1	A	RT	0-140 (step 20 kN)	1	1	1
day 2	Test 2	A	RT	1-75 (cycles)	23,8	23,8	1
day 2	Test 3	A	temp ramp_RT to 45	1-75 (cycles)	23,8	23,8	1
day 2	Test 4	A	45	0-140 (step 20 kN)	1	1	1
day 2	Test 5	A	45	1-75 (cycles)	23,8	23,8	1
day 2	Test 6	A	65	0-140 (step 20 kN)	1	1	1
day 2	Test 7	A	65	1-75 (cycles)	23,8	23,8	1
day 3	Test 1	A	temp ramp_RT to 40-65	1-75 (cycles)	23,8	23,8	1
day 3	Test 4	A	temp ramp_RT to 40-65	1-75 (cycles)	23,8	23,8	1
day 3	Test 5	A	temp ramp_RT to 40-65	0-140 (step 20 kN)	1	1	1
day 4	Test 1	A	temp ramp_RT to -35	0-140 (step 20 kN)	1	1	1
day 4	Test 2	A	-35	1-75 (cycles)	23,8	23,8	1
day 4	Test 3 (repetitive)	A	-35	1-75 (cycles)	23,8	23,8	1
day 4	Test 4	A	-35	0-140 (step 20 kN)	1	1	1
day 4	Test 5	A	temp ramp_-35 to 65	0-140 (step 20 kN)	1	1	1
day 4	Test 6	A	65	1-75 (cycles)		1	1
day 4	Test 1	B	RT	0-140 (step 20 kN)	1	1	1
day 4	Test 2	B	RT	1-75 (cycles)	23,8	23,8	1
day 4	Test 3	B	temp ramp_RT to 40-65	0-140 (step 20 kN)	1	1	1
day 4	Test 4	B	65	1-75 (cycles)	23,8	23,8	1
day 4	Test 5	B	65	0-140 (step 20 kN)	1	1	1

Additionally, a last test, not included in the last table, was done on set A to assess the uncertainty due to the test load machine. This further test consisted of clamping the sample 1 to the test machine but no load and only temperature applied. On sample 2, acting as dummy, only the temperature changes are applied.

6.2.4 INSTRUMENTATION SYSTEMS AND SET UP

The instrumentation systems used in these tests are the following:

- a) Distributed fibre and the corresponding equipment
- b) Bonded FBG and the corresponding equipment
- c) Bonded S/G and the corresponding equipment
- d) Thermocouples type K and the data logger

6.2.5 RESULTS OF THE TESTS

6.2.5.1 RESULTS OF THE LOAD RAMP TEST FROM 0 TO 140 kN (SET A)

Table 6.2.4 Summary table of results for ramp load tests on set sample A.

Set sample A- ramp from 0 to 140 kN				
Number of test	$\mu\epsilon$ difference respect to RT (reference: Day 2-test 1)		Temperature variation ($^{\circ}\text{C}$)	Temperature difference between Sample 1 and sample 2 ($^{\circ}\text{C}$)
	Distributed fiber	FBG		
Day2-test 6	0.7%	0.6%	65	0.013
Day3-test 5	2.5%	0.5%	Ramp from 28 to 65	2.7
Day4-test 4	0.8%	3%	-35	3.2
Day4-test5	4%	1.6%	Ramp from -35 to 65	0.012

Figure 6.2.4 Test reference for ramp load tests on set sample A.

Figure 6.2.5. Ramp load test on set sample A at 65 °C.

Figure 6.2.6. Ramp load test on set sample A with temperature variation from 28 to 65 °C.

Figure 6.2.7. Ramp load test on set sample A at -35 °C.

Figure 6.2.8. Ramp load test on set sample A with temperature variation from -35° to 65 °C.

6.2.5.2 RESULTS OF THE LOAD RAMP TEST FROM 0 TO 140 KN (SET B)

Table 6.2.5. Summary table of results for ramp load tests on set sample B.

Set sample B- ramp from 0 to 140 kN				
Number of test	$\mu\epsilon$ difference respect to RT (reference: Day 4-test 1)		Temperature variation (°C)	Temperature difference between Sample 1 and sample 2 (°C)
	Distributed fiber	FBG		
Day4-test 3	1.4%	1.3%	Ramp from RT to 65	1.4
Day4-test 5	1.2%	1.2%	65	1.3

Figure 6.2.9. Test reference for ramp load tests on set sample B.

Figure 6.2.10. Ramp load test on set sample B with temperature variation from RT to 65 °C

Figure 6.2.11. Ramp load test on set sample B at 65 °C.

6.2.5.3 RESULTS OF THE CYCLIC LOAD FROM 1 TO 75 kN (SET A)

Table 6.2.6. Summary table of results for cyclic load on set sample A.

Set sample A- cycles from 1 to 75 kN				
Number of test	$\mu\epsilon$ difference respect to RT (reference: Day 2-test 2)		Temperature variation ($^{\circ}\text{C}$)	Temperature difference between Sample 1 and sample 2 ($^{\circ}\text{C}$)
	Distributed fiber	FBG		
Day 2-test 7	0.1%	2%	65	0.2
Day3-test 4	2%	2%	Ramp from 28 to 65	2
Day 4-test 3	1%	1.8%	-35	4

Figure 6.2.12. Test reference for cyclic load on sample A.

Figure 6.2.13. Cyclic load on set sample A at 65 °C

Figure 6.2.14. Cyclic load on set sample A with temperature variation from RT to 65 °C.

Figure 6.2.13. Cyclic load on set sample A at -35 °C

6.2.5.4 RESULTS OF THE CYCLIC LOAD FROM 1 TO 75 kN (SET B)

Table 6.2.7. Summary table of results for cyclic load on set sample B.

Set sample B- cycles from 1 to 75 kN				
Number of test	$\mu\epsilon$ difference respect to RT (reference: Day 4-test 2)		Temperature variation (°C)	Temperature difference between Sample 1 and sample 2 (°C)
	Distributed fiber	FBG		
Day4_test 4	0.5%	1.3%	65	1.5

Figure 6.2.16. Test reference for cyclic load on sample B.

Figure 6.2.17. Cyclic load on set sample B with temperature variation from RT to 65 °C.

6.2.5.5 RESULTS OF THE TEST WITH NO LOAD AND ONLY TEMPERATURE VARIATION FROM -35 TO 65°C (SET A)

Table 6.2.8. Summary table of results for temperature variation test with no load.

Set sample A- no load, only temperature variation			
Number of test	Distributed fiber: difference between sample 1 (clamped) but only temperature and sample 2 (dummy) only temperature	Temperature variation (°C)	Temperature difference between Sample 1 and sample 2 (°C)
Additional test-cooling step	±50 microstrain	RT to -35 °C	From 0 to 2 °C
Additional test-heating step		From -35 to 65 °C	From 0 to 4 °C

Figure 6.2.18. Temperature variation from RT to -35 and 65°C.

6.2.6 MAIN CONCLUSIONS OF TEMPERATURE COMPENSATION TESTS

1. In all test cases, the Compensating 'Dummy' Gage method was used to perform temperature compensation. With this compensation technique, both the 'loaded' coupon and the unloaded 'dummy' coupon were inside the thermal chamber. Strain measurements from the unloaded 'dummy' coupon were directly subtracted from measurements from the 'loaded' coupon to remove temperature induced apparent strain and provide compensated strain results.
2. Even though the two samples were inside the chamber, it was really difficult to keep both of them at the same temperature over the time. The different position of the samples, the heating/cooling system in the chamber or the fact that one sample was clamped and the other one free are really important factors with influence on the thermal inertia of the samples. However these issues, to some extent, are representatives of the real conditions in the a/c for this compensation method and therefore have enabled to get a conservative value in terms of the accuracy with the dummy compensation method.
3. The results of the tests have demonstrated that temperature compensated distributed sensing fiber measurements are very similar than compensated FBG measurements. The tests hence constitute a new evidence of the similar performance of FBG and distributed fiber sensors. This was confirmed for static and dynamic test cases and also where temperature was held firstly constant at -35, 45 and 65 °C and then varied from -35 to 65°C.
4. The results of the tests have provided compensated measurements differing from 0.5% to 4% respect to the same test at RT.
5. The higher differences, up to 4%, were found in those tests wherein a ramp load and simultaneously a temperature variation were applied. These cases are representative of flight conditions such as taking off, strong ascent or descent and landing.
6. When a stable temperature was reached and kept, any of the strain variations measured by the sensors provided a deviation respect to RT not higher than 1%. These cases are representatives of stable conditions such as cruise.
7. The results also outcome no important differences between the temperature compensation results between bonded fiber and embedded fibers.
8. An additional test was also done to try to evaluate the possible uncertainty in the test configuration due to the load variation around zero and introduced by the test machine. This test outcome a maximum deviation around 1% when temperature varies from -35 to 65°C and respect to RT.
9. In summary, this compensation method have demonstrated enough consistency to be used in many practical applications providing it can be ensured that the dummy parts are subjected to the same temperature than the parts and no mechanical

stress at all. These conditions should be found for all the sensing points in the distributed fiber.

6.3 STRAIN MONITORING DURING LIGHTNING STRIKE

6.3.1 OBJECTIVES OF THE TESTS

The objective of these tests are to demonstrate the capability of optical fiber sensors, in this case FBG sensors, to measure the strain and temperature variation on an aluminum plate sample when subjected to direct effects of lightning strike in Lab conditions and therefore non-interference of this strong electromagnetic field during the measurement process.

6.3.2 DESCRIPTION OF THE TESTS SAMPLES

Square 7075 T6 Aluminum flat sample. Dimensions 400 x 400 and 2 mm thickness.

6.3.3 INSTRUMENTATION

One array with two FBGs, the first one (left side) subjected only to temperature and the second one (right side) surface bonded and hence subjected to temperature and strain.

The next figure 6.3.1 shows the location of the sensors in the sample.

Figure 6.3.1. Test sample and location of the FBG sensors.

6.3.4 INSTRUMENTATION SYSTEM

A FBG interrogator unit, with maximum acquisition speed of 2 kHz, was used in the acquisition of the test.

6.3.5 CONFIGURATION OF THE TESTS

Initially the square sample was fixed in their four sides. Once the sample was fitted and the sensors configuration done, two artificial lightning strikes were applied by means of a high voltage pulse generator where the rise time from zero to peak voltage was 1.2 μ s. The voltage peak amplitude in the two tests was 200 kA.

The exact conditions of the test corresponded to Zone 1A and 2A according to RTCA Do160- Section 23.

The next figures show the configuration of the test samples before and after the two reproduced lightning strikes 1 and 2.

Figure 6.3.2. Test configuration before and after the two artificial lightning strikes (TRL: C. Miguel).

6.3.6 RESULTS OF THE TESTS

Figure 6.3.3. Plot strain vs time corresponding to artificial lightning strike 1.

Figure 6.3.4. Plot temperature variation vs time corresponding to artificial lightning strike 1.

Figure 6.3.5. Plot strain vs time corresponding to artificial lightning strike 2.

Figure 6.3.6. Plot temperature variation vs time corresponding to artificial lightning strike 2.

