Applications of Fiber Bragg Grating sensors in the composite industry

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Abstract

Optical-fiber sensors based on fiber Bragg gratings (FBGs) provide accurate, nonintrusive, and reliable remote measurements of temperature, strain, and pressure, and they are immune to electromagnetic interference. FBGs are extensively used in telecommunications, and their manufacture is now cost-effective. As sensors, FBGs find many industrial applications in composite structures used in the civil engineering, aeronautics, train transportation, space, and naval sectors. Tiny FBG sensors embedded in a composite material can provide *in situ* information about polymer curing (strain, temperature, refractive index) in an elegant and nonintrusive way. Great improvements in composite manufacturing processes such as resin transfer molding (RTM) and resin film infusion (RFI) have been obtained through the use of these sensors. They can also be used in monitoring the "health" of a composite structure and in impact detection to evaluate, for example, the airworthiness of aircraft. Finally, FBGs may be used in instrumentation as composite extensometers or strain rosettes, primarily in civil engineering applications.

Keywords: *composite materials, fiber Bragg gratings, laminates, mechanical properties, optical-fiber sensors, optoelectronics, optical properties.*

Introduction

Composite materials have been used for many years in the aerospace industry, owing to their high specific stiffness and strength. They are also used more and more in the transportation industry, and in mechanical engineering and civil engineering for the rehabilitation and reinforcement of structures and cables. Composites display good short-term and long-term (fatigue) mechanical behavior, and good environmental stability (withstanding fire, corrosion, lightning strikes, etc.).

Optical-fiber sensors have been embedded into composite materials for more than 12 years.[1] For aerospace applications, we may distinguish three main applications for optical-fiber sensors, one related to manufacturing control, a second linked to "health" diagnostics (in-flight or for maintenance), and a third related to smart structures (control damping and shape control).[2]

Embedded optical-fiber sensors may be used to provide in-flight, real-time information to an on-board controller able to drive actuators with the purpose of damping vibrations or noise, or controlling the shape of a structure: this is the well-known concept of smart structures, that is, structures able to sense their environment and to correct autonomously for any perturbation.

Until now, much of the research in this area has been directed toward the use of optical-fiber sensors in the continuous improvement of manufacturing processes. During the manufacture of composite materials, it may be necessary to monitor temperature, pressure, void content, resin front progression, shrinkage, or residual stress, as well as inline cure monitoring (degree of cure). For the last five years, progress has been made in inline manufacturing monitoring by using fiber remote absorption spectrometry[3] or refractometric methods (Fresnel reflection, slanted fiber Bragg gratings),[4,5] to such an extent that manufacturers are willing to consider these nondestructive methods in order to shorten the qualification time for new structures, improve the quality of manufacturing, and reduce the number of rejected parts.

Optical-fiber sensors also have been widely investigated for strain monitoring in civil engineering applications (mining,[6] bridges,[7–12] highways,[13] and nuclear-power plants[14–16]) and for operational monitoring and maintenance of aircraft;[17,18] once parts are made, the failure modes of the composite structures (e.g., delamination) cannot be predicted analytically and are not well understood. Application of a new composite material is slowed down by high manufacturing costs and risk arising from the inability to predict damage and understand the material's mechanisms, especially in the case of heavily loaded structures. It is also inherently difficult to incorporate a nonintrusive optical connection to a composite part—a problem that has not yet been industrially solved.

This article will focus on recent applications of optical-fiber sensors in composite materials. The industrial aspects are summarized in Table I.

Smart Manufacturing

In many structures, the key parameter of interest is strain. A fiber Bragg grating (FBG) is formed by exposing the core of a Ge-doped fiber to alternating regions of intense short-wavelength laser light (around 244 nm). This is typically done with a high-power UV laser and an interferometer or a phase mask forming an interference pattern imaged on the fiber core. Due to constructive internal interference, an FBG acts as a sharp reflecting filter for a characteristic wavelength (the Bragg wavelength). When subjected to strain, pressure, or a temperature change, the Bragg wavelength of such a filter is shifted proportionally. Accurate measurements of these shifts can be used to extract the strain information, free of temperature influence, if a differential approach is used (e.g., one FBG sensing strain and temperature, and a second FBG only sensing temperature). Moreover, in telecommunication systems, for example, spectral demultiplexing allows the measurement of several Bragg wavelengths reflected by a set of gratings

Table I: Overview of the Use of Optical-Fiber Sensors in Monitoring Composite Structures.

	Industry	Applications	Parameters	Specific Problems
Composite materials: carbon, glass-epoxy, glass-polyester	Aeronautics Space Defense Nuclear power Transportation (trains, automobiles, ships) Civil engineering (e.g., rehabilitation of structures)	Smart processing Quality control "Health" monitoring Off-line and on-line control of reinforcement in old structures	Strain/stress Temperature Pressure Degree of cure Delamination Internal defects Impact detection and damage assessment	Obtaining optical information from structures in industrial use Monitoring large structures Repairing sensors in case of failure or break in optical fibers High manufacturing cost of composite materials Long-term behavior in harsh environments (extreme cold, moisture, humidity)

photo-written on the same fiber (i.e., to form a distributed measurement system).

