



HAL
open science

FBG-Based smart composite applications

Pierre Ferdinand, V. Dewinter-Marty, Laurent Maurin, Jonathan Boussoir,
Stéphane Rougeault, Sylvain Magne

► **To cite this version:**

Pierre Ferdinand, V. Dewinter-Marty, Laurent Maurin, Jonathan Boussoir, Stéphane Rougeault, et al..
FBG-Based smart composite applications. EWSHM 2002 - First European Workshop on Structural
Health Monitoring 2002, Ecole Normale Supérieure Cachan, Jul 2002, Cachan, France. cea-04107144

HAL Id: cea-04107144

<https://cea.hal.science/cea-04107144>

Submitted on 26 May 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

FBG-Based Smart Composite Applications

P. FERDINAND, V. MARTY-DEWYNTER, L. MAURIN,
J. BOUSSOIR, S. ROUGEAULT and S. MAGNE

ABSTRACT

Optical Fiber Sensors (OFS) and mostly Fiber Bragg Grating (FBG)-based optical sensors provide accurate, non-intrusive, electromagnetic interference-immune and reliable remote measurements of temperature, strain and pressure. Tiny FBG sensors, embedded into the composite material, provide *in-situ* informations about polymer curing (strain, temperature, degree of cure) in an elegant and non-intrusive way. Great improvements in the composite manufacturing processes such as RTM or RFI are obtained with this method. Since the FBGs sensors are embedded into the composite material, they may be used for health monitoring of the structure and impact detection to evaluate air-worthiness of a flying structure. Finally, FBGS may be used as composite extensometers or plane rosette, or embedded on CFRP reinforcement plates mostly for civil engineering applications.

STATE OF THE ART

Composite materials are very useful for the “high-tech” applications due to their stiffness and resistance associated to a light weight. That makes possible the design of powerful structures, with very good mechanical behaviour often unrivalled by bulk materials. However, the large exploitation of these « new » materials is slowed down by the quasi-inability of men-of-art to anticipate failures due to delaminations for instance.

FBG have been identified since early 90's as the most reliable sensors for composite monitoring. They may be involved in 3 steps of composite structures life cycle:

1. during the manufacturing stage, the FBGs may provide engineers with real-time information on curing process to enable a quick optimisation in order to save time and money by reducing the number of rejected parts and providing better quality of manufacturing. Based on these *in-situ* data, a Man-Machine-Interface can provide a diagnostic and the traceability of the composite during its full life cycle,

Pierre Ferdinand, Véronique Marty-Dewynter, Laurent Maurin, Jonathan Boussoir, Stéphane Rougeault, Sylvain Magne, CEA - List - DIMRI/SIAR - Laboratoire de Mesures Optiques, Centre d'Études de Saclay, 91191 Gif-sur-Yvette Cedex, France – pierre.ferdinand@cea.fr

2. during part qualification stage, this instrumentation enables to obtain validation data (static and dynamic tests as well),
3. finally, such embedded OFS are able to provide significant life-cycle cost reductions *via* new maintenance concepts based on *in-situ* fatigue and damage monitoring.

So, FBG sensors incorporated during manufacturing stage, make it possible to accurately control curing process, locally and between plies, through various parameters such as: temperature, pressure, strain, degree of cure... and can lead to process improvements. These points deal with the « intelligent manufacturing » aspect, the « Non Destructive Testing » phase, and further by the Structural Health Monitoring [1, 2, 3, 4].

FIBRE BRAGG GRATING SENSOR PRINCIPLE

A FBG is a microstructure photo-written in an optical fibre thanks to the exposure of two interfering UV laser beams. The induced periodic refractive index perturbation acts as a fine stop-band filter: all the light passes through the FBG excepted a tiny part of the spectrum, around the Bragg wavelength (λ_B) which is back reflected. λ_B is given by the Bragg relationship: $\lambda_B = 2.n.\Lambda$; where n ($n \sim 1.45$ for silica) is the refractive index of the fiber core and Λ the pitch of the photo-written fringe pattern ($\Lambda \sim 0.5 \mu\text{m}$).

