SMARTFIBER

Miniaturized structural monitoring system with autonomous readout micro-technology and fiber sensor network

Collaborative Project

ICT – Information and Communication Technologies

D8.1 First Technology white paper

Date of preparation : September 2011	**Revision:** Final
Contributors: imec (A. Trita)	
Dissemination: Restricted	
Start date of project : September 1, 2010	**Duration:** 36 Months
Project Coordinator : Dries Van Thourhout	**Project Coordinator Organisation**: imec
Grant Agreement: 257733	

Abstract

Seven partners joined forces in the framework of the FP7 European project SmartFiber, for the implementation of the world's first optical "health monitoring" system for composite materials, which can be fully embedded in the composite itself. This disruptive approach will enable continuous monitoring of composite structures, allowing a full exploitation of their unique characteristics, removing the paradigm of conservative design and/or conservative modus operandi. Four state of the art technologies are being exploited to meet this ambitious target: nano-photonics, advanced Fiber Bragg Gratings sensors (FBGs), automatic embedding and wireless data and power transmission which combined together will enable the implementation of a "smart composite".

1 Introduction

The spectrum of applications relying on composite materials is constantly growing.
In whatever business you are involved: aerospace, wind-power, marine, automotive, etc., you well know that using composite materials for the fabrication of heavily loaded structures is highly favourable, because of their superior characteristics: superior specific strength (strength-to-weight ratio), damage tolerance, excellent durability, corrosion resistance, etc.
The enormous potential of these materials however has not yet fully been exploited. The reason for this lies in the gradual degradation of composite structures and in the inability to continuously monitor the integrity of the structure.
Let's better explain this concept. Every material undergoes natural degradation, so do composite materials. However, the damage modes in composite materials are completely different and more complex than in well-known conventional materials like steel, aluminum, etc.. Small cracks and delaminations naturally occur in the structure, often inside the material where they are invisible, in most cases without posing an immediate threat to the integrity of the structure. However, the problem is that a sudden growth of these phenomena may occur, leading in the worst scenario to a catastrophic failure of the structure. This unpredictability of damage growth forces engineers to design composite structure with larger safety margins, thus limiting the full exploitation of the potential of the composite material.
A solution to overcome this limitation is the use of a structural health monitoring (SHM) system that continuously detects and interprets adverse "changes" in a structure.
A continuous health monitoring system, measuring the mechanical load, strain and damage state of the composite structure in service, not only guarantees a safe modus operandi, but it also allows removing the paradigm of conservative design and/or conservative modus operandi. Optimal design and use of composites, only possible when continuous health monitoring is in place, will lead to lighter structures, and for example will reduce fuel consumption in aerospace and automotive industries or will enable wind turbines to operate much closer to their design limits, increasing wind energy capture and thus electrical energy output.
Standard techniques for diagnostics including for example visual surveillance, radiography or ultrasonic inspection, are not suited for continuous monitoring, being in addition labor intensive and thus expensive.
Fiber Bragg Grating sensors (FBGs) are generally recognized as the most suitable technique for continuous SHM of composites thanks to their undisputed advantages, namely: compactness, lightweight, immunity to electromagnetic interferences (EMI), high resistance to corrosion and high temperature capacity. They can be multiplexed, allowing the measurement of strain and stress at multiple locations along a single fibre line, and in addiction during fabrication of the composite, the

FBGs fibre can be embedded in between the reinforcement fibres, causing negligible distortion of the composite structure, especially if the optical fibre has small diameter [1].
Despite those advantages, SHM using FBG sensor technology has not yet achieved the widespread success it deserves, for a few reasons: the first one, merely economical, is the high cost associated with the complex interrogation apparatus which limits the use of this technology only to high-end applications. A second reason, more technical, is the entry point of the optical fibre lead in the composite material, which is prone to breaking, both during manufacturing of the composite as during operational use. The fragile nature of the fibre exiting the composite, in combination with the harsh and dynamic environment where these structural monitoring systems are used, reduces the estimated life time of the monitoring system considerable. Finally, the current methods for FBGs fibers embedding are labor intensive, and don't ensure an adequate placement repeatability which is an essential requirement for reliable quality control and system efficiency.