6.3.7 MAIN CONCLUSIONS OF LIGHTNING STRIKE TESTS

After the analysis of the results, these are the main conclusions of these two tests:

1. First of all it is worth noting that the measurements presented in this section cannot be carry out with traditional sensors such as electrical strain sensors since they would be destroyed by the high electrical current during the test. FBG sensors can be used thanks to some of the advantages highlighted in the chapter 3, in particular, they are non-conductive sensors, sensible to strain and temperature and also immune to electromagnetic interferences.
2. The FBG sensors, bonded and only closed, resisted the test conditions in the two tests.
3. The test results showed repeatability of the temperature and strain measurements in the two tests.
4. In the case of the temperature variation measurement, the result was an increase of 4 °C for both tests. The acquisition speed was quite enough to catch properly this dynamic event.
5. For the case of the strain measurement, the increase value was also in the two tests approximately 100 microstrains. Based on these last plots, and focusing on the first instants of the strike, the acquisition speed seems not high enough to catch properly this complete dynamic event. Furthermore some sensor data were missing at the instant of the strike, very probably not because of an inadequate sensor response but due to the electromagnetic noise affecting to the interrogator unit at the moment of the strike.
6. With independency of the adequate acquisition rate, the results of the tests enable to demonstrate the capability of optical fiber sensors to monitor strain/temperature in scenarios susceptible to strong electrical interferences such as produced by lightning strike.
7. Definitely, the concept of using FBG sensors in this scenario is innovative and opens many new possibilities for the mechanical and thermal characterization of the aeronautical structures subjected to direct and indirect lightning strike effects, and the relation between the electrical energy with the material damage. The same application on poor conductive composite materials, where the electrical energy is highly localized in the impact region, would allow to get more quantitative values, very useful from material design point of view.

6.4 TENSILE-COMPRESSION COUPON TESTS FOR THE EVALUATION OF THE STRAIN CAPABILITIES OF DISTRIBUTED FIBRE

6.4.1 OBJECTIVES OF THE TESTS

The main objectives of these tests are:

- The assessment of the maximum positive strain level when measuring with distributed optical fiber sensors.
- The demonstration of the capability to measure cyclic strain with distributed optical fiber sensors when subjected to periodical cyclic loads.

6.4.2 DESCRIPTION OF THE TESTS SAMPLES:

a) Dimensions of the CFRP coupons:

Composite coupons with dimensions 100 x 280 mm and 3 mm thickness. The coupons owns four hole drills, 10 mm diameter, to produce an non-uniform strain profile when subjected to axial load, tension and compression.

The next figure 6.4.1 show the coupons with the bonded taps.

Figure 6.4.1. Test coupons.

b) Number of samples and instrumentation:

Three samples have been tested. The instrumentation on each sample is described as follows:

- Sample 1: embedded distributed optical fiber, bonded distributed optical fiber and bonded FBG sensors.
- Sample 2: embedded distributed optical fiber and bonded strain gages.
- Sample 3: embedded distributed optical fiber and bonded FBG sensors.

Figure 6.4.2. Scheme of instrumentation on the test samples.

c) Implementation of the fibers.

The samples were manufactured from a composite panel in Airbus composite Lab. The fibers for each of the sample were located manually two layers from top surface. Surface ingress-egress fiber was selected and prepared so that no impact with the trimming process of the samples and compatible with composite manufacturing process.

6.4.3 LOAD SEQUENCE

The load sequence on sample 1 and 2 consisted of static cases with load steps of 20 kN from 0 to 90 kN and then 10 kN from 90 kN up to breakage.

The load sequence on sample 3 consisted of cyclic load cases according to the table 6.4.1

Table 6.4.1. Cyclic load in sample 3.

Dynamic test		
<i>Number of test</i>	<i>Frequency (Hz)</i>	<i>Spectrum load (kN)</i>
1	1	+/- 15 kN
2	1	+/- 25 kN
3	1	+50 kN/- 25 kN
4	1	+75 kN/0 kN
5	2.5	+50 kN/0 kN
6	4	+50 kN/0 kN
7	5	+50 kN/0 kN

Figure 6.4.3. Test samples installed in the test machine. (a) tension and (b) compression (Airbus Proprietary).

6.4.4 INSTRUMENTATION SYSTEMS

- a) Embedded distributed fiber and static interrogator unit.
- b) Bonded distributed fiber and dynamic interrogator
- c) Bonded FBG and equipment
- d) Strain gages sensors and system

The table 6.4.2 summarize the possible correlations between the different technologies performed on each sample.

Table 6.4.2. Correlation between the different strain technologies.

Nº of sample	Technology 1	Technology 2	Test conditions
Sample 1	Embedded distributed OFS	FBGs (2 sensors)	Static
	Bonded distributed OFS		
Sample 2	Embedded distributed OFS	Strain gages (2 sensors)	Static
Sample 3	Embedded distributed OFS	FBGs (2 sensors)	Dynamic

6.4.5 RESULTS OF THE TESTS

The next graphs are a pictorial summary of the results of the tests on the samples 1, 2 and 3.

- a) For sample 1:
 - Strain profile from the distributed fiber along the sample.
 - Detailed graph showing the strain gradients in the areas close to the holes.
 - Graph comparing the strain measurement with FBG and the closest distributed optical fiber segment.
- b) For sample 2:
 - Strain profile of the distributed fiber along the sample.
 - Graphs comparing the strain measurement with strain gauges and the closest distributed optical fiber segment.
- c) For sample 3:
 - Cyclic strain graphs in accordance with table 6.4.1 and comparing embedded distributed optical fiber with the bonded FBG sensor as detailed in figure 6.4.2.

6.4.5.1 SAMPLE 1, 2 AND 3.

Figure 6.4.4. Tensile tests on sample 1. Strain profile from distributed fiber.

Figure 6.4.5. Tensile tests on sample 1. Strain gradients measured close to the drill holes.

Figure 6.4.6. Tensile tests on sample 1. Local correlation between distributed fiber and FBG.

Figure 6.4.7. Tensile tests on sample 2. Strain profile from distributed fiber.

Figure 6.4.8. Tensile tests on sample 2. Local correlation between distributed fiber and strain gage 1.

Figure 6.4.9. Tensile tests on sample 2. Local correlation between distributed fiber and strain gage 2.

Figure 6.4.10. Tensile tests on sample 3. (a) 1Hz/±15 kN, (b)
Note: dotted line- distributed fiber, solid line-FBG

6.4.6 MAIN CONCLUSIONS OF THE TENSILE-COMPRESION TESTS

After the analysis of the results of the tests, these are their main conclusions:

1. The compatibility of the fiber and all the auxiliary materials used in the Manufacturing process of the composite samples and the demonstration of the resistance of the integration procedure of the embedded fibers; from Manufacturing to later Mechanical Tests.
2. The outputs of the sensors, distributed fiber, FBG and S/G, in the tests of the three samples have demonstrated:
 - a) The repeatability of the distributed fiber technology for the static tests on sample 1 and 2, not only on the central area where the strain field is uniform but also in the areas close to the drills. The repeatability is a consequence not just after comparing the results of the samples each other, but even when comparing the response of the segment fiber 1, 2 and 3 on the same sample.
 - b) The capability of distributed fiber, embedded or bonded, to measure the strain profile over the sample. As expected, the strain measurements for bonded and embedded fiber were very similar (differences lower than 2%).
 - c) The distributed results on sample 2, embedded fiber, are very useful to confirm the no degradation of the backscattering of the fiber when the process is done properly, just the same than when working with FBG sensors.
 - d) The excellent cross-correlation (within 2%) between distributed fiber and bonded FBG sensor in sample 1, and distributed fiber and strain gauges in sample 2. The comparison was done on the center area far away from the stress concentration.

- e) The capability of distributed optical fiber to measure strain level above 10000 microstrains. This level is more than enough for composite structural tests and flight tests.
 - f) The capability of distributed fiber to measure strain in dynamic conditions. The results were compared with FBG sensors and correlation was within 1-2%. Notice that the maximum frequency of these tests was established to 5 Hz but this limitation came from the sample and anti-buckling rig, and not from the distributed strain technology that can sample several times higher the value chosen in these tests.
3. To sum up, these tests constitute a new evidence on the capability of distributed optical fiber, bonded or embedded, to measure strain profiles up to more than 10000 microstrains, in static and dynamic conditions.

6.5 LARGE METALLIC STRUCTURAL PANEL: WING LOWER SKIN

6.5.1 OBJECTIVES OF THE TEST

The objective of this test is the demonstration of the capability of distributed sensing optical fiber to measure strain profiles in large metallic structures. This objective would include the following aspects:

- The robustness of the installation procedure for sensing distributed fiber on metallic structures (preparation, bonding and protection)
- The performance of the strain distributed optical fiber technologies in static test and the comparison with FBG sensors and classical strain gages.

6.5.2 DESCRIPTION OF THE TEST SPECIMEN

The test specimen consists of a wing lower skin section representative of a real aircraft (4000 x 1200 mm including grips) and made of aluminum alloy series 2000.

The test section is located vertically in a test machine according to figure 6.5.1.

The specimen is supported and aligned from both sides, left and right, to introduce properly tensile and compression loads.

The structural test is carried out at room temperature and without any environmental conditioning.

Figure 6.5.1. Test specimen configuration and optical fiber systems (Airbus Proprietary).

6.5.3 INSTRUMENTATION

The official strain measurement method in the test was surface bonded classical strain gages.

In addition, two optical fiber technologies were installed surface bonded:

- Distributed sensing optical fibre. The fibre was installed following a selected route to enable the measurement comparison with as many as possible local strain gages. The fibre was installed between two dummy ribs on the front and rear side (figure 6.5.2).
- FBG sensors. Two FBG sensors were also installed to include them in the comparison with S/G and distributed fiber. These sensors were located in positions 1 and 2 according to front side picture (figure 6.5.3).

Figure 6.5.2. General scheme of the test specimen (Airbus Proprietary).

The next two figures 6.5.3 and 6.5.4, -front and back sides- show the details of the sensing areas on the front and back side. The numbers painted in white colour on the structure are the reference numbers used for the designation of the different comparison areas (see table 6.5.1). These numbers are later on referred in this document – touching to locate- in the results of the tests.

Figure 6.5.3. Front side of the test specimen and sensing areas (Airbus Proprietary).

Figure 6.5.4. Back side of the test specimen and sensing areas (Airbus Proprietary).

The optical fiber interrogator units were located in front of the test specimen and separated by a transparent protection screen as the test was running.

6.5.4 IMPLEMENTATION OF THE FIBERS AND TOUCHING TO LOCATE.

The distributed optical fiber and FBG sensors were manually installed according to the procedure described in chapter 5.

After the installation, a distance correlation between distributed fiber distances and real location in the structure was carried out. The next table 6.5.1 sum-up the results of this task. The distances of the points used for strain gages correlation are in bolted in the table.

Table 6.5.1. Distributed optical fiber distances and correlation points –in bolted.

Position	Distance DF (m)	Position	Distance DF(m)	Position	Distance DF(m)	Position	Distance DF(m)
C1	2.97	C11	3.65	C21	4.42	C31	5.35
C2-DF S1 SG:E1093-016 FBG1	3.01	C12	3.74	C22- DF S7	4.59	C32	5.56
C3	3.07	C13- DF S4 SG:E1093-013	3.80	C23	4.64	C33- DF S10 SG:E1093-07	5.60
C4	3.18	C14	3.85	C24	4.67	C34	5.66
C5	3.25	C15- DF S5 SG:E1093-008	4.04	C25	4.77	C35	5.83
C6- DF S2 SG:E1093-103 & 101 FBG2	3.29	C16	4.08	C26- DF S8 SG:E1093-003	4.90	C36- DF S11 SG:E1093-012	5.87
C7	3.34	C17	4.12	C27	4.94	C37	5.91
C8	3.48	C18	4.22	C28	4.98	C38	6.13
C9- DF S3 SG:E1093-095	3.51	C19- DF S6 SG:E1093-006	4.33	C29	5.26	C39- DF S12 SG:E1093-017	6.18
C10	3.55	C20	4.37	C30- DF S9 SG:E1093-02	5.30	C40	6.23

6.5.5 TEST LOAD SEQUENCE

Two types of static tests were performed in the test specimen, tensile and compression tests:

The tests were actually repeated twice in identical conditions and the strain measurements were done during the up-load phase and down-load phase.