The principle used in any FBG measurement system consists in monitoring the spectral shifts $\Delta\lambda_B$ of the reflected Bragg signals induced by the changes in the measurands (strain ϵ , temperature T or pressure P) according to: $\Delta\lambda_B = a.\Delta T + b.\Delta\epsilon + c.\Delta P$. At $1.55 \mu\text{m}$, $a \equiv 11 \text{ pm}/^\circ\text{C}$; $b \equiv 1.2 \text{ pm}/(\mu\text{m}/\text{m})$; and $c \equiv -5 \text{ pm}/\text{MPa}$. Moreover, FBGs are able to measure many other parameters (force, tilt, impact, refractive index ...) thanks to a special coating or sensor design. With the spectral shift $\Delta\lambda_B$, one can deduce measurand values. Selectivity of the measurement is obtained thanks to a differential approach (one FBG is isolated from strain, while a second one is submitted to both strain and temperature). At CEA we have developed several PC-based measurement systems able to address up to 80 FBGs. The basic measurement principle is depicted on Figure 1. An optical source lights the grating array, a demodulation set-up analyses the position of any Bragg wavelength, while the software determines their shifts in real time, by comparison to a reference state. The field of applications is wide: Smart manufacturing (composites, concrete...), Health Monitoring of advanced structures, Non Destructive Evaluation, Smart structures, Process Control...

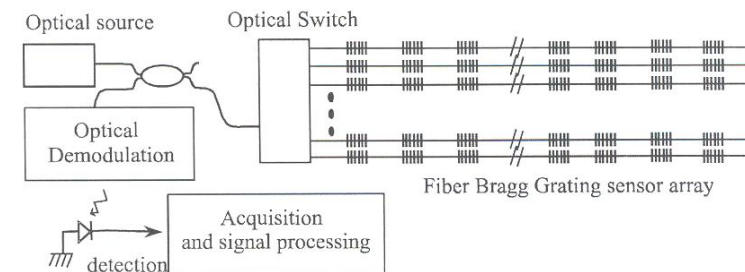


Figure 1. Example of basic measurement system principle: several FBG-based sensors are placed in series along the same fiber (WDM demultiplexing), and several fibers are arranged in parallel

FBG-BASED SMART MANUFACTURING

In order to increase the performances of transportation means (planes, trains, ships ...), Advanced Fibre Reinforced Composites (AFRC) are being used extensively. For instance, in aerospace industry, they can offer the possibility to enhance payload capacity of aircrafts and spacecrafts, as well as a number of other advantages such as reduced operating costs by lower fuel consumption and associated decrease in pollution.

In order to control manufacturing, the optical sensor network (several transducers are localised on several fibers) must be incorporated into the structure before the curing cycle (temperature up to 200°C and pressure of several bar for instance). By the way, some information which is not achievable with traditional means (strain gages, ultra-sonics ...) could be provided: internal temperature, local strain levels, refractive index (degree-of-cure, resin voids) ... Some laboratories have demonstrated that it is possible to achieve these goals using OFS in order to really improve quality control of manufacturing. These approaches could be adapted to any manufacturing process (autoclave, RTM ...) depending on end-user requirements. The idea consists of embedding fibers during the manufacturing process, and remotely measuring key parameters depending on the process.

Today, as a first step, the most important field of applications for the FBG technology concerns smart manufacturing, *i.e.* the control and the monitoring of the cure of a composite material. Several methods exist to elaborate a composite structure (autoclave, filament winding, Resin Transfer Molding (RTM), and Resin Film Infusion (RFI)) [5]. Nevertheless, in any case, fibers are small enough to be non-intrusive, passive, EM-immune, and allow one to multiplex data from many sensors along a single fiber. FBGs provide stable and reproducible measurements since they are based on a spectral signature.

Over recent years, research laboratories, and now the manufacturers of composite structures, perceived the advantages they could get from OFS and FBGs in order to enhance the quality of their processes and the cost reductions associated with development phases. This aspect is particularly acute with regard to the RTM (Resin Transfer Molding) process. As an example, we mention a recent project dedicated to a propeller's blade manufacturing process (the blade was instrumented with 38 FBGs distributed into 4 lines on each face). The objective of this project, led by Ratier-Figeac (France), was to use the advanced CEA measurement system based on embedded FBG sensor technology, able to get insight of process sequences and to map resin-flow by detecting air-to-resin transitions during the injection (see Figure 2) (in order to check for dry zones or voids in the structure as well as for residual strains), and consequently to improve the quality of manufacturing and to reduce development costs [6, 7, 8].