The "smart composite" concept

Our answer to these issues is an FBG interrogation apparatus so small that it can be embedded as a whole inside the composite, exploiting wireless technology for both signal and power transmission. So small that any cause of structural perturbation of the material is minimized. This, combined with the use of special reduced-diameter FBGs optical fibres which will be automatically embedded in the composite, will lead to the development of a "smart composite".

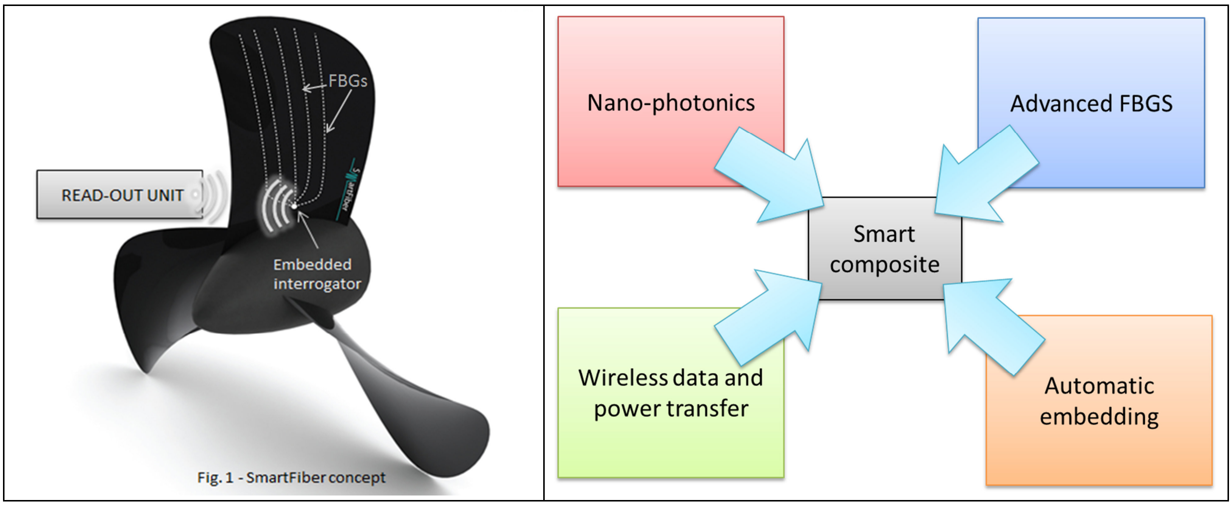

Fig.1 – (a) The "smart composite" concept. (b) Key technologies

Four state of the art technologies will be exploited to meet this ambitious target, enabling the implementation of a "smart composite"': **nano-photonics, advanced FBGs, automatic embedding** of the smart micro-system, **wireless data and power transmission**.
We will discuss these in more detail in section 4. First we will give some more insight in the required specifications and in the overall system architecture.

2 Target Specifications

As a consequence of the strong "end-user" spirit which drives this project, the target specifications of the interrogator were defined matching real-life case-studies. Obviously, each composite structure is designed for a specific function, hence it is difficult to provide general SHM-specifications which meet the demands of any structure.

For this reason, target specifications have been determined so as to cover the widest range of common requirements among the various case studies. In most instances, the prototype requirements are applicable to the full-scale production in-service system as well.

The full list of functional embedding and processing specifications is presented in Table 1 and Table2.

Functional requirements		
	Value/specifications	**Justification/Comments**
Number of FBG's per fibre	4-8 per optical fibre	
Number of fibres per interrogator	1	Simplifies embedding
Max fibre length	Not important for prototype Production:100m from interrogator to last FBG	To enable monitoring of large structures
Frequency and sampling rate	>50Hz	Depends on application, however this is the minimum
Strain range	-10000 < με < +10000	Composite structures are designed to locally strain well within this range
Strain resolution	<10με	
Operating temperature	-20°C < T_service < 70°C	
Temperature compensation	yes	
Embedding depth	Preferably within the laminate stack (as opposed to placement on the exposed surfaces)	
Heat management	<T service +20°C Need for cooling/heat dissipation mechanism	• Carbon fibre composite is a medium heat conductor • Glass fibre composite is an insulator
Expected life time	Prototype: 1000 hours Production: 30 years with redundancy	
General requirements	Waterproof Chemical resistance Stiffness of interrogator housing compatible with composite material Strong adhesion with composite material (i.e. does not debond within expected strain range)	} In case of water or chemical ingression during service If stiffness of housing is too low, the interrogator will carry loads experienced by the structure -> damage