Today, one of the most important applications for FBG sensing technology is in smart manufacturing — in particular, the control and monitoring of the cure of a composite material. Optical fibers are small enough to be nonintrusive and passive when embedded in a composite. They allow data to be multiplexed from many sensors along a single fiber, and due to the fact that FBGs are able to provide *in situ* information in real time, they provide a very stable and reproducible measurement (since they are based on a spectral signature). Optical fibers can be embedded in composite materials during the manufacturing process and then used to remotely to measure temperature, strain, pressure, degree of cure, the presence of resin, and other parameters, depending on the process. Among the well-known methods for forming composite structures are by means of autoclave, filament winding, resin transfer molding (RTM), and resin film infusion (RFI). We will discuss some of these next.

Cure Monitoring in an Autoclave

As an example of an FBG-based smart manufacturing process, we describe here the real-time recording of strain in a composite material, as well as temperature near the composite plate, inside an autoclave used for polymer curing.

For these experiments, a coupon of a typical three-layer composite structure used in aeronautics was prepared in the following way. First, two square layers (150 mm × 150 mm) of a glass/epoxy skin 1 mm thick and a foam core 3 mm thick were glued together. Next, a polyimide-coated FBG ($\lambda_B = 1310$ nm), used as a strain sensor but sensitive to temperature as well, was placed in a U-shaped groove machined in the upper surface of the foam layer. Finally, the second glass/epoxy skin was placed onto the foam and glued. A second FBG ($\lambda_B = 1305$ nm), isolated from strain and spliced in series, was used as a temperature sensor. This FBG was placed outside of but close to the composite sample within the autoclave.[19,20] The difference of the spectral shift of these two gratings gives the absolute strain inside the composite. Both Bragg wavelengths are monitored with a homemade scanning Fabry–Pérot-based wavelength-division multiplexing (WDM) system, as described in References 2 and 15.

The full curing cycle takes 12 h, including the controlled cooling steps. During the cycle, continuous measurements of temperature and strain are performed. The temperatures measured by the FBG temperature sensor (Figure 1, solid curve) are compared with those given by the autoclave controller (Figure 1, open circles) used for regulating the cure. At the same time, the strain inside the material is recorded (Figure 2). Any induced strain is due to two contributions, thermal expansion and polymer shrinkage, which both result from the curing process.

An easy interpretation of the FBG measurements allows one to identify and control every step of the process. The whole process can be divided into the following steps (see Figure 2):

1. Cycle is initiated at time $t = 5$ min by increasing the hydrostatic pressure up to a few bar. This action induces a wavelength shift of −20 pm for the embedded FBG strain sensor (i.e., a compressive strain), and +50 pm for the FBG temperature sensor in the autoclave. One criticism of the experimental setup is that the optical fiber linked to the temperature sensor is not absolutely free in the pressure chamber, but is firmly attached near the composite sample, which could modify the pressure effect.
2. Temperature is increased to T_1. The strain sensor records a positive change (maximum 700 $\mu\varepsilon$), linked to the thermal expansion of the epoxy resin. A somewhat chaotic behavior is observed, perhaps due to a rapid change in the adhesive conditions between the epoxy and the FBG.

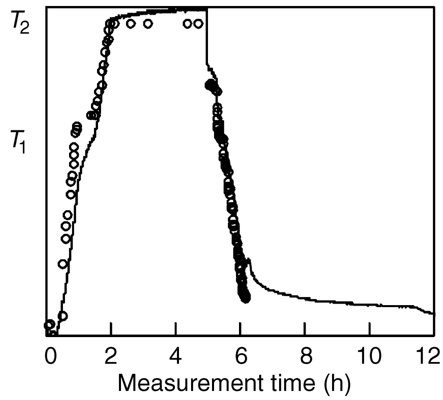

Figure 1. Temperature measurements performed by a fiber Bragg grating (FBG) sensor embedded in a glass/epoxy and foam-core composite during cure in an autoclave (solid curve), compared with the autoclave's controller (open circles).[19,20]

3. Temperature is kept constant at T_1 for a few tens of minutes. From the curves depicted in Figure 1, the temperature inertia of the autoclave can be estimated by comparing the data given by the temperature sensor and the regulation probe. This inertia could be explained by the fact that the temperature probe in the autoclave is far from the FBG location near the composite plate. On the strain curve, a sudden decrease (Point 3 in Figure 2), down to −400 $\mu\varepsilon$, can be observed. The epoxy polymerization begins and, simultaneously, shrinkage occurs.
4. Temperature is increased from T_1 to T_2. The strain sensor shows successive tractions and compressions of about 100 $\mu\varepsilon$ in amplitude centered around −400 $\mu\varepsilon$. At this stage in the cure, two phenomena are competing: the material's thermal expansion, due to the temperature increase inducing a positive strain; and the resin shrinkage linked to the ongoing polymerization.
5. Temperature is kept stable at T_2 for 3 h. The strain remains constant in the composite.