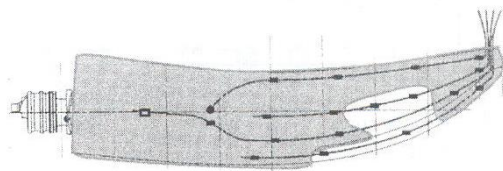


Figure 2. Resin progression on one side as inferred from the FBG data

As another example of FBG sensor devoted to smart manufacturing, we mention a non-intrusive temperature sensor able to be embedded in composite material (see Figure 3). In such sensor, the FBG transducer is carefully packaged in a silica-based micro-capillary: the fiber being glued to the capillary hole, the FBG transducer is able to sustain thermal expansion, free from mechanical strain, when embedded in a host material (see Figure 4).

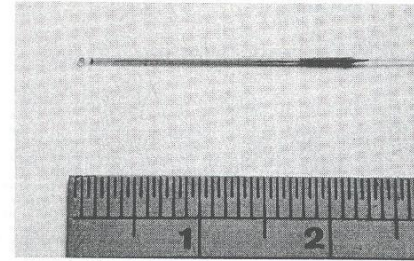


Figure 3. Non intrusive FBG-based temperature sensor for composite materials

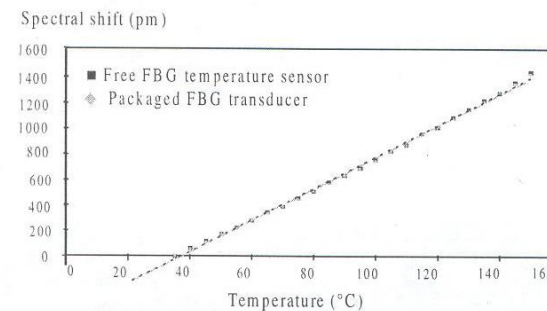


Figure 4. Packaged and non-packaged FBG response versus temperature

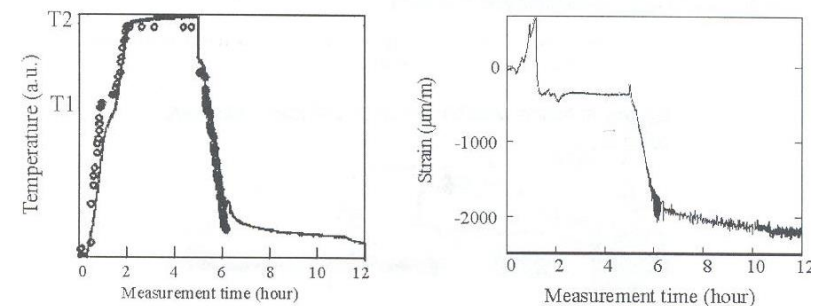


Figure 5. FBG-based temperature (left) and strain measurements (right) inside the composite matrix

Such sensor could be used in any industrial application needing a temperature measurement without intrusivity (composite materials, resin polymerisation, chemical analysis ...). Moreover, as an example of an FBG-based smart manufacturing process, we can mention the real-time recording of strains in a composite material during a curing process, as well as the recording of temperature near the composite plate, inside the autoclave used for polymer curing (see Figure 5) [8].