Table 1 – Functional requirements

Embedding and Processing requirements		
	Value/specifications	**Justification/Comments**
Processing temp	>120ºC	
Processing pressure	1 Bar	
Interrogator dimensions	≤ (50x50x4)mm (First prototype) ≤ (20x20x1)mm (final Demonstrator)	Small size very important so as not to become a defect within the composite structure
General requirements on interrogator and optical fibre	"Water" resistant against liquid polymer during processing Chemical resistance against composite polymer CTE of interrogator matches composite material	 To minimize local residual stresses, hence loading, in and around the interrogator

Table 2 – Embedding and processing requirements

3 Interrogator architecture

The interrogator architecture is sketched in Fig.2. The core of the interrogator is the optical de-multiplexer which separates the spectral components of the light reflected from the FBGs.
The spectral components, separated by the demultiplexer, are revealed through an array of detectors, and then the resulting "rough" electrical data are electronically processed before being transmitted to the read-out unit through the wireless channel. The external read-out unit, in addition, provides the power supply to the interrogator through the wireless channel.

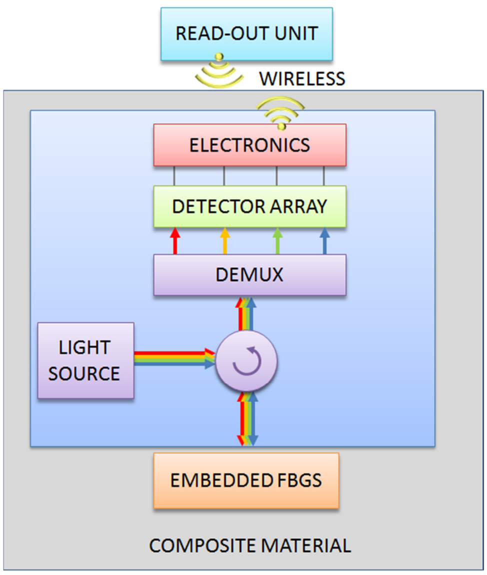

Fig.2 – Interrogator architecture

4 Key technologies

In the following paragraphs, the four key technologies that will enable the implementation of the smart SHM micro-system will be reviewed.

FBGs (Fibre Bragg Grating Sensors)

FBGs are fabricated by creating a periodic refractive index modulation or a so-called Bragg grating in the core of an optical fibre. The operating principle of an FBG is shown in Figure 3. When light from a broadband light source is coupled into an FBGs fibre, only a narrow spectrum of frequencies of the input light is reflected: the central wavelength of this spectrum is commonly called the Bragg wavelength (λ_B). The light that is not reflected by the Bragg grating further propagates through the fibre.

A mechanical strain applied to the fibre with the inscribed Bragg grating will result in a change of the period of the grating and also of the refractive index in its proximity. The resulting relative shift in the Bragg wavelength λ_B, is proportional to the applied strain and thus can be used as a measure for it.

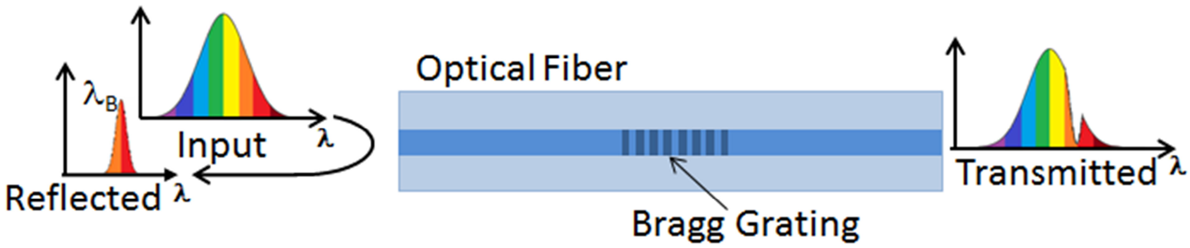

Fig.3 – Fiber Bragg Grating principle

When an FBGs fibre is embedded in the composite, it can negatively affect its mechanical properties such as its strength, and fatigue or impact resistance .