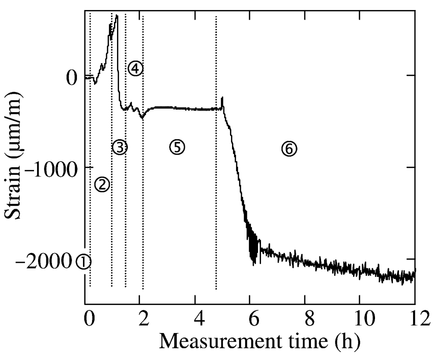

Figure 2. Internal-strain measurements performed by an FBG sensor embedded in a glass/epoxy and foam-core composite during cure in an autoclave, after themal compensation by FBG temperature measurement.[19,20] (1) Cycle is initiated at time t = 5 min by increasing the hydrostatic pressure up to a few bar. (2) Temperature is increased to T_1. The strain sensor records a positive change (maximum 700 $\mu\varepsilon$), linked to the thermal expansion of the epoxy resin. A somewhat chaotic behavior is observed, perhaps due to a rapid change in the adhesive conditions between the epoxy and the FBG. (3) Temperature is kept constant at T_1 for a few tens of minutes. From the curves depicted in Figure 1, the temperature inertia of the autoclave can be estimated by comparing the data given by the temperature sensor and the regulation probe. This inertia could be explained by the fact that the temperature probe in the autoclave is far from the FBG location near the composite plate. On the strain curve, a sudden decrease down to $-400\ \mu\varepsilon$ can be observed. The epoxy polymerization begins and, simultaneously, shrinkage occurs. (4) Temperature is increased from T_1 to T_2. The strain sensor shows successive tractions and compressions of about 100 $\mu\varepsilon$ in amplitude centered around $-400\ \mu\varepsilon$. (5) Temperature is kept stable at T_2 for 3 h. The strain remains constant in the composite. (6) Temperature is decreased step-by-step. As the temperature decreases, the embedded FBG detects an increasing negative strain from $-400\ \mu\varepsilon$ to $-2200\ \mu\varepsilon$, due to the resin's thermal compression. This residual compression, which is relatively small, suggests that the properties of the FBG are probably not affected by the embedment in the composite material and that the FBG sensor can be used for other kinds of measurements. See text for additional details.

6. Temperature is decreased step-by-step. As the temperature decreases, the embedded FBG detects an increasing negative strain from –400 $\mu\varepsilon$ to –2200 $\mu\varepsilon$, due to the resin's thermal compression. This residual compression, which is relatively small, suggests that the properties of the FBG are probably not affected by the embedment in the composite material and that the FBG sensor can be used for other kinds of measurements (see the section on "Impact Detection").

Similar results, showing a compression of about –2400 $\mu\varepsilon$, have been previously reported by Dunphy et al.[21] In the last step, a dramatic decrease in the signal-to-noise ratio occurring at the end of the experiment can be observed. This is due to an optical power decrease, induced by significant stresses (sharp bends, microbends) along the optical fiber supporting the FBGs, that not only considerably reduces the signal-to-noise ratio but also the spectral Bragg peak resolution at the same time. This detrimental effect may occur in textile composites showing periodic microbends. It may be avoided by applying a thicker polymer coating to the fiber.

Smart Resin Transfer Molding Control Process

In recent years, research laboratories and now the manufacturers of composite structures have perceived the advantages offered by optical-fiber sensors in enhancing the quality of their processes and reducing costs associated with these phases of development. This aspect is particularly acute with regard to the resin transfer molding (RTM) process. RTM is a low-pressure molding process that involves packing layers of dry reinforcement fibers or a preform into a tight mold into which a mixed resin catalyst is injected, followed by thermal polymerization. After curing, the mold can be opened and the composite part removed.

The RTM process allows industrial production of parts to their final dimensions, but the long adjustment phase required to achieve the optimal physical parameters is a drawback to its use. It is rather difficult to guarantee injection of the resin into every part of the mold without leaving dry zones that then become points of structural weakness; furthermore, the high reinforcement-fiber volume implies a very dense composite preform, which makes accurate resin-flow modeling difficult. Moreover, as injection followed by polymerization is done within a closed metallic mold, the possibilities for *in situ* control are limited. So, the process adjustment requires many prototypes, since only "post-mortem" analysis (slicing followed by a microscopic analysis) can provide information feedback on suitable parameters. Such an "open loop" approach is very expensive and time-consuming. Therefore, manufacturers are actively looking for a technique that can provide *in situ* measurements of the process as the composite is formed. Optical-fiber sensors and FBGs are able to help in this area, as they are small enough to be nonintrusive, they provide very accurate measurements, they are electromagnetically inert, and they allow multiplexing of many sensing points. With these advantages, they look like a decided asset for this type of problem.[22]