6.5.6 RESULTS OF THE TESTS

The results from the different technologies were compiled in a new file to compare microstrains versus load. The next figure summaries the followed process.

Figure 6.5.5. Process to compare the results of the different technologies.

In order to simplify the description of the results, the most representative graphs of the complete distributed fiber in tension and compression will be shown, and then different graphs comparing the microstrains measured by the different technologies versus load. Apart from the graphs, some detailed photos to illustrate the distances between the strain sensors will be reported as well. Since the results and conclusions are similar for all of areas, only the graphs related to comparison areas from 1 to 2 will be shown, since these two pointed areas included three technologies: strain gauges, distributed optical fiber and FBG sensors.

Figure 6.5.6. Tensile and compression tests –distributed strain profile vs time for the different load steps.

Figure 6.5.7. Position 1. Tensile test. Distributed fiber & S/G & FBG.

Figure 6.5.8. Position 2. Tensile test. Distributed fiber & S/G & FBG.

Figure 6.5.9. Position 1. Compression test. Distributed fiber & S/G & FBG.

Figure 6.5.10. Position 2. Compression Test. Distributed fiber & S/G & FBG.

Figure 6.5.11. Position 1 and 2. Tensile Test. Hysteresis Distributed fiber & S/G & FBG.

Figure 6.5.12. Position 2. Compression Test. Hysteresis. Distributed fiber & S/G & FBG.

6.5.7 MAIN CONCLUSIONS OF THE LARGE METALLIC STRUCTURAL TEST PANEL

After the analysis of the results, the main conclusions of these tests are disclosed as hereafter:

1. The installation procedure of the optical fiber including the preparation of the surface, bonding and protection of the sensors have demonstrated to be compatible with the environmental load and working conditions in the structural test.
2. This installation was also quite useful to demonstrate the reduction of time when installing distributed optical fiber instead of SG.
3. The distributed optical fiber measurements have demonstrated very good correlation in static cases with classical strain gages. The minor differences between the fibre measurements and electrical strain gages seem not to be in fact related with technology uncertainties but with different locations of the sensors which in turn involve variations in the stiffness of the structure.
4. The acquisition during load and unload has enabled to evaluate the hysteresis of distributed optical fiber in comparison with FBG and strain gages. Taking into

account the variation of the load in the static steps when increasing and decreasing, the hysteresis can be estimated lower than 1%.

5. The results of this test can be considered as a new evidence demonstrating the promising performance of the distributed fiber as strain monitoring technology and contribute to consider more seriously the possible application of this technology for structural test applications in future tests.

6.6 LARGE COMPOSITE STRUCTURAL TEST: UPPER SKIN HORIZONTAL TAIL PLANE (HTP).

6.6.1 OBJECTIVES OF THE TEST

The main objective of this test is to demonstrate the capability to measure strain profiles in large composite structures by distributed optical fiber sensors. This objective includes the demonstration of the following aspects:

- The robustness of the installation procedure for sensing distributed fiber and FBG sensors (preparation, bonding and protection) over the complete life of the structural test.
- The performance of the optical fiber technologies in different test conditions: static and dynamic test.
- The comparison between strain distributed fiber measurements with other strain monitoring technologies, FBG and S/G.

6.6.2 DESCRIPTION OF THE TESTS SPECIMEN

The test specimen is a complete composite horizontal tail plane, figure 6.6.1. It is supported on a test rig that ensures the proper loading of the specimen. The load introduction is done at room temperature and without any environmental conditioning.

Figure 6.6.1. Test specimen consisting of horizontal tail plane of commercial a/c (Airbus Proprietary).

6.6.3 TEST PHASES.

The four main phases of the tests were the static strength, the composite damage tolerance, the fatigue phase, and the damage tolerance & residual strength of metallic parts. These test phases are composed of many different cases.

The optical fiber acquisitions were performed during the static cases and the composite damage tolerance phase.

6.6.4 INSTRUMENTATION.

In terms of instrumentation, it can be distinguished, on the one hand, the classical foil strain gages as the official strain sensors of the test, and, on the other hand, optical fibre instrumentation, -distributed fiber and FBGs-, installed for strain monitoring development purposes.

All the sensors were surface bonded following the methodology explained in chapter 5.

6.6.5 STATIC LOAD CASES.

6.6.5.1 DISTRIBUTED SENSING FIBER

A long distributed optical fibre, in total more than 16 sensing meters, were surface bonded over the upper skin of the HTP, and between stringer 4 and 5 (figure 6.6.2).

This sensing fibre covers the length of the left upper skin, continue to the right upper skin and end up on an optical fibre connector that is in turn plugged into the interrogator units located a few meters close to the specimen.

Figure 6.6.2. Test Distributed sensing fiber over the upper skin, left & right side (Airbus Prop.)

This fiber was firstly used during the static cases and correlated versus selected strain gages. The selection of the proper S/G to be compared with the distributed sensing was done based on the proximity with the fibre and also taking into account the requirement of having similar direction. The next figure, 6.6.3, summarizes the four correlation points selected for the comparison during the static phase.

Figure 6.6.3. Correlation segments between distributed fiber and S/G (Airbus Proprietary).

Later on, during the damage tolerance phase, the distributed fiber was reduced only to the right side of the HTP.

6.6.5.2 FIBER BRAGG GRATING SENSORS.

These discrete sensors were additionally installed on the right upper skin and extremely close to the distributed sensing fibre. They were used during the damage tolerance phase. These FBG sensors were distributed in three fiber arrays, each one with five FBG sensors. The centre wavelength of each FBG are identified in the figure 6.6.4 and 6.6.5.

Figure 6.6.4. FBG sensors bonded on the right upper skin and close to distributed fiber (Airbus Proprietary).

Figure 6.6.5. Location of the three fibers containing five FBG each one (Airbus Proprietary).

The table 6.6.1 summarizes the position of the FBGs and the corresponding distributed sensing distances to be compared.

Table 6.6.1. Correlation between FBG sensors and distributed fiber distances.

Point	Distance for static OBR (mm)	FBG designation	Distance for dynamic OBR (gap due to sensor definition)
1	170	3.5 (CH3)	670
2	678	3.4 (CH3)	1178
3	1478	3.3 (CH3)	1978
4	2468	3.2 (CH3)	2968
5	3318	3.1 (CH3)	3818
6	3988	2.5 (CH2)	4488
7	4628	2.4 (CH2)	5128
8	5118	2.3 (CH2)	5618
9	5718	2.2 (CH2)	6218
10	6318	2.1 (CH2)	6518
11	6818	1.1 (CH1)	7318
12	7278	1.2 (CH1)	7778
13	7658	1.3 (CH1)	8158
14	8158	1.4 (CH1)	8658
15	8758	1.5 (CH1)	9258

6.6.6 LOAD SEQUENCE

As explained in the instrumentation section, the distributed fiber was interrogated during the selected static cases:

- Combination Torsion-Bending
- Hinge Moment
- Max negative bending
- Max Positive bending
- Negative torsion
- Rolling Manoeuvre

These load cases were acquired for several load levels respect to the limit load, -0.8, 1.2 and 1.5-, allowing even to observe the repeatability of the results.

Apart from the static cases, the distributed optical fiber and FBG sensors were interrogated during selected cycles belonging to damage tolerance phase. The damage tolerance phase was composed of a certain number of flight segments representatives of real flight conditions in the horizontal tail plane and in accordance with Certification Authorities. The plots shown in the result section depict some of these profiles for the positions where the FBGs were installed.

6.6.7 INSTRUMENTATION SYSTEMS

Three optical fiber equipment were used during these tests, figure 6.6.6:

- a) Bonded distributed fiber and distributed sensing interrogator for Static cases.
- b) Bonded distributed fiber and distributed sensing interrogator unit for cycling tests
- c) Bonded FBG and dynamic interrogator unit

Figure 6.6.6. Optical fiber equipment located close to the structural test (Airbus Proprietary).

6.6.8 RESULTS OF THE TESTS

6.6.8.1 STATIC CASES

For simplicity, we will show one graph for each static case. Then additional graphs are presented to the relative error of distributed fiber respect to the closest strain gages in the selected load cases.

Table 6.6.2. Results of selected static cases.

Graph identification	Type of load	Level load respect to LL
Graph 1	Combination Torsion-Bending	1.5
Graph 2	Max negative bending	1.5
Graph 3	Max Positive bending	1.5
Graph 4	Negative torsion	1.15
Graph 5	Rolling Manoeuvre	1.5

Figure 6.6.7. Strain vs Length. Combination load Torsion & Bending at 1.5 LL.

Figure 6.6.8. Strain vs Length. Max negative bending at 1.5 LL.

Figure 6.6.9. Strain vs Length. Max positive bending at 1.5 LL.

Figure 6.6.10. Strain vs Length. Max negative torsion at 1.15 LL.

Figure 6.6.11. Strain vs Length. Rolling manoeuvre at 1.15 LL.

Table 6.6.3. Strain gages used as reference for static cases.

Graph identification	Type of load	Strain gages used as reference
Graph 6	Combination Torsion-Bending	5111072x-o 5111017x-o 5111023x-o 5111080x-o <div style="border: 1px solid black; padding: 5px; margin-top: 10px;"> — 5110031X — 5111072X — 5111017X — 5111023X — 5111080X </div>
Graph 7	Max negative bending	
Graph 8	Max Positive bending	
Graph 9	Negative torsion	
Graph 10	Rolling Manoeuvre

Figure 6.6.12. Relative error distributed fiber vs S/G. Combination Load torsion- bending at 1.5 LL.

Figure 6.6.13. Relative error distributed fiber vs S/G. Max positive bending at 1.5 LL.

Figure 6.6.14. Relative error distributed fiber vs S/G. Max negative bending at 1.5 LL.

Figure 6.6.15. Relative error distributed fiber vs S/G. Max negative torsion at 1.15 LL

Figure 6.6.16. Relative error distributed fiber vs S/G. Rolling at 1.5 LL

6.6.8.2 DYNAMIC CASES

Several acquisitions were performed during the damage tolerance phase. This phase integrates load sequence blocks representative of real flight sessions. The next graphs, 6.6.17, 6.6.18, and 6.6.19, show the results of the FBG sensors from fiber 1, 2 and 3 during one of the block (1200 seconds approximately of duration each one).

Figure 6.6.17. Microstrain vs time. Fiber 1. FBG sensors A1 to A5.

Figure 6.6.18. Microstrain vs time. Fiber 2. FBG sensors B1 to B5.

Figure 6.6.19. Microstrain vs time. Fiber 3. FBG sensors C1 to C5.

The following graphs conform some snapshots from the continuous acquisitions done during the damage tolerance phase and including distributed fiber and FBG sensors. The blue line of the graph correspond to the distributed sensing fiber and goes from the central box up to the tip. The red points overlapped over the blue line correspond to the FBG sensors installed as close as possible to the distributed fiber as disclosed in figure 6.6.4.