SMART COMPOSITE STRUCTURE QUALIFICATION

Some companies in Europe aim to develop new functionalities for trains. In France, Alstom Transport S.A., has been working for several months on a new project involving composite materials for a new bogie (see Figure 6). An important part of this development consisted in validating the mechanical behaviour of the bogie spring blade. So we will present the results of accelerated aging tests, carried out by Alstom, and its partners DDL consultants and the CEA in a climatic chamber to simulate environmental conditions close to the real ones (cycle of stress, of intense cold, heat, moisture, strong lightning...). In this framework, several parts of composite bogies have been instrumented with *in situ* FBG sensors. Dynamic fatigue tests were carried out with a powerful actuator in a climatic chamber. The stress levels were induced according to three cycles of dynamic loading added to a static one [$27 \text{ kN} \pm (8 \text{ kN} @ 7 \text{ Hz})$; $32 \text{ kN} \pm (10 \text{ kN} @ 7 \text{ Hz})$; $38 \text{ kN} \pm (11 \text{ kN} @ 7 \text{ Hz})$]. Corresponding strain was about $2500 \mu\text{m/m}$ up to $3500 \mu\text{m/m}$ in static and $700 \mu\text{m/m}$ to $1000 \mu\text{m/m}$ in dynamic mode. Such tests also include temperature and humidity cycling in the same time. To perform *in situ* measurements, an optical fiber with 4 FBGs was embedded in a composite blade during its manufacturing; three of them were dedicated to strain measurements, and the last one to temperature compensation (see Figure 7).

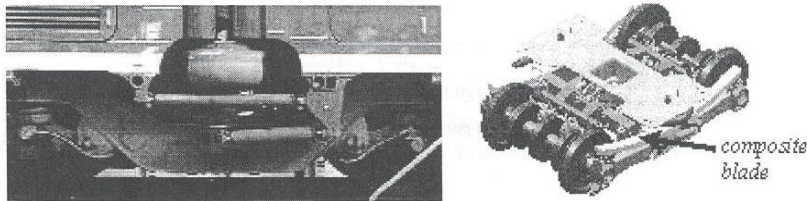


Figure 6. Comparison between traditional metallic bogie for railway rolling stock and new composite Bogie for trains. Courtesy of Alstom, France

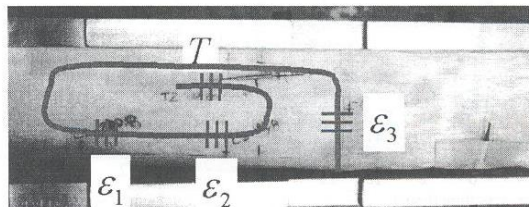


Figure 7. The instrumented composite blade. Courtesy of Alstom, France

With 16 hours per thermal cycle, the blade underwent more than 16×10^6 cycles during 26 days of experiments, including 6×10^6 cycles at 38 kN exceptional load, which is, to our knowledge, the most severe test ever done with FBGs. In comparison, electrical gages glued on surface failed after 10^6 cycles [9, 10, 11]. The results showed a perfect agreement of the measurements with the modelling which proved that these new composite blades retain a constant stiffness, with no observable ageing, nor mechanical behaviour evolution.

STRUCTURE HEALTH MONITORING (IMPACT PLUS DELAMINATION DETECTION AND MONITORING)

After manufacturing and testing phases, the third great motivation of composite structure manufacturers, and of course end-users, deals with Structure Health Monitoring. That is to say the evaluation of the lifetime of a panel or a whole structure. This seems to be more crucial today, after the crash on Nov. 12, 2001 into a New York neighbourhood of American Airlines Flight 587, an Airbus 300-600 series that plummeted after hitting wake turbulence - swirling air that trails behind the wingtips of a plane - and then losing its graphite-epoxy tail in flight, killing 265 people (a typical tail consists of 85 % of composite materials and poses a big challenge to detect the damages). Nevertheless, as composite parts have a very good reputation among aeronautical engineers, they have been in widespread use since the 70's. This quest for greater aircraft efficiency will be more a matter of concern in the future. Let us mention the Airbus A380 which will probably use CFRP, GLARE (Glass reinforced Aluminium),... and the future Boeing Co.'s Sonic Cruiser, a proposed fast airliner which would fly about 15% faster than existing planes. More than half of its structure, including the wing, would probably be in CFRP too.

FBG sensors, are potential candidates for such non destructive instrumentation. One specific topic deals with the evaluation of permanent damage induced by low energy impacts as well as the delaminations due to fatigue. The FBG which is a quasi-distributed sensor, localised along the fiber, exhibits a spectral shift proportional to the local permanent strain, added to the influence of temperature. The idea is to detect permanent damage characterised by a permanent strain in its surroundings. To demonstrate the potential of FBG instrumentation in the assessment of material integrity following impacts, we will present a project led by the French DGA with the ONERA and the CEA, which has consisted to test impact effects on composite samples embedded with FBGs (see Figure 8).