To illustrate this, we next describe a project that uses optical-fiber sensors to supervise the manufacturing airplane propeller blades of the type shown in Figures 3 and 4. The objective of this project, led by French aeronautics equipment manufacturer Ratier-Figeac in collaboration with the CEA-LIST (the Atomic Energy Commission, Laboratory for Systems and Technology Integration), was to use an advanced measurement system, based on embedded FBG sensor technology, to obtain insights into the process sequence, map resin flow by detecting air-to-resin transitions during the injection, check for dry zones or voids in the structure, and consequently improve the quality of manufacturing and reduce development costs.[23]

In this experiment, 38 FBG sensors were installed in an RTM propeller-blade mold (36 strain sensors and 2 temperature sensors), divided into 4 lines on the face of each blade (Figure 5). The FBG temperature sensors, located at either end of an optical fiber, are based on a CEA proprietary design and make use of an FBG transducer placed inside a microcapillary (20 mm in length with a 350-μm external diameter) externally coated with polyimide (Figure 6). The optical fiber is maintained at the input of the capillary with a special high-temperature (350°C) sealing cement. At the other closed end, the fiber is free to move inside the capillary. In this way, the FBG temperature sensor is isolated from mechanical stress induced by the composite structure, enabling differential strain measurements free from the influence of temperature.

At the beginning of the injection process, the temperature difference between the resin and the mold is small (a few degrees Celsius). Consequently, it is not practical to use only thermally induced effects to map resin flow. The useful measurement parameter is the Bragg wavelength shift that happens when the resin flow reaches a sensor location. This effect, however, occurring inside the tightly packed preform in the mold, is small, in either compression or tension. Experimental sensor response ranges between 20 $\mu\varepsilon$ and 400 $\mu\varepsilon$. These small values make real-time data interpretation difficult, particularly defining the strain threshold in order to identify the interaction of the resin flow with the sensors. This is the reason why careful postprocessing of the measurements is needed in order to extract valuable results regarding resin-flow behavior.

With this restriction in mind, resin-flow analysis is possible using internal constraint modifications experienced by the optical FBG sensor network, leading to a smart approach in RTM manufacturing. Figure 7 shows the progression of the resin flow in the mold, based on an interpretation of the sensor response.

As a variation of RTM, the resin film infusion (RFI) process is now being used by some manufacturers as an alternative to the usual pre-impregnation processes because it yields improvements in quality and promises a significant cost reduction. In RFI, a dry layer of reinforcement is used along with a cast layer of catalyzed resin. Under pressure and heating, the resin envelops the reinforcement fibers, and thus the part is made. The great benefit of the RFI process is to reduce the void content of the laminate because the dry reinforcement fibers allow air transport out of the stack during polymerization.[24] It is advantageous for large structures and for the use of high-viscosity resins (which are difficult to work with in traditional RTM). With this new process, optical-fiber sensors and FBGs should be useful in controlling physical parameters such as degree of cure, cure rate, and temperature.

Impact Detection

For manufacturers and end users of composite structures, a second motivation for using optical-fiber sensors, after manufacturing and testing, is "health" monitoring, that is, evaluating the lifetime of a component or a whole structure. This is essential in applications in which safety is a concern. An example is the radome (nose) of an airplane, which is typically made of a thick, sandwich-type composite structure that is transparent to electromagnetic waves. Optical-fiber sensors and, more specifically, FBG sensors, are potential candidates for nondestructive instrumentation to measure stress and damage in such a structure.

One specific topic concerns the evaluation of permanent damage induced by low-energy impacts (less than 30 J, i.e., too small to cause visible defects on the surface) as well as delamination due to fatigue.[19,20]

The FBG, which is a quasi-distributed sensor localized 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 characterized by a permanent strain in its surroundings.

To demonstrate the potential of FBG-based instrumentation in the assessment of material integrity following impacts, several composite samples were manufactured with embedded FBGs. One of them includes three embedded FBGs placed 10 mm, 30 mm, and 50 mm, respectively, away from the point of impact located in the center of the sample, as described in Figure 8.

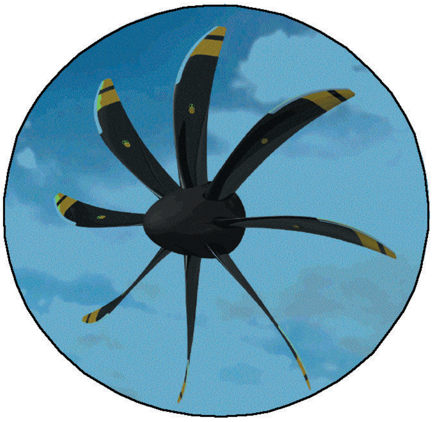

Figure 3. Airplane propeller blade with embedded FBG sensors. Courtesy of Ratier-Figeac, France.