Figure 6.6.20. Time stamp 0.72 min. Microstrain vs distance. Distributed fiber (blue line) and FBG (red points).

Figure 6.6.21. Time stamp 4.42 min. Microstrain vs distance. Distributed fiber (blue line) and FBG (red points).

6.6.9 MAIN CONCLUSIONS OF THE LARGE COMPOSITE STRUCTURAL TESTS

After the analysis of the results, these are the main conclusions of these tests:

1. The installation procedure of the optical fiber sensors (bonding and protection) have demonstrated the compatibility with the ambient and load conditions, static and dynamic cases, over the complete life of the structural test.
2. The comparison in the static cases between distributed optical fiber measurements with conventional strain gages have demonstrated good correlation (within 2%) in those locations where both technologies were installed close. The correlation values were different in function of static cases applied. The best correlation values correspond to positive and negative bending, and combination loads. The worst correlation values correspond to torsion and rolling. This difference is justified in the profile of the gradient of the strain with the distance, much more significant in the cases of rolling and torsion than bending for example.
3. In order to eliminate the influence of the distance between sensors, additional FBG sensors were installed previous to damage tolerance phase and as close as possible to the distributed fiber. The distributed optical fiber and the FBG sensors were interrogated during the dynamic cases enabling the comparison between both technologies. The correlation was within 1%. This last results serve to confirm the excessive distance between distribute fiber and strain gages as the main reason of the worst correlation values for rolling and torsion.
4. Definitely this test has enabled to demonstrate the performance and potential of distributed fiber for strain monitoring in large composite structural tests such as the horizontal tail plane or the wings. The same number of measurement points with conventional strain gages would require the installation of more than 150 aligned sensors with the substantial effort as for installation and the vast number of cables and acquisition channels.

6.7 COMPOSITE STRUCTURAL TEST PANELS AND BONDED REPAIR PATCHES.

6.7.1 OBJECTIVES OF THE TESTS

The main objectives of these tests are:

- The demonstration of the capability to embed repetitively and following a ruggedized procedure optical fiber sensors inside composite repair patches.
- The demonstration of the capability of the embedded optical fiber sensor to resist fatigue conditions in structural tests.
- The demonstration of the robustness of the installation procedure for bonding sensing distributed fiber (preparation, bonding and protection).
- The demonstration of the performance by the comparison between different technologies, optical fiber sensors and strain gages.

6.7.2 DESCRIPTION OF THE TESTS SPECIMEN

d) Geometry and dimension of the specimen.

The specimen consists of a square composite panel 985 x 985 mm. In the center of the panel a square repair patch, 327 x 327 mm was prepared and cured in Out of Autoclave (OoA) conditions.

The thickness on the center of the panel was 4.048 mm. The repair patch covers 2.5 mm thickness and 1.472 mm thickness for the parent material. The repair layers overlap inside the patch 6 mm. The panel was also reinforced in the edge up to 7.36 mm. The next figure 6.7.1 shows the details of the panel and the cross sections.

Figure 6.7.1. Geometry and dimensions of the test specimen.

6.7.3 NUMBER OF SAMPLES:

Three specimens were originally manufactured with the parent material and afterwards they were repaired by composite patch in the center area, figure 6.7.3.

Figure 6.7.2. Three composite samples manufactured from the parent material.

Figure 6.7.3. Three composite samples after performing the composite repair patch (Airbus Proprietary).

6.7.4 REPAIR PROCESS AND IMPLEMENTATION OF FBG SENSORS.

The main steps of the repair process are firstly the removing of the layers carefully and respecting the overlap defined by Stress point of view, then cleaning the surface and next the placement of the adhesive film. On the adhesive film, the artificial defects and the FBG

arrays were located. Next the different layers from the lowest and largest size were located up to complete the entire lay-up. Finally the vacuum bag was prepared, the thermal blankets positioned adequately and the cycle set up. After the curing cycle the panel was air cooled and the sensors were checked.

The next figure 6.7.4 constitutes a pictorial summary of the key phases of the repair and OFS implementation.

Figure 6.7.4. Pictorial summary of the key phases of the process, (a) parent panel, (b) replacing layers, (c) fiber arrays locations, (d) repair lay-up and (e) curing process. (Airbus Proprietary)

6.7.5 **INSTRUMENTATION:**

Two different technologies were implemented into the panels: FBG sensors and distributed fibre.

6.7.5.1 **EMBEDDED BRAGG GRATING SENSORS.**

The FBG sensors were introduced inside the bonded repair between adhesive film and repair material layers. A total of seven arrays were introduced. These arrays were grouped in four sets as detailed in the figure 6.7.4.

Figure 6.7.5. FBG arrays on the adhesive layer.

The FBG arrays were manufactured previously according to the preselected distances and encapsulated in a specific polyimide film to survive the curing procedure. The figure 6.7.6 depicts the details of the two types of FBG set installed in the corners of the repairs.

Figure 6.7.6 Configuration of the FBG arrays.

The number of sensors per array and their wavelength are indicated in the table 6.7.1:

Table 6.7.1. Details of the FBG sensors in the arrays/channels.

Channel	Number FBG	WC1 (nm)	WC2(nm)	WC3(nm)	WC4(nm)	WC5(nm)
1.1	4	1525,063	1535,013	1545,025	1554,925	
1.2	5	1525,175	1535,425	1545,325	1555,187	1564,961
2.1	3	1535,512	1545,202	1555,625		
3.1	4	1524,837	1535,342	1544,787	1554,801	
3.2	5	1525,537	1535,275	1545,75	1555,025	1564,837
4.1	4	1524,787	1535,062	1544,938	1555,013	
4.2	5	1525,037	1535,087	1545,263	1555,125	1564,787

6.7.5.2 BONDED DISTRIBUTED FIBER.

The distributed fiber was only bonded on the third panel. It was bonded on both sides of the panel and covering the areas with higher tension and compression. After the surface bonded the fiber was mechanically protected by the proper top coat. In function of the fiber access side, two configurations were defined:

- a) The configuration 1 resulting from the access to the panel through side A and that was used for the first 3000 cycles of the test.
- b) The configuration (2) when accessing the panel through side B and that was used from the 3000 cycles on.

CONFIGURATION 1

Figure 6.7.7. Bonded distributed fiber -Configuration 1.(a) side A and (b) side B. (Airbus Proprietary).

Table 6.7.2. Details of the segments and distances of the fiber configuration 1.

CONFIGURATION 1

Segment	Point	Distances (m)
Segment 1	(1)	3.001
Segment 3	Segment 2 (2)	3.169
	(3)	3.368
Segment 5	Segment 4 (4)	3.587
	(5)	3.813
Segment 7	Segment 6 (6)	4.013
	(7)	4.215
Transition Segment front to back side	Segment 8 (8)	4.404
	(9)	4.617
Segment 10	Segment 9 (10)	5.556
	(11)	5.719
Segment 12	Segment 11 (12)	5.919
	(13)	6.142
Segment 14	Segment 13 (14)	6.360
	(15)	6.583
Segment 16	Segment 15 (16)	6.800
	(17)	7.001
	(18)	7.183

Figure 6.7.8. Distributed strain profile for fiber configuration 1.

CONFIGURATION 2

Figure 6.7.9. Bonded distributed fiber -Configuration 2.(a) side A and (b) side B. (Airbus Proprietary).

Table 6.7.3. Details of the segments and distances of the fiber configuration 2.

CONFIGURATION 2			
POINT	DISTANCE (M)	SEGMENT	SIDE
1	1,16	S1	A
2	1,345	S1-S2	A
3	1,51	S2	A
4	1,551	A	A
5	1,598	S2	A
6	1,773	S2-S3	A
7	1,982	S3-S4	A
8	2,001	B	A
9	2,039	S5	A
10	2,218	S5-S6	A
11	2,399	S6	A
12	2,44	C	A
13	2,483	S7	A
14	2,645	S7-S8	A
15	2,819	S8	A
16	3,806	S9	B
17	3,972	S9-S10	B
18	4,001	S10	B
19	4,174	D	B
20	4,332	S11	B
21	4,38	S11-S12	B
22	4,571	S12	B
23	4,59	E	B
24	4,615	S13	B
25	4,817	S13-S14	B
26	4,957	S14	B

Figure 6.7.10. Distributed strain profile for fiber configuration 2.

6.7.6 TEST PHASES

The test specimen was installed in a special rig. It consists of an articulated rhombic frame where the panel is clamped by bolts over the edges. By this configuration, the panel is working at pure shear and the tension load on the test rig is converted into tension and compression in the two diagonals of the panel. The next pictures clarify these details.

Figure 6.7.11. Test panel in the test rig (Airbus Proprietary).

The specimens were subjected to a test campaign consisting of cyclic tests blocks combined with static load cases just before and after the cyclic block. The level of the loads for the third panel were the following:

- The static cases: load steps from 0 to 400 kN in 50 kN load interval (some cases up to 500 kN).
- The fatigue test: cycles from 0 to 300 kN at 0.15 Hz.

Ultrasonic inspections were performed periodically after each fatigue block.

6.7.7 RESULTS OF THE TESTS

As a general summing up, the results shown here includes only selected graphs for the last test panel. The objective is not to go in detail to the analysis of the results with the cycles but to illustrate the type of graphs that is possible to get with these technologies and some comparisons to demonstrate the equivalences between the measurements from different technologies. The selected graphs correspond to the followings cases:

- a) Example of embedded FBG results in panel 3 during static test.
- b) Example of FBG results in panel 3 during fatigue test.
- c) Example of distributed fiber results in panel 3 during static test.
- d) Example of distributed fiber results in panel 3 during fatigue test.
- e) Plot details of the buckling of the panel.

Figure 6.7.12. Example of embedded FBG results in panel 3 during static test. Compression lines (a,b and d). FBG sensor 1 and 2.

Figure 6.7.13. Example of embedded FBG results in panel 3 during static test. Compression lines (a,b and d). FBG sensors 3 and 4.

Figure 6.7.14. Example of embedded FBG results in panel 3 during static test. Tension lines (c,e). FBG sensors 1,2,3,4 and 5.

Figure 6.7.15. Example of embedded FBG results in panel 3 during fatigue test. Compression lines (a,b and d). FBG sensors 1 and 2.

Figure 6.7.16. Example of embedded FBG results in panel 3 during fatigue test. Compression lines (a,b and d). FBG sensors 3 and 4.

Figure 6.7.17. Example of embedded FBG results in panel 3 during fatigue test. Compression lines (c,e). FBG sensors 1,2,3,4 and 5.

Figure 6.7.18. Example of distributed fiber results in panel 3 static test. Configuration 1.

Figure 6.7.19. Example distributed fiber results in panel 3 fatigue test. Configuration 1.

Figure 6.7.20. Effect of panel buckling measured by bonded distributed fiber. Side A (Airbus Prop.)

Figure 6.7.21. Effect of panel buckling measured by bonded distributed fiber. Side B.(Airbus Prop.)