To avoid these detrimental effects, within this project, FBGs-Technologies is developing a draw tower fibre Bragg gratings (DTG®s) with a reduced diameter and an optimized fibre coating.

The target 60 um cladding diameter DTG®s will be tackled in a few steps.

A dedicated and specially designed high photosensitive silica preform will be used to draw the smaller diameter fibre (Fig.4a) .

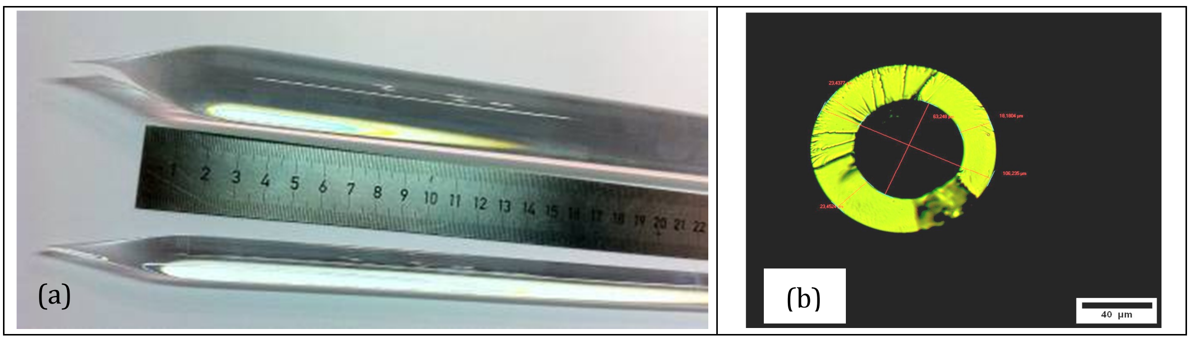

Fig.4 (a) Dedicated photosensitive fibre preform developed for the 60µm DTG®s (bottom) in comparison to a standard commercial preform for 125µm DTG®s. (b) Cross section of the first prototype with a 63µm cladding and 106µm coating diameter

At this stage, the stability of the fibre diameter is a crucial requirement, to be able to write stable in-line FBGs. If fluctuations occur, this could lead to discontinuities in the fibre and FBG properties, on the mechanical as well as on the optical level.
After the in-line FBG writing, the fibre will be directly finished with a suitable thin polymer coating layer. The coating should in first instance serve as a protection layer for the fibre, but additionally, certainly in the case of an (embedded) strain sensor, it should ensure a good strain transfer from the host material to the sensor, and at the same time it should act as a buffer to have low peak distortion because of transverse effects.
An example of the cross section of the first 60µm FBG prototype is shown in Fig. 4b. The measured characteristics are very promising.
The optical, opto-mechanical and thermo-optic properties match those of standard FBGs, however, its mechanical properties are enhanced compared to standard diameter sensors (Table3).

Parameter	Unit	Value
Fibre diameter (cladding)	µm	63±1 (first design)
Core diameter	µm	≈4.3
Coating fibre diameter	µm	≈106 (variable value)
Fibre attenuation	dB/km	>15 @1550nm
FBG length	mm	8 (typical)
FBG Reflectivity	%	≈ 20
FBG FWHM	pm	≈120
Fibre Numerical Aperture	-	≈ 0.23
FBG centre wavelength	nm	C + L band
Temperature sensitivity	K^{-1}	Linear: $6.5 \cdot 10^{-6} = (\alpha_n + \alpha_f)$
	K^{-1} , K^{-2}	Quadratic: $S_1 = 6.37 \cdot 10^{-6}$, $S_2 = 7.3 \cdot 10^{-9}$
Strain sensitivity	$\mu\varepsilon^{-1}$	$7.78 \cdot 10^{-7}$
Operational Temperature range	°C	-180 …+200
Tensile stress	GPa	5.3
Tensile strain	%	7.4