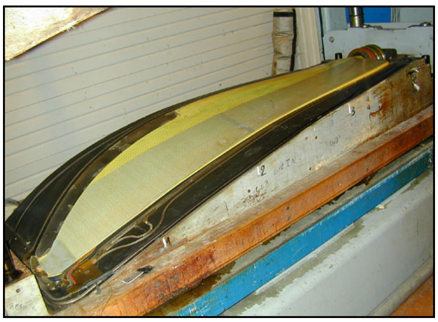

Figure 4. Propeller blade mold, with FBG sensors installed, after curing. Courtesy of Ratier-Figeac, France.

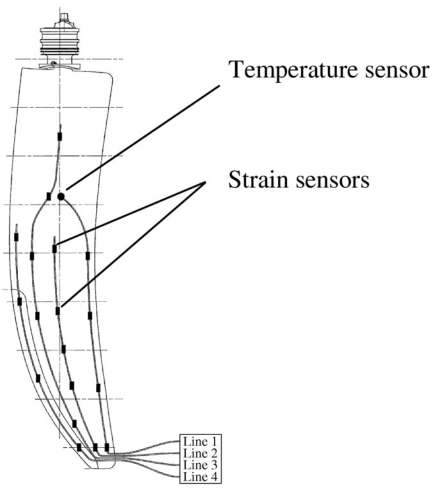

Figure 5. FBG instrumentation on one face of a propeller blade.[23]

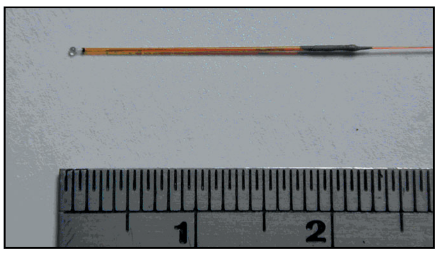

Figure 6. FBG temperature sensor for in situ *measurements in a composite propeller blade. Courtesy of CEA/Marty.*

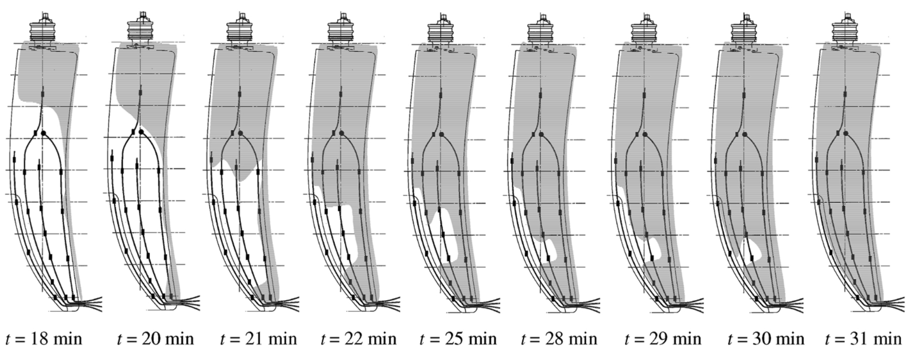

Figure 7. Progression of the resin flow in a propeller blade mold, as inferred from the FBG data.[23]

The plate was submitted to nine successive impacts with energies ranging from 2 J to 20 J. The impact-energy threshold for the three successive FBGs were, respectively, 8 J, 10 J, and 12 J (Figure 9). It is interesting to note the strain saturation for the FBGs, about −500 $\mu\varepsilon$, after the impact of 18 J in such a sandwich structure.

The method we have developed to record a given permanent defect (invisible on the surface) in sandwich composite material arising from an impact is the first step toward a mapping method able to determine and localize all of the defects present in the whole structure. Because the method for measuring impacts is to detect the strains induced by them (primarily internal delamination or foam crushing), the embedded FBG sensing grid needs to be dense enough (typically 10 cm × 10 cm) to sense any zone of the structure. The next step in this global damage-detection study is to model the sensor response in order to localize and quantify a given defect by triangulation.

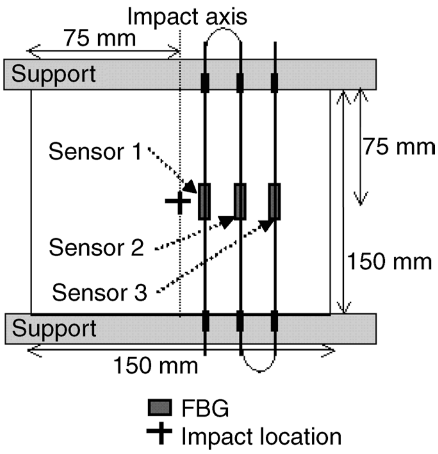

Figure 8. Schematic illustration of a composite plate embedded with three FBG sensors placed 10 mm, 30 mm, and 50 mm, respectively, away from a point of impact located in the center of the sample. This setup is used to demonstrate the potential of FBG-based instrumentation in the assessment of material integrity following impacts.[19,20]