6.7.8 MAIN CONCLUSIONS OF THE BONDED COMPOSITE REPAIR TESTS

These are the main conclusions of these tests:

1. This test constitutes a clear evidence of the capabilities of optical fiber sensors to be embedded during the manufacturing process of bonded composite repair and therefore to be used for the online inspection of the repair, based on the strain changes when damage such as disbond are produced.
2. The adopted ingress-egress solution has demonstrated the enough robustness to resist the curing conditions. Furthermore, this solution has demonstrated the resistance to work during the static and fatigue cycles over the life of the structural test.
3. The survivability of the FBG sensors during these tests have demonstrated the excellence resistance of embedded optical fiber sensors against fatigue conditions.
4. This test has also demonstrated the capability of distributed optical fiber sensors to measure the strain profile over the structure in static and dynamic conditions.
5. The comparison between distributed optical fiber measurements with strain gages in static cases have demonstrated good correlation (within 1-2%) in those locations where both technologies are very close.
6. The comparison between the embedded and surface optical fiber sensors provide very reasonable results, taking into account that the buckling of the panel produces different strain profile on the surface and in the interior of the panel.
7. The results of the test have also enabled to demonstrate the potential of measuring the strain profile as for example to determine and study more in depth the buckling process in the structure.
8. In summary, the success in the manufacturing process and subsequent static/fatigue tests enable to consider seriously the use of embedded and surface bonded optical fiber sensors for the online inspection of composite repair patches and therefore to extend the use of the bonded composite repair concept further to the currently permitted by Aeronautical Certification Authorities.

6.8 ROOT JOINT WING COVER. FIBER AND CONNECTORS EMBEDDED.

6.8.1 OBJECTIVES OF THE TEST

These are the main objectives of this test:

- The demonstration of a successful methodology to embed optical fiber and connectors inside the composite manufacturing process.
- The demonstration of the optical performance of embedded optical fiber connector in structural tests.
- The correlation between strain distributed optical fiber measurements and numerical model.

6.8.2 DESCRIPTION OF THE TEST SPECIMEN

The test specimen consisted of a run out skin-stringer configuration representative of the wing lower cover in the area where it is jointed to center wing box (Figure 6.8.1). The specimens were manufactured at the Airbus Production Plant according to the following sequence: firstly the automatic tape layup & curing of the skin, secondly the co-bonding of the stringer to the skin, thirdly the secondary bonding between the thickness control material (TCM) and the stringer foot, and finally the clamping of the triform and buttstrap at the run-out end.

Figure 6.8.1. (a) Full aircraft, (b) Wing Lower Cover Root Joint Area, (c) Section A-A of Root Joint Area and (d) Test specimen (Airbus Proprietary).

A total of three specimens were manufactured and instrumented with embedded optical fibers. The first specimen was the calibration specimen, normally used only to determine the level of impact energies that are necessary to produce barely visible impact damage (BVID) in composite structures. The manufacturing process of this first specimen served to determine the methodology for embedding the fibers and connectors inside the material. The second and third specimens, referred hereinafter as the test specimens 1 and 2, were also instrumented by distributed optical fiber bonded on top of the stringer web. These two specimens were subjected to mechanical tests in the test facilities. Each specimen was introduced in a test rig and anti-buckling system to ensure the proper loads and stress distribution. The structural tests were performed at room temperature.

6.8.3 DESCRIPTION OF THE INTEGRATION OF EMBEDDED OPTICAL FIBER.

FBG sensors were installed in the test specimen under two scenarios: embedded between skin layers during production time, and surface bonded on the stringer foot and then hidden by the secondary bonded thickness control material.

6.8.3.1 EMBEDDED FBG SENSORS BETWEEN SKIN LAYERS DURING PRODUCTION TIME.

The first step consisted of the preparation of the FBG sensor arrays according to the dimensions of the part, the specification of the positions of the sensors in the structure and the requirements defined in chapter 5. Two configuration arrays were initially prepared, named as 1 and 2 and depicted in the Figure 6.8.2.

Figure 6.8.2. FBG arrays configurations and locations.

The second step was the assembly of the fibers to a special trimmable connector device. This trimmable connector was specially designed and manufactured in order to be compatible with all the steps in production and comprised the following elements (Figure 6.8.3):

- (a) A first connecting element (1) embedded in the composite material and located inside a resistant compartment. This first element comprises a precisely positioned optical ferrule (2) connected to a sleeve guide (3) for directing and centering with the optical fiber core coming from external interrogator unit.
- (b) A protective element (4) that makes the first connecting element perfectly sealed during the manufacture process, and thus preventing the intrusion of resin into the first connection element. This protection is withdrawn once the structure is cured and before the trimming operation.
- (c) A second connection element (5) that is fit to the first connection element after removing the previous protective element when the sensors need to be interrogated.
- (d) Finally a mechanical protection joined to the second connecting element, and whose purpose is to protect mechanically the first and second connection elements in a way that any mechanical effort (vibration, shock, etc.) is absorbed by this protective element.

Figure 6.8.3. FBG arrays configurations and locations (Airbus Proprietary).

The fibers with the connectors were installed in production time during the automatic tape lay-up process (ATL). The precise location of the fibers and sensors inside the laminate were done taking as reference two special marks purposefully made on manufacturing tools, one in the axial direction and the other one transversally. These marks were in turn referenced to an additional permanent mark done on all the FBG arrays. After the location of the fibers on the pre-preg, the rest of the layers were laid up to complete the skin stacking. Finally the fresh skin was placed in the autoclave to complete the cure process according to the corresponding cycle conditions.

Figure 6.8.4 shows the location of the optical fiber connectors during different times of the process sequence; firstly on the lay-up, secondly before being covered by composite layers, thirdly covered by layers, fourthly after curing and finally after trimming process.

Figure 6.8.4. Integration of the optical fiber connector in Production (Airbus Proprietary).

6.8.3.2 SURFACE BONDED FIBER SENSORS ON THE STRINGER FOOT

Two FBG fibers were surface bonded on the stringer foot. The configuration of the FBG sensors coincides with the configuration 1 defined previously for the embedded fibers. After the bonding process they were covered by a TCM and finally sandwiched between metallic butt straps.

Initially this configuration of the fibers presented two important issues to solve, on the one hand the possible breakage of the fiber during manufacturing tasks when installing the TCM on the transition points of the fiber, and on the other hand there was also a risk of distortion of the FBG peaks by the transversal stress once the set is complete assembled. In order to deal with these two issues and to ensure the effectivity of the fiber sensors in the test, a special solution was prepared and accepted by Stress and Manufacturing. It consisted of the preparation of two precise grooves on the stringer foot during the curing time of the stringer to locate the fibers. These grooves were made by means of two calibrated metallic wires that were selected by the results in previous manufacturing trials done in the Composite Lab. Once the grooves were formed, the FBG arrays were installed and bonded inside, then the TCM were bonded to the stringer foot and finally the metallic buttstrap and triform were adjusted, drilled and fitted by the fasteners. External fibers were protected by optical fiber cable. Figure 6.8.5 summaries the complete process followed for the installation of these two fibers on the stringer foot.

Figure 6.8.5. Integration of the surface bonded fiber sensors (Airbus Proprietary).

6.8.3.3 BONDED DISTRIBUTED FIBER IN MANUFACTURING PROCESS

The distributed fiber was bonded on the edge of the stringer web (figure 6.8.6).

Figure 6.8.6. Distributed fiber on the top of the stringer.

A fiber length of 1.5 m was bonded on the top of the stringer web. For the specimen 1, the fiber crossed an impact point with an important delamination introduced in the panel for impact sessions. As it will be appreciated in the results, this impact produce clear distortion of the strain profile.

In the specimen 2, the distributed fiber was bonded in round trip in such a way that two segments of the same fiber was monitored on the top of the stringer web. This configuration was done to obtain double of data in the same area.

6.8.3.4 CLASSICAL STRAIN GAUGES ON THE METALLIC PLATES AND STRINGER FOOT SURFACE

In addition to the described optical fiber sensors, strain gauges were also surface bonded on the metallic triform, buttstrap and on the composite skin. These sensors were the instrumentation used by Stress to ensure and control the proper introduction of the load in the specimen during the structural test. Figure 6.8.7 displays the sections and the plan view with the locations of the strain gauges and FBG sensors in the stringer run out area.

Figure 6.8.7. Locations of the strain gauges and FBG sensors in the stringer run out area.

6.8.4 TEST CASES AND LOAD SEQUENCE

During the structural test, the test specimens 1 and 2 were subjected to the following load sequence:

- Static cases of tension and compression up to Limit Load (LL) at 650 kN and -300 kN respectively.
- Fatigue test campaign. This campaign was composed of 10 fatigue blocks reaching a maximum load of 650 kN and minimum load of -140 kN.
- Final tension up to Limit Load (LL) and compression tests beyond Ultimate Load (UL) up to -610 kN.

6.8.5 INSTRUMENTATION SYSTEMS AND OPTICAL ACQUISITIONS

Embedded and bonded FBG sensors and equipment.
Bonded distributed fiber and equipment.

As mentioned before the two test specimens, 1 and 2, were monitored with optical fiber. For the specimen 1, the test cases acquired with optical fibers were, before fatigue, tension and compression up to Limit Load (LL), and after fatigue, compression up to Ultimate Load (UL). For the specimen 2, the acquisitions were done after the fatigue phase and corresponded to tensile static test up to UL and compression static test up to load higher than UL.

6.8.6 OPTICAL FIBER SENSORS RESULTS

The results are divided in FBGs and distributed sensing fiber.

6.8.6.1 FBG RESULTS.

Since the main objective of these tests are to demonstrate the capability to integrate the fibers in Production and the performance of the fibers/connectors during the tests, only the results of the tests specimen 1 will be shown here.

Figure 6.8.8. Specimen 1-Root joint -Before fatigue -tensile LL- Channel A

Figure 6.8.9. Specimen 1-Root joint -Before fatigue -tensile LL- Channel B.

Figure 6.8.10. Specimen 1-Root joint -Before fatigue -tensile LL- Channel C

Figure 6.8.11. Specimen 1-Root joint -Before fatigue -tensile LL- Channel D

Figure 6.8.12. Specimen 1-Root joint -After fatigue -compression UL- Channel A.

Figure 6.8.13. Specimen 1-Root joint -After fatigue -compression UL- Channel B.

Figure 6.8.14. Specimen 1-Root joint -After fatigue -compression UL- Channel C.

Figure 6.8.15. Specimen 1-Root joint -After fatigue -compression UL- Channel D.

Figure 6.8.16. Specimen 1- FBGs embedded on stringer foot-tensile & compression after fatigue.

6.8.6.2 DISTRIBUTED FIBER RESULTS.

Firstly the results correspond to the tension and compression tests on specimen1 up to LL. The measurements of the fiber are compared with the prediction obtained by FEA (Finite Element Analysis) model. As it can be seen the correlation is very good for both type of solicitations, not only as for the strain profile but also even as for the quantitative values.

Figure 6.8.17. Specimen 1- Distributed measurement with optical fiber – tension up to LL.

Figure 6.8.18. Specimen 1- Distributed measurement optical fiber – Compression up to LL

Next figure 6.8.18, correspond to the specimen 2, where the same fiber was installed in duplicity. The results in both ways of the fiber were identical and very similar to the model prediction as it can be seen.

Figure 6.8.19. Specimen 2- Distributed measurement optical fiber – Tension up to LL

6.8.7 MAIN CONCLUSIONS OF THE ROOT JOINT WING COVER TESTS

These are the main conclusions of these tests:

1. Successful methodology to integrate embedded optical fiber sensors and connectors for strain monitoring purposes into a composite structural part representative of the root joint area of the wing lower cover of a real aircraft. The process was prepared and carried out under the main premise of being compatible in the production phase and ensuring the subsequent performance of sensors and connectors in the structural test phase. It can be considered one of the first, if not the first, demonstration of the integration of embedded optical fiber sensors in a composite wing structure during production in an aeronautical composite plant.
2. The trimmable optical fiber connectors were specifically designed and manufactured for this real application and have enabled the trimming of the structure after autoclave curing process and the robust interrogation of the embedded FBG during the structural tests.
3. The analysis of the strain, load transference and curvature [71] have demonstrated good correlation between fiber sensors and electrical strain gauges in those locations where they are installed nearby, and also the consistency of optical fiber sensor results, FBG and distributed fiber, after being compared with the predictions from an FEA model carried out for the test.
4. To sum up, the methodology and results of these tests can be considered strong evidence of the satisfactory integration of embedded optical fiber sensors inside the automatic tape layout process during production and definitely contributes to the serious consideration of embedded optical fiber sensors with structural health monitoring purposes for serial composite structural test applications in the near future.