Table 3 – FBGs fibre parameters

Nano-photonics

Only exploiting nano-photonics, one can think to tackle the ambitious goal to fabricate an FBG interrogator so small that it can be embedded directly in the composite.
Nano-photonics is an emerging technology that allows the fabrication of "Photonic Integrated Circuits" (PICs), the optical equivalent of electronic ICs, which encompass several functions on the same substrate: light guides, light sources, detectors, optical modulators and switches, optical sensors, optical filters, optical wavelength (de) multiplexers, etc.
PICs can be manufactured from many different materials. A particularly appealing platform for fabrication is silicon in combination with silicon oxide (Silicon on Insulator platform - SOI).
The reasons for such an interest are firstly the fact that PICs can be manufactured using the same technology used for electronic chips. This means that for their fabrication, one can rely on an immense technological maturity and industrial production infrastructure (which in turn means mass production and hence low cost). Secondly, the remarkable optical properties of Silicon, in

particular the high refractive index contrast between Si and SiO_2 which allows the fabrication of extremely miniaturized optical structures.

The extensive experience of imec in the fabrication of Si-nano-photonic devices, of which imec is one of the pioneers, is combined in this project with the established III-V detectors technology at Xenics, for the implementation of the optical core of the interrogator (Fig. 5).

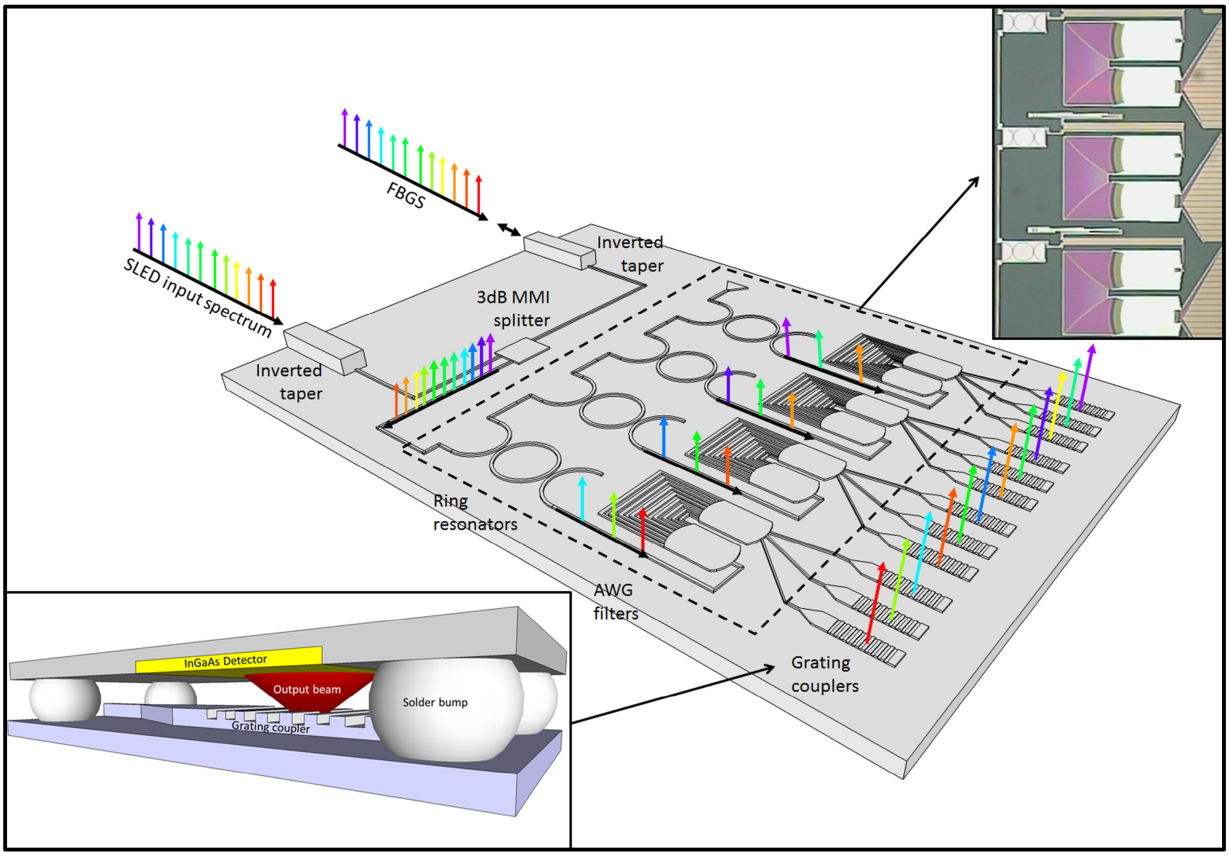

Fig.5 – Schematic of the optical core of the interrogator. (Bottom inset) Flip-Chipped detector on top of the grating coupler. (Top inset) Optical microscope photography of the fabricated Demux

Using silicon-photonics waveguide technology, very compact filters can be fabricated but they feature either large free spectral range[1] (FSR) and limited resolution or high resolution and small FSR.
To satisfy the challenging requirements of the interrogator both characteristics will be conveniently combined in a two-stage architecture.
The first stage of the demultiplexer (see Fig. 5) is composed of narrow band ring filters for narrow spectral sampling of the incoming spectrum (Fig. 6), the second stage of AWG filters for spatial separation of the channels.