Smart Bogies for Fast Trains

Mobility is an important factor for economic growth. Enhancing train transportation will become a key issue in future years, as competing means of transportation such as road and air will gradually become saturated in capacity. In a recent study, the German government predicted a saturated situation for these systems within the next 10 years if today's rate of development continues. One consequence may be a load shift of transportation to rail. The European Union is promoting this by developing initiatives and enhancing the competitiveness of the rail grid by means of deregulation and interoperability. This process has been nearly completed in Great Britain, with some consequences. Additionally, the European Union is supporting this process with a planned upgrade to the existing rail network, the Trans-European Net. This will require the upgrade of 40,000 km of existing rail tracks for use at speeds of up to 200 km/h instead of the 160 km/h typical today, and the development of 20,000 km of new rail tracks for use at speeds of greater than 230 km/h.

Within this framework, some companies in Europe are working to develop new functionalities for trains. In France, Alstom Transport SA, the train division of the Alstom Co., has been working for several months on a new project involving composite materials for a new railcar bogie (Figure 10). Bogies are the swiveling undercarriages at either end of a railroad car on which the wheels are fixed and which serve to damp vibrations transmitted to the car. As we have already discussed, composite materials present many advantages, including lower density and a higher strength-to-weight ratio than metals. However, their use in this area of the transportation industry is new; previously, bogies were made from metallic materials. Consequently, one important part of this development is validating the mechanical behavior of the bogies. A mechanical simulation was led by DDL Consultants (a small company specializing in modeling) with Samcef software; the monitoring technology that achieved the experimental validation was implemented by the Optical Measurements Laboratory of the CEA-LIST, by the use of several optical FBGs during static and dynamic trials.

Several parts of composite bogies were instrumented with *in situ* FBG sensors. An optical line is composed of several strain FBG sensors for static and dynamic tests, while an extra FBG is devoted to temperature compensation. Accelerated aging tests were carried out by Alstom and the CEA in a climatic chamber to simulate in-use environmental conditions (e.g., cycles of stress, intense cold, heat, moisture, and strong lighting). For these accelerated life tests, an optical line containing three FBG strain sensors and one extra FBG for temperature compensation was embedded during manufacturing of the structural element.

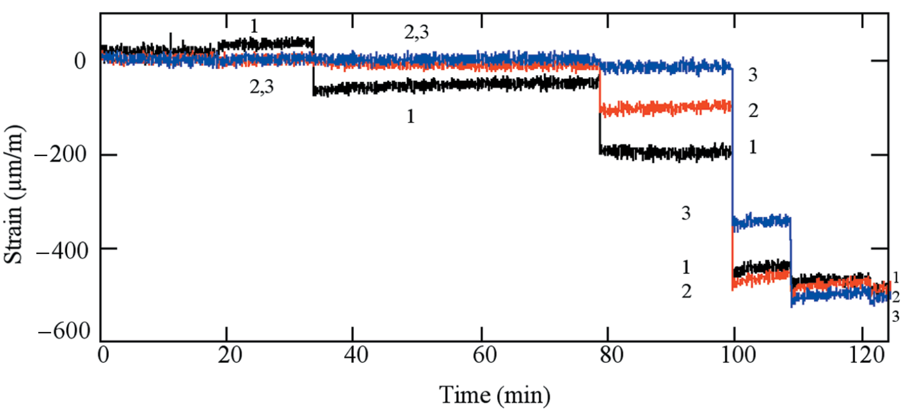

Figure 9. Real-time detection of impacts with energies ranging from 2 J to 20 J by means of three FBG sensors (labeled 1, 2, and 3) embedded in a composite material. Each step corresponds to an impact of increasing energy.[19,20]

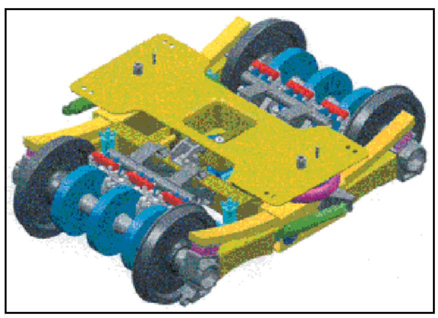

Figure 10. Design of a new composite bogie for fast trains. Bogies are the swiveling undercarriages at either end of a railroad car on which the wheels are fixed and which serve to damp vibrations transmitted to the car. Courtesy of Alstom, France, from Reference 25.