6.9 LOAD MONITORING BY FBG SENSORS

6.9.1 BACKGROUND AND OBJECTIVE

New aircraft programs always require the surveillance during first flight test campaign of the structural loads such as shear, bending, torque or rolling moments in selected parts of the a/c such as the wings or the tail surfaces and because of the effect of aerodynamic or inertia external loads.

This load monitoring process is done indirectly by strain monitoring sensors, traditionally classical strain-gage bridges, installed in selected areas and locations on the a/c, and avoiding stress concentrations. The figure below, 6.9.1, is an example of the strain bridges that need to be installed for the load measurements in the Horizontal Tail Plane (HTP).

Figure 6.9.1. Example of the strain gauge bridges to install for the load monitoring in HTP box.

The conversion from strain to load is done by a special methodology, also known as the Skopinski method, requiring a serial of on-ground load test calibration cases before first flight and delivering some equations wherein the load in a given structural member is expressed as a function of the strain bridges readings.

This method was developed by T.H.Skopinski from the NACA in the 50's and has been used by all aircraft manufacturers ever since [72].

In this section is given an overview of the work done to demonstrate the capability of strain optical fiber sensors, in particular FBG, to monitor flight loads in a composite component of commercial a/c. Details of the installations of the sensors, on-ground calibration tests, processing of the calibration results and measurements in flights are briefly discussed.

6.9.2 STRUCTURE AND PROCEDURE.

The structure selected was the horizontal tail plane (HTP) of commercial a/c. Details of the installations of the sensors, on-ground calibration tests, processing of the calibration results and measurements in flights are briefly discussed in this section.

This is a brief summary of the main steps were followed:

1. Installation of the FBG sensors during the final assembly line (FAL).
2. Execution of on-ground load calibration cases.
 - a. Acquisition of calibration result matrixes.
 - b. Determination of the influence matrix.
 - c. Determination of load measurement equations (shear, bending or torsion)
3. Completion of the optical fiber installation inside the a/c.
4. Performing flight tests and use of load measurement equations to determinate flight loads in flight.

6.9.2.1 FBG INSTALLATION IN HTP

A total of 26 FBG sensors were installed in the HTP, in the left internal box formed by front and rear spar, upper and lower skin, and between rib 5 and 6. All the sensors were surface bonded and some other bonded on composite plates for temperature compensation. The sensor outputs are used to determine bending moment (M_x), shear (F_z) and torsion moment (M_y). Note that rolling moment (M_r) was not considered in this study.

Figure 6.9.2. Moments and forces in the a/c.

The next table, 6.9.1, compiles flight parameters, type of load, location of the sensors in the internal box, wavelength centers and acquisition channel in the multiplexer optical interrogator.

Table 6.9.1. List of parameters and FBG sensors in HTP box.

Parameter number	Load	Location	FBGs (nm)	Fiber /MUX channel
50510000	BENDING	Front Spar (Up)	1530	Channel 9
		Front Spar(Low)	1560	
50510010	SHEAR	Front Spar (-)	1545	Channel 13
		Front Spar (+)	1575	
50510020	TORSION	Upper close to FS (-)	1530	Channel 15
		Upper Skin close to FS (+)	1560	
50510030	BENDING	Rear Spar(Low)	1545	Channel 4
		Rear Spar(Up)	1575	
50510040	SHEAR	Rear Spar(+)	1530	Channel 14
		Rear Spar(-)	1560	
		Rear Spar(-)	1545	Channel 5 (Spa.)
		Rear Spar(+)	1575	
50510050	TORSION	Upper Skin close to RS(-)	1545	Channel 6
		Upper Skin close to RS(+)	1575	
50510060	BENDING	Front Spar (Up)	1545	Channel 11
		Front Spar(Low)	1564	
50510070	SHEAR	Front Spar (+)	1530	Channel 12
		Front Spar(-)	1560	
50510080	BENDING	Rear Spar (Up)	1530	Channel 2
		Rear Spar(Low)	1560	
50510090	TORSION	Lower Skin close to RS(-)	1530	Channel 7
		Lower Skin close to RS(+)	1560	
00000001	TEMPERATURE	Upper Skin	1530 (CP1)	Channel 16
			1545 (CP2)	

The figure below, 6.9.3, shows an example of the installation of the FBG sensors on front spar.

Figure 6.9.3. (a) Scheme of the FBG sensors on the front spar (b) Photo of the sensors on the front spar (Airbus Proprietary).

6.9.2.2 EXECUTION OF ON-GROUND LOAD CALIBRATION CASES.

As explained before, the calibration process requires firstly from the assembly of the test specimen (HTP) on a special test rig, and then the introduction of a serial of on-ground calibration tests. These calibration tests will enable to determine the linear combination coefficients that applied to the FBG measurements will calculate the loads during flight.

For a high accuracy in the load results, a high number of calibration cases has to be introduced. These are the cases introduced for the HTP box application:

- 6 symmetric load cases on the HTP box on LH and RH sides (LHS1 to LHS6)
- 6 asymmetric cases on the HTP box on LH side (LHL1 to LHL6)
- 6 asymmetric load cases on the HTP box on RH side (LHR1 to LHR6)
- 3 symmetric load cases on the HTP elevator on LH and RH side (LHE1 to LHE3)

Each load case is defined by the positions of the load points on the HTP. Load points in turn define the lever arms that are used to convert the load applied into bending/torque quantities measured at the loads sections.

Figure 6.9.4. Position of the symmetrical load cases.

Every calibration load case is part of the complete spectrum in the aircraft life and therefore the combination of the load cases can reproduce the load spectrum in the life aircraft. The level of the load in the calibration cases is not more than 10-15% of the limit load.

The next table, 6.9.2., summarizes the HTP load cases:

Table 6.9.2. Summary of the load calibration cases for HTP.

Case number	Case name	Side/Symmetry	Load location
1	LH02L	Left	HTP box
2	LH02R	Right	HTP box
3	LH02S	Symmetric	HTP box
4	LH03L	Left	HTP box
5	LH03R	Right	HTP box
6	LH03S	Symmetric	HTP box
7	LH01L	Left	HTP box
8	LH01R	Right	HTP box
9	LH01S	Symmetric	HTP box
10	LH04L	Left	HTP box
11	LH04R	Right	HTP box
12	LH04S	Symmetric	HTP box
13	LH05L	Left	HTP box
14	LH05R	Right	HTP box
15	LH05S	Symmetric	HTP box
16	LH06L	Left	HTP box
17	LH06R	Right	HTP box
18	LH06S	Symmetric	HTP box
19	LHE1S	Symmetric	HTP elevator
20	LHE1S	Symmetric	HTP elevator
21	LHE1S	Symmetric	HTP elevator

The loads in these cases are introduced point by point in specific locations and in consecutive steps. The level of each step is defined by a percentage of the maximum calibration load: 0%, 20%, 40%, 60%, 80%, 100%, 80%, 40%, 0%.

Figure 6.9.5. Different steps for each load case.

The calibration test cases enables to get the incremental loads from a well-known reference condition, as the calibration will not deliver absolute values. In order to get the absolute values, reference conditions will be defined and all the readings will be adjusted to this reference conditions.

6.9.2.2.1 ACQUISITION OF CALIBRATION RESULT MATRIXES.

After all load cases are applied, plots as the example in figure 6.9.6 (case 3- parameter 50510060) are presented for each FBG sensor that in turn corresponds with a specific parameter that is also associated with a type of load.

Figure 6.9.6. Example of the graph obtained after acquisition of a load calibration tests on a particular position (bending sensors).

The level of the strain provided by each sensor in each of the steps of the load case allows to determine the calibration result matrix of the load case. The table 6.9.3 corresponds to the realization of the matrix for the case LH2S (table 6.9.2) showing only four parameters: 50510000, 50510010, 50510020 and 50510030.

Once the matrixes are completed (in total 21 matrixes) is necessary to determine for each parameter and load case the influence coefficients (figure 6.9.7). The influence coefficient correspond to the slope (A) of the linear equation $Y=A.X + B$. This equation is obtained by least square procedure over all load steps (table 6.9.3).

Table 6.9.3. Example of the graph obtained after acquisition of a load calibration test on a particular position (bending sensors).

					Load Case: LH2S										
Parameter	Location	Unit	Load Step									Slope Calculation			
			0%	20%	40%	60%	80%	100%	80%	40%	0%	A	B	corr. Koef.	
	nominal Load	daN	0	800	1600	2400	3200	4000	3200	1600	0				
LH2S	real calibrated load lh	daN	39,0	799,0	1605,0	2399,0	3190,0	3992,0	3202,0	1597,0	100,0				
50510000--	LHHTP, FS, bending 1														
	up	µs	11	-20	-51	-85	-119	-151	-119	-54	11				
	lw	µs	3	28	60	92	119	150	122	62	3				
	difference	µs	8	-48	-111	-177	-238	-301	-241	-116	8	-7,9626E-02	1,5142E+01	0,999737	
50510010--	LHHTP, FS, shear 1														
	(+)	µs	11	20	25	34	43	50	43	28	11				
	(-)	µs	9	-4	-21	-40	-59	-77	-59	-24	9				
	difference	µs	2	24	46	74	102	127	102	52	2	3,2220E-02	-1,7996E+00	0,998470	
50510020--	LHHTP, FS, torsion 1														
	(+)	µs	8	3	-6	-16	-27	-36	-27	-6	8				
	(-)	µs	16	57	101	144	192	240	198	101	16				
	difference	µs	-8	-54	-107	-160	-219	-276	-225	-107	-8	-6,9087E-02	1,0341E+00	0,999079	
50510030--	LHHTP, RS, bending 1														
	up	µs	5	-15	-47	-78	-108	-138	-111	-49	5				
	lw	µs	14	39	69	96	122	154	126	69	14				
	difference	µs	-9	-54	-116	-174	-230	-292	-237	-118	-9	-7,2975E-02	3,7743E-02	0,999426	

Calibration Results - Load Case n										
Calibration Results - Load Case										
Calibration Results - Load Case 2										
Calibration Results - Load Case 1										
		Load step [j]								
		0,0	0,2	0,4	0,6	...	0,0			
calibration Load		$F_{1,1}$	$F_{1,2}$	$F_{1,3}$	$F_{1,4}$		$F_{1,j}$	Influence coefficient	Influence coefficient	Influence coefficient
Parameter number	1	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$	$a_{1,4}$		$a_{1,j}$	$\mu_{1,1}$	$\mu_{2,1}$	
	2	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$	$a_{2,4}$		$a_{2,j}$	$\mu_{1,2}$	$\mu_{2,2}$	
	3	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$	$a_{3,4}$		$a_{3,j}$	$\mu_{1,3}$	$\mu_{2,3}$	
	...	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	m	$a_{m,1}$	$a_{m,2}$	$a_{m,3}$	$a_{m,4}$		$a_{m,j}$	$\mu_{1,m}$	$\mu_{2,m}$	

Figure 6.9.7. Collection of the matrixes obtained after the load case application.