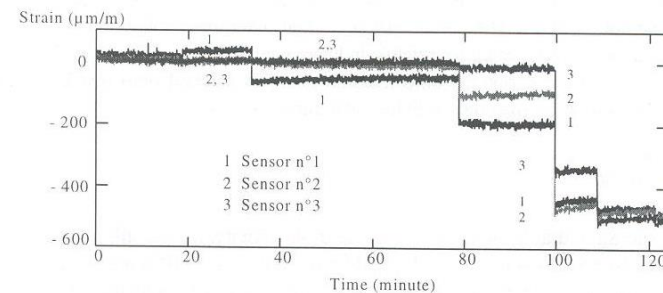


Figure 8. Example of real-time impacts detection from with 3 FBGs embedded at different distance from impact location (sensor # 1 is the closest form the impact area)

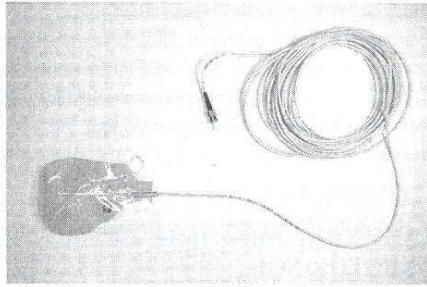


Figure 9. A Delta rosette (equilateral triangle which edge is 10 mm-long) incorporating 3 FBGs as strain gauges and one FBG for temperature compensation, connectorised and sealed for industrial applications.

In the scope of making strain measurements using FBG, rosettes can also be designed in order to instrument existing composite structures like panels, for which embedment of traditional sensors is not possible [12]. They are made of 2 or 3 non-collinear strain gauges, mounted on a common substrate at 45° or 60° to form 'rectangular' or 'Delta' rosettes respectively. Rosettes are extensively used in experimental stress analysis to measure the 2 principal strains and the orientation of the principal axis whenever it is not known *a priori*.

FBG rosettes are easy to manufacture (amenable to batch process manufacturing). They may be assembled by hand or using numerical command machines driving a positioning ultrasonic transducer head, leading to mass production. At least two lay-out designs may be considered. The first design uses a single fiber loop with 3 Bragg gratings in series and operates in wavelength-division multiplexing. A second design uses three Bragg gratings in parallel (one fiber for each FBG) and operates with an optical switching unit, or a parallel analyser. The first lay-out necessitates to cross the fibers whereas there are no crossings in the second one. For instance, 'Delta' rosettes patches with one fiber (FBGs in series) are made in the Optical Measurement Lab. (see Figure 9).

After fiber positioning with the help of a reticle, a kapton® cover (Dupont de Nemours) is finally applied onto the substrate, sealed with acrylic glue and cured. This second kapton® sheet may leave partially uncovered the fiber triangle (sensing region) for further direct fiber bonding. For industrial applications, we start from a connectorized optical cable ($\varnothing = 3$ mm) from which the fiber is stripped off along about 50 cm and on which the Bragg gratings are photo-written. The rosette patch is then assembled following the previous procedure and the cable is sealed for reliable industrial applications. The polyimide support of the rosette can then be bonded onto metallic parts, or stitched onto textiles or either embedded into composite materials with the cable running out of it.

CONCLUSION

Composite Structural Monitoring is a ten-year old activity. So it's still a new technical field in many aspects. Nevertheless, OFS and more particularly FBGs are more and more incorporated in process developments, due to their advantages and potentialities, which are very useful in many industrial composite applications.

In the last years, a number of national and international R&D programs have addressed the use of OFS as temperature and strain/stress/pressure/vibration/refractive index sensors, and there are now many prototypes of systems, and some products available. The main applications are nowadays in aeronautics, and in several transportation sectors, as well as in civil engineering. Today, OFS and FBGs bring their capabilities to composite sensing: it is possible to use them from the manufacturing stage until the end of structure life. The studies relate in particular to enhancing manufacturing processes of composite materials, the quality control of manufactured elements, the health monitoring (impact detection, integrity assessment), as well as improving flight conditions (aerodynamics) and therefore help to decrease operational and fuel costs, as well as atmospheric pollution.