The stress levels were induced according to three cycles of dynamic loading added to a static one: 27 kN ± (8 kN @ 7 Hz), 32 kN ± (10 kN @ 7 Hz), and 38 kN ± (11 kN @ 7 Hz). The corresponding strain ranged from about 2500 $\mu\varepsilon$ up to 3500 $\mu\varepsilon$ in the static mode and from 700 $\mu\varepsilon$ to 1000 $\mu\varepsilon$ in the dynamic mode. The thermal cycles (as specified in the International Union of Railways standard UIC-515-4) were completed every 16 h. The instrumented elements underwent more than 10 million cycles during three weeks of testing, which represents, to our knowledge, the most severe fatigue tests carried out to date with an FBG-based monitoring system.[25]

The results of these experiments showed a perfect agreement of the measurements with the modeling, which proved that these new bogies retain a constant stiffness with no observable aging or mechanical-behavior evolution (Figure 11).

FBG-Based Strain Rosette

In the area of strain measurement using FBG sensors, rosettes can be designed to instrument existing composite structures for which embedded sensors are not possible (Figure 12).[26,27] Rosettes are made of two or three noncollinear strain gauges mounted on a common substrate at 45° (to form a rectangular rosette) or at 60° (to form a "delta" rosette).

Such strain rosettes are used extensively in experimental stress analysis to measure the two principal strains (and stresses) and the orientation of the principal axis whenever it is not known *a priori*. Besides this classical application, we have also described an innovative way to use this rosette as a uniaxial strain gauge that is rigorously independent of temperature effects as well as its orientation on the structure under test. The uniaxial strain, the angular orientation, and the temperature are accurately recovered from data given by the three gauges.

FBG rosettes are potentially easy to manufacture, as they are amenable to batch processing. They may be assembled by hand or automatically using numerical command machines driving a positioning ultrasonic transducer head, leading to mass production. At least two layout designs may be considered. The first design uses one fiber with three Bragg gratings in series and operates in WDM. A second design uses three Bragg gratings in parallel (one fiber for each grating) and operates with an optical switching unit or a parallel analyzer. The bending radius cannot be too small, for reasons of mechanical reliability (the bending radius in Figure 12 is 10 mm). The first layout requires the fibers to cross each other, whereas there are no crossings in the second design. Some delta rosette "patches" containing one fiber have been realized in the laboratory, accurately positioned with the help of a reticle (Figure 13). The sides of the delta rosette are 30 mm long, but a smaller length can be designed.[28]

After positioning, a polyimide cover is applied to the substrate, sealed with acrylic glue, and cured. This second polyimide sheet may leave the fiber triangle (sensing region) partially uncovered for further direct fiber bonding. For industrial applications, we start from a connected optical cable (0.9 mm or 3 mm in diameter) from which the fiber is stripped off for about 30 cm. Then, the fiber may be hydrogenated, and the Bragg gratings are photowritten. The rosette patch is then assembled following the procedure described, except that the cable is sealed so that the patch can be handled as easily as any normal electrical strain-gauge rosette. The polyimide support of the rosette can then be bonded onto metallic parts, stitched onto textiles like a patch, or embedded into composite materials.

Long-Gauge Glass-Epoxy Extensometers

Fiber-reinforced plastics may also be used as proof-bodies for extensometers. Unlike extensometers with surface-mounted fibers, the sensing fiber is incorporated into the composite material itself during the pultrusion process.[29] Pultruded structural composites are lighter and more corrosion-resistant than their metallic equivalents, resulting in easier handling and lower cost. Moreover, they are electrically insulated (immune to electromag-

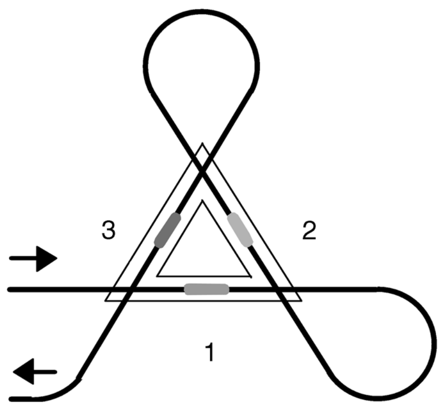

Figure 12. Delta strain rosette with three FBGs.[26]

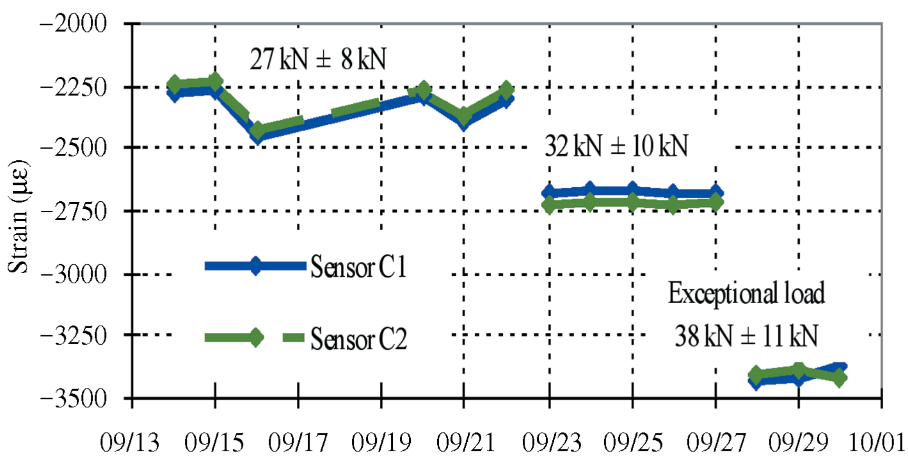

Figure 11. Comparison of a numerical simulation with optical FBG measurements.[25]