The next graph, 6.9.8, is an example of the linear behavior of different parameters (FBG outputs versus load) and the influence coefficient as the slope of the graphs.

Figure 6.9.8. Example of the linear behavior of a flight test parameter versus load.

Once the coefficient matrix for each load case and each parameter are obtained, the next step is to organize these coefficients in a different matrix called influence matrix of load calibration in which there are so many columns as parameters (n) and rows as load cases (m).

Table 6.9.4. Example of influence matrix of load calibration cases.

	parameters					
load case	p1	p 2	p 3	p 4	...	p n
LC 1	μ_{11}	μ_{12}	μ_{13}	μ_{14}	...	μ_{1n}
LC 2	μ_{21}	μ_{22}	μ_{23}	μ_{24}	...	μ_{2n}
LC 3	μ_{31}	μ_{32}	μ_{33}	μ_{34}	...	μ_{3n}
LC 4	μ_{41}	μ_{42}	μ_{43}	μ_{44}	...	μ_{4n}
...	...	...	...	...	...	
LC m	μ_{m1}	μ_{m2}	μ_{m3}	μ_{m4}	...	μ_{mn}

This last matrix is used for the calculation of the beta- coefficients of the Skopinski equations.

6.9.2.2.2 DETERMINATION OF THE SKOPINSKI EQUATIONS.

With the influence matrix, example in table 6.9.4, is possible to compose the load measurement system equations for shear, bending and torsion:

$$[V_{sm}=\text{shear}]=[\mu_{smn}] \times [\beta_{sn}] \quad (6.9.1)$$

$$\begin{bmatrix} V_{S1} \\ V_{S2} \\ \vdots \\ V_{Sm} \end{bmatrix} = \begin{bmatrix} \mu_{s11} & \cdots & \mu_{s1n} \\ \vdots & \ddots & \vdots \\ \mu_{sm1} & \cdots & \mu_{smn} \end{bmatrix} \times \begin{bmatrix} \beta_{s1} \\ \beta_{s2} \\ \vdots \\ \beta_{sn} \end{bmatrix} \quad (6.9.2)$$

In this equation V_{sm} and $\mu_{sm,n}$ are data and therefore β_{sn} coefficients can be determined by isolating in this equation.

$$[V_{Bm}=\text{load x lever arm bending}]=[\mu_{Bmn}] \times [\beta_{Bn}] \quad (6.9.3)$$

$$\begin{bmatrix} V_{B1} \\ V_{B2} \\ \vdots \\ V_{Bm} \end{bmatrix} = \begin{bmatrix} \mu_{B11} & \cdots & \mu_{B1n} \\ \vdots & \ddots & \vdots \\ \mu_{Bm1} & \cdots & \mu_{Bmn} \end{bmatrix} \times \begin{bmatrix} \beta_{B1} \\ \beta_{B2} \\ \vdots \\ \beta_{Bn} \end{bmatrix} \quad (6.9.4)$$

In this equation V_{Bm} and $\mu_{Bm,n}$ are data and therefore β_{Bn} coefficients can be determined by isolating in this equation.

$$[V_{Tm}=\text{load x lever arm torsion}]=[\mu_{Tmn}] \times [\beta_{Tn}] \quad (6.9.5)$$

$$\begin{bmatrix} V_{T1} \\ V_{T2} \\ \vdots \\ V_{Tm} \end{bmatrix} = \begin{bmatrix} \mu_{T11} & \cdots & \mu_{T1n} \\ \vdots & \ddots & \vdots \\ \mu_{Tm1} & \cdots & \mu_{Tmn} \end{bmatrix} \times \begin{bmatrix} \beta_{T1} \\ \beta_{T2} \\ \vdots \\ \beta_{Tn} \end{bmatrix} \quad (6.9.6)$$

In this equation V_{Tm} and $\mu_{Tm,n}$ are data and therefore β_{Tn} coefficients can be determined by isolating in this equation.

Once $[\beta_{sn}]$, $[\beta_{Bn}]$ and $[\beta_{Tn}]$ are determined, Skopinski equations for shear, bending and torsion are obtained by expressing linear combination of strain measurements (μ_{mn} -obtained in flight) affected by beta coefficients:

$$V_s = \beta_{s1} \cdot \mu_1 + \beta_{s2} \cdot \mu_2 + \dots + \beta_{sn} \cdot \mu_n \quad (6.9.7)$$

$$V_B = \beta_{B1} \cdot \mu_1 + \beta_{B2} \cdot \mu_2 + \dots + \beta_{Bn} \cdot \mu_n \quad (6.9.8)$$

$$V_T = \beta_{T1} \cdot \mu_1 + \beta_{T2} \cdot \mu_2 + \dots + \beta_{Tn} \cdot \mu_n \quad (6.9.9)$$

The parameters (1-n) to combine for each of the load, V_S , V_B , and V_T are based on the experience and in most of the cases the final combination is confirmed after by trial and error process.

Figure 6.9.9. Summary of the process to obtain loads in flight.

6.9.2.3 COMPLETION OF THE OPTICAL FIBER INSTALLATION INSIDE THE A/C.

After the calibration test in the HTP, this component was finally installed with the rest of the a/c. The completion of the optical fiber sensor installation requires two additional tasks:

- a) The routing of the single optical fibers cable connecting the FBG sensors, already installed in left side HTP, with interrogator unit located in the cabin. These cables shall cross the bulkhead.
- b) Installation of the interrogator unit and MUX inside the a/c and connection the optical fiber cables to the interrogation system.

The next scheme is an illustration of the type of optical fiber connectors used in the installation:

- MIL 38999 for the connection of the fibers in the HTP into a common bundle to cross the bulkhead.
- FC/APC, as the individual connectors used to connect the fibres to the MUX channels.

Figure 6.9.10. Scheme of the optical fiber connectors and their positions in the optical installation.

6.9.2.4 RESULTS OF THE TESTS

6.9.2.4.1 CALIBRATION TESTS

As explained in the section 6.9.2.2, a total of 21 cases were introduced in order to determine the matrix coefficient. For simplicity, the graphs shown here correspond to the acquisition of all parameters, 00 to 90, for one case (LH02L). The acquired data from the rest of the cases are compiled and shown directly in the influence matrix (slopes). On that basis can be obtained later the matrix coefficient that will be used inside the Skopinski equations to determine the flight loads based on the online measurements from the strain sensors (FBG).

Graphs for calibration case LH02L. Parameters 50510000 to 50510090.

Figure 6.9.11. Calibration case LH02L. Parameters 50510000 to 50510050.**Table 6.9.5.** Compilation of the results for 1 cases (LH2L as example)

Parameter	Location	Unit	Load Step									Slope Calculation		
			0%	20%	40%	60%	80%	100%	80%	40%	0%	A	B	corr. Koef.
LH2L	nominal Load	daN	0	800	1600	2400	3200	4000	3200	1600	0			
		daN	100,0	801,0	1598,0	2396,0	3208,0	4000,0	3201,0	1588,0	99,0			
50510000--														
FBG	up	$\mu\epsilon$	9	-15	-47	-78	-109	-141	-111	-50	9			
FBG	lw	$\mu\epsilon$	8	33	62	90	117	145	116	59	8			
FBG	difference	$\mu\epsilon$	-1	48	109	168	226	286	227	109	-1	7,3595E-02	-8,8284E+00	0,999906
50510010--														
FBG	(+)	$\mu\epsilon$	16	23	28	35	40	47	38	25	16			
FBG	(-)	$\mu\epsilon$	14	0	-17	-33	-51	-65	-52	-18	14			
FBG	difference	$\mu\epsilon$	2	23	45	68	91	112	90	43	2	2,8317E-02	-5,7122E-01	0,999647
50510020--														
FBG	(+)	$\mu\epsilon$	13	3	-7	-14	-25	-35	-26	-6	13			
FBG	(-)	$\mu\epsilon$	21	62	108	154	202	253	205	105	21			
FBG	difference	$\mu\epsilon$	8	59	115	168	227	288	231	111	8	7,1356E-02	2,8790E-01	0,999552
50510030--														
FBG	up	$\mu\epsilon$	8	-18	-48	-79	-112	-142	-111	-50	8			
FBG	lw	$\mu\epsilon$	17	41	72	100	129	158	129	70	17			
FBG	difference	$\mu\epsilon$	9	59	120	179	241	300	240	120	9	7,4713E-02	8,3860E-01	0,999941
50510040--														
FBG	(+)	$\mu\epsilon$	14	13	13	13	10	10	12	13	14			
FBG	(-)	$\mu\epsilon$	6	-10	-31	-52	-72	-94	-75	-35	6			
FBG	difference	$\mu\epsilon$	8	23	44	65	82	104	87	48	8	2,4747E-02	5,3923E+00	0,996887
50510050--														
FBG	(+)	$\mu\epsilon$	5	-36	-84	-135	-185	-233	-187	-85	5			
FBG	(-)	$\mu\epsilon$	14	30	52	67	91	111	88	45	14			
FBG	difference	$\mu\epsilon$	-9	-66	-136	-202	-276	-344	-275	-130	-9	-8,6103E-02	1,7758E+00	0,999596
50510060--														
FBG	up	$\mu\epsilon$	11	-8	-30	-53	-74	-94	-75	-34	11			
FBG	lw	$\mu\epsilon$	14	33	54	77	99	120	97	52	14			
FBG	difference	$\mu\epsilon$	3	41	84	130	173	214	172	86	3	5,4388E-02	-2,0124E+00	0,999795
50510070--														
FBG	up	$\mu\epsilon$	10	-4	-22	-40	-58	-77	-59	-24	10			
FBG	lw	$\mu\epsilon$	20	30	41	55	68	79	68	41	20			
FBG	difference	$\mu\epsilon$	-10	-34	-63	-95	-126	-156	-127	-65	-10	-3,7670E-02	-5,1063E+00	0,999493
50510080--														
FBG	up	$\mu\epsilon$	8	-18	-47	-75	-103	-130	-105	-47	8			
FBG	lw	$\mu\epsilon$	16	46	77	111	146	179	147	80	16			
FBG	difference	$\mu\epsilon$	8	64	124	186	249	309	252	127	8	7,7459E-02	1,2098E+00	0,999745
50510090--														
FBG	(+)	$\mu\epsilon$	16	58	102	150	198	245	199	103	16			
FBG	(-)	$\mu\epsilon$	6	-6	-17	-27	-39	-50	-38	-15	6			
FBG	difference	$\mu\epsilon$	-10	-64	-119	-177	-237	-295	-237	-118	-10	-7,2899E-02	-3,1529E+00	0,999898

Table 6.9.6. Result of the Influence matrix for all -21- cases.