[1] The FSR is the spacing in optical frequency or wavelength between two successive reflected or transmitted optical intensity maxima or minima of a diffractive optical element

The broad band light source, a super luminescent light emitting diode (SLED), will not be directly integrated in the PIC. Source light is coupled into the PIC through inverted tapers [2] which are exploited also for coupling light from and to the FBGs fibre. As on chip circulator technology is not yet mature enough, a MMI 3dB splitter will be used to redirect the reflected signal from the FBGs fibre to the demultiplexer.

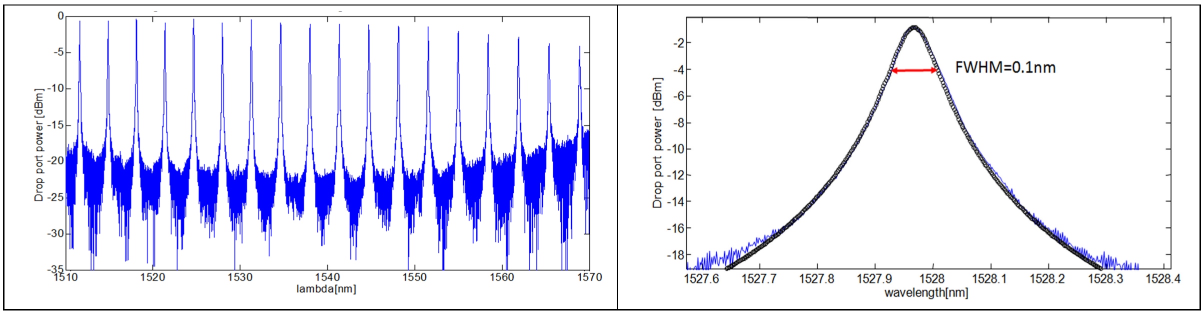

Fig.6 – Measured SOI ring resonator response

Integrated detectors on the SOI platform are available (Ge detectors), however this technology has not yet reached a sufficient level of maturity to ensure reliable operation for the full expected interrogator life-time. For this reason, the more mature III-V detector technology, mastered by Xenics, will be exploited. A linear array of InGaAs detectors will be flip-chipped on top of the PIC, aligned to the array of grating couplers [3] which are used to couple out the spectral content of each channel (Fig. 5 - Bottom inset).

Automatic embedding of a minimal intrusive smart micro-system

FBGs Embedding

A key issue when dealing with FBGs for health monitoring of composite materials, is the embedding strategy. Current (manual/semi-automated) methods for FBGs embedding are labor intensive, and don't ensure the placement repeatability which is required for reliable structural health testing and for the robustness of the monitoring system.

Automatic placement strategies, developed for composite manufacturing such as Automated Fiber Placement (AFP) or automated textile manufacturing combined with resin infusion, should be adopted so to remove the roadblocks for an efficient exploitation of FBGs SHM systems.

Main issue with automatic fibre embedment is whether the optical fibres will survive the process in the placement machines especially with respect to bending and guiding the fibres. The fibres are quite brittle and can easily get damaged. Another issue is how to ensure that the FBG sensor is placed at the correct location.