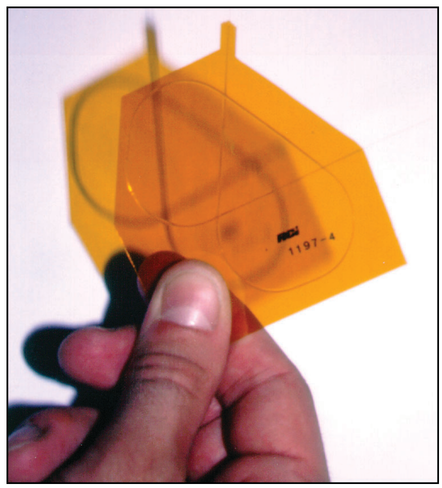

Figure 13. A rosette sensor. Courtesy of CEA/Magne.

netic interference) and display good mechanical performance (linearity and fatigue). Their mechanical properties depend on the type of reinforcement used (glass, Kevlar), resin type, and profile geometry. The fiber may be located at the center of the composite rod, preserving the fiber from degradation and rendering the measurement free from torsion influence. The fiber runs in and out so that each extensometer may be placed in series along a single cable line and may operate in transmission or in reflection, depending on the network configuration.

In the pultrusion process, parallel glass fibers are bundled and projected through a resin-impregnation furnace and through heating zones. The polymerization is then carefully controlled, as well as the cooling of the composite part. The composite profile may then be cut to the desired length. The composite extensometer has a cylindrical shape, but other profiles may be obtained on demand. Once the composite cylinder is made and cut, threaded sheaths are crimped onto each end. Extensometers are screwed onto fasteners fixed onto concrete or embedded into the concrete while casting (Figure 14).

Conclusions

Monitoring of composite structures is a 10-year-old activity, still a new technical field in many aspects. Nevertheless, optical-fiber sensors, and particularly fiber Bragg gratings, are being considered more and more often for such purposes, due to their advantages in many industrial composite applications.[2]

In the last decade, a number of national and international research and development programs have addressed the use of optical fibers as temperature, strain, stress, pressure, vibration, and refractive-index sensors, and there are now many prototypes of systems and some products available. The main applications are in aeronautics and transportation as well as in civil engineering sectors. Other applications are found in space (antenna stabilization, shuttle or satellite monitoring, the space station, etc.) and the naval industry.[30]

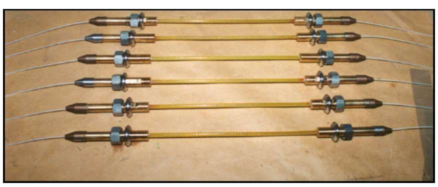

Figure 14. Composite-based FBG extensometers for civil engineering applications. Courtesy of CEA/Magne.

In a few years, a "health diagnosis" of specific or critical parts of any aircraft will be able to be carried out periodically, or on demand according to security requests, thanks to airborne or ground-based FBG-based optical-fiber sensor measurement systems. Such industrial instrumentation will allow one to guarantee the conformity of these parts with respect to their specifications and consequently to certify that an aircraft is or is not able to fulfill its mission. Certainly, the checklist carried out by a pilot before takeoff will integrate new parameters such as structure monitoring.

In this context, research studies are being carried out around the world, relating in particular to enhancing the manufacturing process, ensuring quality control of manufactured elements, and monitoring their health in use (impact detection plus assessment of integrity), as well as achieving cuts in operational and fuel costs.

Indeed, the subject on which the aeronautical sector will focus in the coming years concerns smart (or "intelligent") structures, also called adaptronics. This term relates to all of the means (materials and software) necessary to obtain a better understanding of the real-time parameters involved in any phase of flight, namely, takeoff, cruising, and landing, in order to increase safety, reduce noise, and decrease fuel consumption.

Fiber-optic measurement methods have already shown excellent promise in laboratory tests and in some field trials. Of course, there is a need for scientific research and development to produce some specific sensors, embed fibers routinely, enhance the performance, reliability, and ruggedness of the measurement systems, and reduce their costs. Recent trials have shown that FBG-based optical-fiber sensors offer the possibility of enabling industrial smart-structure technology, as they are able to provide critical information for smart manufacturing, nondestructive evaluation, health monitoring, and damage control. Moreover, they are fully synergistic with the expanding telecommunications market, enabling potential low costs in the mid-term.

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