Indeed, later on, the subject on which actors will focus, deals with the real smart (or "intelligent") structures, which now takes the name of 'adaptronics'. It will relate to all the means (material and software) necessary to get a better understanding of the structure behaviour. In such a context, FBGs will certainly have a major rule to play.

REFERENCES

1. Ferdinand P., Magne S., Dewynter-Marty V., Martinez C., Rougeault S., Bugaud M., "Applications of Bragg Grating Sensors in Europe", OFS'12, Williamsburg, USA, Oct 28-31, 1997, pp. 14-15.
2. Dewynter-Marty V., Ferdinand P., Bocherens E., Carbone R., Beranger H., Bourasseau S., Dupont M., and Balageas D., "Embedded fiber Bragg grating sensors for industrial composite cure monitoring", Journal of Intelligent Materials Systems and Structures, Vol. 9 Issue 10, Oct. 1998
3. Dunphy J.R., Meltz G., Lamm F.P., W.W. Morey, "Multi-function, distributed optical fiber sensor for composite cure and response monitoring", Proc SPIE, Vol 1370, Fiber Optic Smart Structures & Skins III, 1990, pp. 116-118.
4. Dewynter-Marty V., Rougeault S., Ferdinand P., Bugaud M., Brion P., Marc G. et Plouvier P., "4 technologies de CFO pour le suivi de fabrication de matériaux composites", 19^{èmes} JNOG, 6-8 déc. 1999, Limoges, pp. 67-69. In French.
5. Ness D., "SPRINT a novel Composite Processing Technology", Proceedings of the 22nd Intern. SAMPE Europe Conference. La Défense, Paris, France, March 27th - 29th, 2001, pp. 89-100.
6. Bocherens E., Bourasseau S., Dewynter-Marty V., Py S., Dupont M., Ferdinand P. and Berenger H., "Damage detection in a radome sandwich material with embedded Fiber Optic Sensors", 4th ESSM and 2nd MIMR Conf., Harrogate, 6-8 July, 1998, pp. 381-387.
7. Balageas D., Bourasseau S., Dupont M., Bocherens E., Dewynter-Marty V., and Ferdinand P., "Comparison between non destructive evaluation techniques and integrated fiber optic health monitoring systems for composite sandwich structures", Journal of Intelligent Materials Systems & Structures, vol. 11, part 6, June 2000, pp. 426-437.
8. Dewynter-Marty V., Rougeault S., Ferdinand P., Bugaud M., Brion P., Marc G. et Plouvier P., "Contrôle de la fabrication de pièces en matériaux composites réalisées par procédé RTM à l'aide de capteurs à réseaux de Bragg", JNOG 2000, 20-22 nov. 2000, Toulouse, France. In French.
9. Maurin L., Boussoir J., Rougeault S., Bugaud M., Ferdinand P., Landrot A., Chauvin T. et Grunevald Y-H., "Instrumentation de Bogie composite par capteurs à fibres optiques à réseaux de Bragg", JNOG 2000, 20-22 nov. 2000, Toulouse, France. In French.
10. Ferdinand P., Magne S., Dewynter-Marty V., Rougeault S., and Bugaud M., "Optical fiber Bragg grating sensors make composite structures smart, SAMPE Europe Conference'99, Paris, April 1999
11. Maurin L., Boussoir J., Rougeault S., Bugaud M., Ferdinand P., Landrot A.G., Grunevald Y-H., and Chauvin T., "FBG-based smart composite bogies for railway applications" Optical Fiber Sensor Conference OFS 2002, 6-10 May 2002, Portland, USA.
12. Magne S., Rougeault S., Vilela M. and Ferdinand P., "State-of-strain evaluation with Fiber Bragg Grating rosettes: Application to discrimination between strain and temperature effects in fiber sensors", Appl. Opt., vol. 36, n°36, 1997, pp. 9437-9447.