Airborne Technology Centre, within this project will explore the feasibility of automatic embedding of FBGs optical fibres in composite material.

After some preliminary manual embedding trials, which have been already carried out (an example is shown in Fig.7a), a robot platform with a dedicate placement head will be used, for testing the automated placement of the optical fibre. The robot platform (Fig. 7b) is installed at Airborne Technology Centre and will be used to test various method of placing the optical fibre sensor.

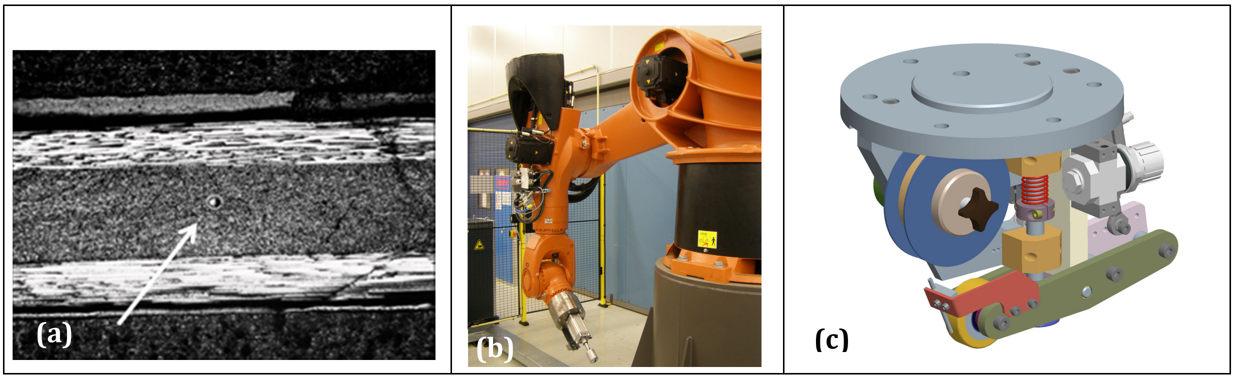

Figure 7- (a) Preliminary manual embedding test (b)Robot cell at ATC. (c) Optical fibre placement head

For the placing of the of OF sensor on a laminate, a concept for a special placement head has been designed (Fig. 7c). The placement head is capable of placing either a bare optical fibre onto a tacky substrate, e.g. prepregs, or alternatively laying down a narrow prepreg tape with an optical fibre already embedded. For future work the placement head can also be adapted to put down the interrogator together with the optical fibre.

Interrogator embedding

Even small (target size for the first prototype is 50x50x4mm), the interrogator is expected to perturb the composite structure in which it is embedded. Being one order of magnitude ticker than a typical composite layer thickness, definitely layers will be interrupted or diverted around the interrogator. In addition the surface area will affect the stiffness and thermal distribution in the composite part, if the interrogator has a different mechanical and thermal behavior.
Although the impact of embedding a structure in composite material can never be eliminated, an optimum can be achieved by tuning the geometry of the structure to the specific behavior of the composite material. In a first iteration, UGent has performed several experiments on embedded structures in composite materials (Fig. 8(a)) which enabled to locate the difficulties in developing a finite element model (FE-model) and define some specifications that the model must meet to generate realistic results.