Load cases	50510000	50510010	50510020	50510030	50510040	50510050	50510060	50510070	50510080	50510090
LHL01	0.08395	0.06967	0.03386	0.06486	-0.07193	-0.02770	0.04418	-0.09700	0.07095	0.02137
LHL02	0.07360	0.02832	0.07136	0.07471	0.02475	-0.08610	0.05439	-0.03767	0.07746	-0.07290
LHL03	0.13209	0.05122	0.02262	0.12752	-0.02960	-0.02168	0.10518	-0.07280	0.13680	0.03375
LHL04	0.12340	0.01861	0.05302	0.13596	0.05171	-0.06805	0.11343	-0.02559	0.14138	-0.04674
LHL05	0.19284	0.02994	0.00935	0.20774	0.02781	-0.01249	0.18445	-0.04289	0.21975	0.04794
LHL06	0.18901	0.00703	-0.03433	0.21652	0.08887	-0.04655	0.19088	-0.00862	0.22362	0.01559
LHS01	0.08683	0.07477	0.02939	0.06144	-0.06430	-0.02718	0.04585	-0.10378	0.06523	0.00723
LHS02	0.07963	0.03222	0.06909	0.07298	0.02945	-0.08881	0.06836	-0.04244	0.07357	-0.08520
LHS03	0.13732	-0.01669	0.01834	0.12286	-0.02050	-0.02107	0.10869	-0.08009	0.12775	0.01249
LHS04	0.13091	0.02511	-0.05107	0.12790	0.06051	-0.06622	0.10898	-0.03364	0.13113	-0.06544
LHS05	0.20314	0.04062	0.00135	0.20289	0.03928	-0.01297	0.18826	-0.05399	0.21196	0.01918
LHS06	0.19741	0.01370	-0.02873	0.21148	0.10123	-0.04673	0.19280	-0.01953	0.21619	0.03984
LHSE1	0.07314	-0.00201	-0.09947	0.07419	0.10198	-0.13053	0.06655	0.00000	0.07488	-0.14717
LHSE2	0.12641	-0.00123	0.07903	0.14384	0.12387	-0.10846	0.12690	0.00622	0.14532	-0.12642
LHSE3	0.17171	-0.00333	-0.06525	0.19341	0.13891	-0.09262	0.17536	0.01032	0.19547	-0.10445
LHR01	0.00534	0.00442	-0.00307	-0.00335	0.00681	-0.00018	0.00212	-0.00628	-0.00479	-0.01385
LHR02	0.00415	-0.00303	-0.00258	-0.00227	-0.00527	-0.00046	0.00124	0.00502	-0.00387	-0.01152
LHR03	0.00715	0.00617	-0.00368	-0.00414	0.00937	-0.00066	0.00240	-0.00794	-0.00705	-0.01973
LHR04	0.00627	0.00551	-0.00317	-0.00374	0.00738	-0.00646	0.00283	-0.00648	-0.00539	-0.01737
LHR05	0.00979	0.00832	-0.00609	-0.00596	0.01103	-0.00154	0.00343	-0.01235	-0.00988	-0.02670
LHR06	0.00858	0.00757	-0.00532	-0.00590	0.01030	-0.00086	0.00400	-0.01002	-0.00949	-0.02465

6.9.2.4.2 FLIGHT TEST RESULTS

In this section, and as an example, are presented the results of the flight loads calculated after measuring with FBG sensors and applying Skopinski equations calculated according to Section 6.9.2.2. The graphs correspond firstly to the bending, shear and torsion for the complete flight and then, the detailed graphs of the load for several segments of the flight: take off, turns, cruises, steps at different altitude and descent.

Figure 6.9.13. Calculated Bending from FBG sensors during a flight test.

Figure 6.9.14. Calculated Torque from FBG sensors during a flight test.

Figure 6.9.15. Calculated Shear from FBG sensors during a flight test

Figure 6.9.16 Take off: Bending, Torque and Shear (in the left, right and center respectively)

Figure 6.9.17 Turn: Bending, Torque and Shear (in the left, right and center respectively)

Figure 6.9.18 Cruise: Bending, Torque and Shear (in the left, right and center respectively).

Figure 6.9.19 Descent: Bending, Torque and Shear (in the left, right and center respectively).

Figure 6.9.21 Step 4700 ft: Bending, Torque and Shear (in the left-to-right order).

6.9.3 MAIN CONCLUSIONS OF THE FLIGHT TESTS

These are the main conclusions of this aircraft installation and tests:

1. The compatibility of the optical fiber installation procedure and way of working with normal process in Production and final assembly line of civil aircraft.
2. The durability and resistance of the sensors and connectors, as well as the adequacy of the installation procedure has been demonstrated. The sensors were installed inside the HTP box in Production and so far there is no trouble reported with any of the sensors.
3. The temperature compensation by the use of compensated plate has been demonstrated.
4. The successful calibration of the FBG sensors during the on-ground calibration tests. The outputs of the FBG sensors during calibration cases have enabled to determine the Skopinski equations that are necessary for the flight load measurements.
5. The performance of FBG technology in flight and their capability to determine the loads in flight has been demonstrated. Note that the analysis and determination of the accuracy of the loads in comparison with the values determined by S/G is out of the scope of this work because time schedule issues.
6. To sum up, all the preparatory work and the results of the flight tests can be considered a real evidence on how optical fiber sensors can be successfully installed in the a/c and the how they can function in aeronautical conditions.

7 CHAPTER 7. CONCLUSIONS AND OUTLOOK

7.1 MAIN CONCLUSIONS OF THE THESIS

The initially stated purpose of this doctoral thesis was the technical development of optical fibers sensors technologies, particularly fiber Bragg grating sensors and distributed fiber based on Rayleigh backscattering frequency, in aeronautical composites structures and the demonstration of their applicability for structural health monitoring applications.

While recognizing this objective as very ambitious and overarching for a doctoral thesis, this has been certainly achieved, and in the following are listed the main conclusions of this research work:

1. The working procedure and results reported in this Thesis contribute in outstanding way to the technological development of the optical fiber sensors – FBG and distributed fiber based on Rayleigh frequency- for structural health monitoring applications in aeronautical structures.
2. The work and tests developed lead to demonstrate the capability of the two optical fiber technologies in order to function properly in aeronautical scenarios.
3. The strain/load monitoring and in service-damage detection were the general scenarios in order to identify the main requirements to be defined.
4. A technical configuration was developed and probed in each of the test.
5. The performance of the sensors were demonstrated at different scales: coupons in the Lab, panels and components in structural test facilities and last but not least flight tests.
6. The comparison between optical fiber strain measurements and classical electrical strain gauges demonstrated good cross-correlation whenever within 2%.
7. The fatigue resistance of these sensors was also clearly evidenced, and demonstrated to be very well above classical strain sensors when the fibers are embedded.
8. The temperature compensation was identified as one of the key aspects in aeronautical scenarios. For this purpose, a 'dummy' gage method for both FBG and distributed fiber was developed and demonstrated the sufficient consistency to be applied in practical applications.
9. The durability tests -immersion and functional tests- showed satisfactory results when applying the appropriated installation procedure as well as very low drift of the sensors over the immersion time.
10. The immunity of the fiber sensors to electromagnetic field was demonstrated by measuring strain and temperature under the effect of an artificial lightning strike.

This test particularly opens new possibilities for the characterization of the materials in these very particular conditions.

11. The integration procedure was also highlighted as one of the more important steps in the process.
12. Two integration procedures, surface bonded sensors and embedded sensors configurations, were developed and demonstrated in the typical application scenarios, lab, production, final assembly line or in-service maintenance.
 - The integration surface bonded procedure proved to be the most flexible and successful method for structures already manufactured or wherein production constraints might make embedded fibers unworkable. The design of the installation, the skills/experience of the optical fiber installers and the material selection (fibers, adhesives, protections, or cables) denoted to be essential aspects in the process.
 - The integration embedded fiber procedure was developed as the most attractive and built-in integration way and revealed the optimum protection and sensitivity transference from host material to sensor. The ingress-egress demonstrated the need to be very well managed in order to ensure the optical performance, compatibility with Manufacturing and resistance over the operational life. Two solutions were developed, one of the them was even integrated in production phase of a real Composite Manufacturing Plant and both are today in the industrialization process.
13. The final checking of the installation including the connections cleanness, continuity, dynamic range measurements or correlation distances demonstrated to be also absolutely mandatory in order to ensure the successful outcome of the measurements.

To sum up, the methodology followed in the Thesis and results obtained in the tests constitute very useful and innovative evidences demonstrating the capabilities and unique advantages of the optical fiber sensors for structural monitoring in aeronautical structures. Undoubtedly, the time for the systematic use of these technologies is close, firstly in aeronautical structural test platforms and secondly, once consensus of the benefit is reached, in serial aircraft, in the latter case not only for SHM purposes but even for other applications such as for example temperature monitoring.

SCIENTIFIC AND TECHNOLOGICAL ACHIEVEMENTS

In the following, the most significant scientific and technological achievements of this thesis.

1. The development of optical fiber sensors for structural Health Monitoring applications has been carried out from the basic tests in the Lab, durability or performance, to final test in the aircraft.

2. The immersion tests in the lab and methodology followed has enabled to evaluate the adequacy of the application procedure as well as the assessment of the drift of the sensors in very harsh aeronautical conditions. These tests are useful to estimate the possible error in long term measurements and also to establish when periodically would be convenient to reset the reference of the sensors in cases this effect need to be corrected.
3. The concept of using FBG sensors for monitoring during lightning test is very innovative and opens many new possibilities for the mechanical and thermal characterization of the aeronautical structures subjected to direct and indirect lightning strike effects, and the relation between the electrical energy with the material damage.
4. The performance and capabilities of distributed fiber, embedded or bonded, on coupon tests to measure the static and dynamic strain profiles has been demonstrated even with elongations higher than 1%.
5. The performance and potentials of distributed fiber for strain monitoring in large composite structural tests such as the horizontal tail plane or the wings in static and dynamic conditions has been also demonstrated. The same number of measurement points with conventional strain sensors would require the installation of an enormous number of sensors with the substantial effort as for installation and the vast number of cables and acquisition channels.
6. It has been demonstrated the methodology to integrate embedded optical fiber sensors and connectors for strain monitoring purposes in a composite structural part. The process was prepared and carried out under the main premise of being compatible in the production phase and ensuring the subsequent performance of sensors and connectors in the structural test phase. It can be considered one of the first, if not the first, demonstration of the integration of embedded optical fiber sensors in a composite wing structure during production in an aeronautical composite plant.
7. The succeeding in using embedded and surface bonded optical fiber sensors for the online inspection of composite repair patches has been demonstrated. This is one of the necessary conditions to get the acceptance for the application of these technologies on bonded composite repairs and so aim to extend the use of this structural concept further to the currently permitted by Aeronautical Certification Authorities.
8. It is the first time that the complete process for using FBG sensors in flight tests civil aircraft for load monitoring has been demonstrated. In particular, the compatibility of the optical fiber technology with all installation systems in the aircraft and the durability of the installation procedure in flight environment has been proven.

7.2 RECOMMENDATION OF FUTURE RESEARCH ACTIVITIES.

Hereafter, there is a proposal including issues that would require further investigation. These additional studies would benefit the knowledge of the sensors behavior and could optimize the values of these technologies for aeronautical applications:

1. Additional exploration of the effects of combined environmental conditions and loads. This further research might involve the study of the behavior of the sensors in areas subjected to combinations of mediums and under different load spectrums.
2. In-depth examination of practical approaches to improve the dynamic range of distributed optical fiber technologies so that the sensing fiber length can be further extended and some optical budget installation issues can be relaxed.
3. Further research in optical fiber connection devices that will enable simplify the ingress-egress of embedded optical fibers in composite manufacturing process.
4. Further research on repair methodologies for optical fibers, very specially when the optical fibers are embedded in the composite structures. The current procedures result many times impractical and the redundancy of the fibers is in many occasions the most convenient approach to mitigate this risk.
5. It would be also very helpful additional investigation on material protection and methodologies to decouple temperature from strain and vice versa. These studies could certainly simplify the application procedures or extend quickly the monitoring applications with optical fiber sensors in the aircraft.

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