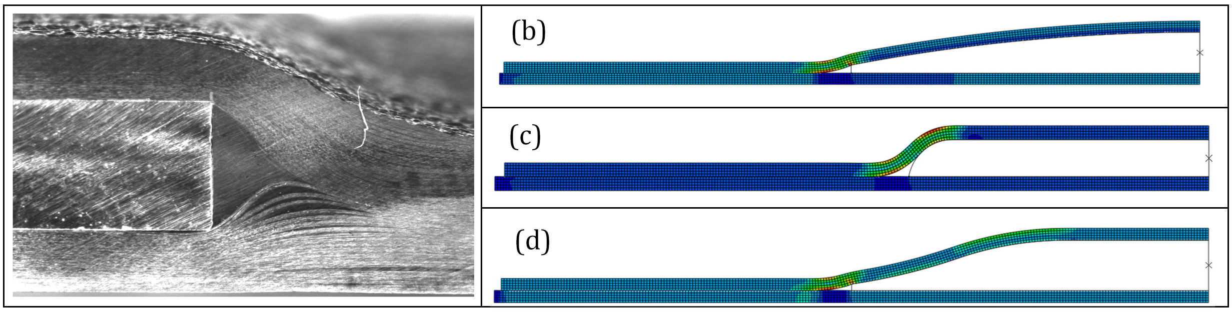

Fig. 8 – (a) Embedding experiments showing (i) the existence of resin rich zones surrounding the embedded part, reducing total strengt (ii) influence of embedded part shape on resin-rich zones (and thus strenght). (b)(c)(d) Optimization results for different parametric interrogator shapes.

In the FE-model, a parametric shape representing the interrogator is used in a genetic algorithm to determine the optimal shape. The boundary conditions were set to accommodate for the target interrogator size (50 mm x 50 mm x 4 mm), and optimization was done towards a minimum resin pocket. Three different parametric shapes have been investigated and compared (Fig. 8(b-d)), and it was decided that the 'double curvature' model (Fig. 8 (d)) was the best trade-off between resin pocket size and local thickening of the composite structure. In a second iteration, the optimum model will be improved as to obtain a minimal maximum stress during loading of the composite (Several load cases will be envisaged).

Wireless

Wireless technology does not need much of an introduction: all of us are accustomed with the unique comfort and flexibility offered by this technology.
In the context of this project its exploitation results particularly beneficial, as a wireless link for both data and power transmission allows minimizing the perturbation to the composite material induced by the embedded interrogator. Fraunhofer IIS, with its long term experience in Wireless communications, will be responsible for its development.
As the embedding material has a strong impact on the characteristics of the wireless link (e.g. a carbon composite act as metals strongly attenuating the electromagnetic energy while fiberglass acts as a dielectric that slightly attenuates the electromagnetic signal) the design is very challenging, and must be adapted to the composite material in which the interrogator is embedded. Furthermore, the material of the optimized outer interrogator shell must be considered, since the antennas will be embedded together with it.

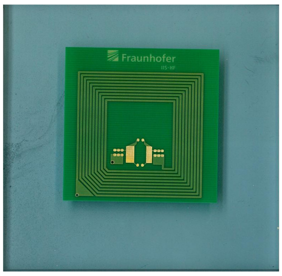

Fig.9 – HF Antenna (13.56 MHz)

In this project a wireless link compatible with fiberglass will be tackled. However, in principle a design compatible with carbon reinforced composites should also be feasible.
Wireless power and data transmission require two different approaches, with the amount of transmitted power being the design constraint in the former case, and the data-rate in the latter.
After a careful evaluation of the target requirements, a wireless link at LF frequencies (125 kHz) has been decided for the power transfer, because of the higher power that can be transmitted and the lower influence of the surrounding materials at these frequencies. For the wireless data transfer a HF (13.56 MHz) wireless link has been chosen instead, since higher data rates than those possible at LF are required. Both technologies work by means of inductive coupling, which is well known from LF and HF passive RFID applications. An example of HF antenna (13.56 MHz) integrated into glass fibre composite material is shown in Fig. 9. The target characteristics of the wireless link are summarized in table 4.

Specification	Targeted value
Wireless power transmission	**1.5 W @ 3.3 V**
Data rate	**< 500 Kbps**
Transmission distance	**< 10 cm**
Size	**< 10 x 10 x 3 mm**
Materials	**GFRP, Epoxy**

Table 4 – Overview of the specification for the wireless link

5 Summary

SmartFiber will enable a new generation of miniaturized, low power, low cost FBGs interrogators, so small that can be embedded in the composite itself, thus making the composite a “smart composite”.

This ambitious target will be tackled by exploiting a combination of four state of the art technologies: nano-photonics, advanced FBGs, automatic embedding of the smart micro-system, wireless data and power transmission.

This disruptive approach can have a transformative impact on the composite industry, finally allowing a full exploitation of the huge potential of composite materials, which will directly translate in an increased yield of the designed structures.

Learn more

For more information about SmartFiber visit:

http://www.smartfibre-fp7.eu/

6 References

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