Monitoring of Smart Composite Materials by Optical Fiber Sensors: From Fabrication to Mechanical Characterization

X. CHAPELEAU and M. DRISSI-HABTI

ABSTRACT

In this work, composite materials were instrumented by optical fiber sensors with the scope to monitor the instrumentation of pultruded profile made out of composite materials. Then after, using Fiber-Bragg Gratings, were used to monitor strain under quasi-static and fatigue loading under 3-point bending. Results show that optical fiber sensors perform well in either cases. The results that are reported are part of the French Program decid2 aiming at building a large dimensions plateform (20m x 3,5m, DECID2 Project).

KEYWORDS : Smart Composites, pultrusion, Optical Fiber Sensors (OFS), Fiber-Bragg Gratings (FBG), Structural Health Monitoring (SHM), Fatigue

INTRODUCTION

Polymer matrix composites are increasingly used as structures in various industrial fields. Their good mechanical properties, excellent corrosion-resistance, their rigidity/weight ratio higher than steels, their good processability and ease of installation are their main advantages. However, despite these, some key questions remain about their sustainability and environmental performance over the long term. It is therefore of a prime importance to develop suitable and reliable structural health monitoring technique that will enable fine estimates of strain in various localizations. The so-called smart composite concept is a promising technique to conventional methods and consists in embedding various types of sensors within composites. So the behavior of composite structures under various stress sollicitations can be finely monitored.

Optical fiber sensors (OFS) better fulfill the requirements of embedded sensors in composite materials than piezoelectric sensors. They offer a good thermal resistance and a high mechanical strength, especially under tension, which prevents

Xavier Chapeleau, Monssef Drissi-Habti. Pres LUNAM, IFSTTAR, Dept. MACS, CS4 Route de Bouaye, 44344 Bouguenais. xavier.chapeleau@ifsttar.fr ; monssef.drissi-habti@ifsttar.fr

them from being damaged during the manufacturing process. Moreover, thanks to their very small size (diameter less than 250µm), they do not compromise significantly the structural integrity of composite materials [1, 2, 3].

The French Project Decid2 aims to build a 20m x 7m demonstrator made out of smart composite material that use fiber optic sensors. The smart composites are processed by pultrusion. The optical fiber used as strain sensors provides a structural health diagnosis *in-situ* and in real time. The platform is intended to be sought outdoor, in fatigue and creep under low stresses (well below the end of proportionality).

In this work, optical fiber sensors are used to monitor continuously the process of pultrusion using Optical Backscattering Reflectometer (OBR). Fiber-Bragg-Gratings (FBG) were also used to monitor strain during quasi-static and fatigue loadings under 3-points bending. In both cases, results show that these sensors are performing very well and that reliable results can be obtained.

MATERIALS & METHODS

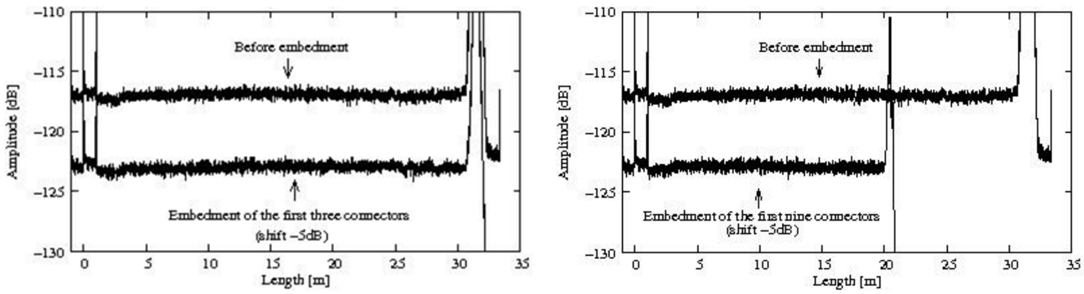
The material considered in this study is a composite matrix type vinylester and fiberglass with a very high volume fraction (Vf = 66%) which gives it great rigidity and a high mechanical strength. The vinylester resin is popular for its low production cost, ease of implementation, but especially for protection against chemical corrosion of the fibers; glass fibers for their own good price/performance ratio.

The manufacturing process retained in the project Decid2, pultrusion, provides constant section beams unlimited length. This manufacturing process is a major asset, especially now that the assembly and bonding of composite materials are barriers to its use. In our study, the optical fiber is directly embedded within the material during the pultrusion process, as well as the reinforcing fibers. This produces an embedded sensor in the material.

The section studied here is rectangular and of dimensions 16 mm x 40 mm. It may be noted that it is relatively large compared to the bibliography. Indeed in a study of fatigue where the size effect is quite large, it is important to work with thicknesses close to the actual beams, even if they do not have the same geometry.

MONITORING OF THE EMBEDMENT OF OPTICAL FIBER SENSOR DURING PULTRUSION PROCESS

To monitor continuously the process of pultrusion or more precisely to check whether optical fibers were successfully pultruded within composite profiles, Rayleigh based sensing technique has been used. It is a recent optical fiber sensor technology which allows distributed strain measurements. Therefore, broken optical fibers can easily be detected. It is based on an interferometric measurement which offers a high spatial resolution. To summarize the operating principle, the Rayleigh sensing technique is based on the measurement of the wavelength shift between two local spectra. The measurements of the local spectral of an optical fiber segment is achieved by an interferometric technique called Optical Frequency Domain Reflectometry (OFDR) technique. By repeating this measurement for all the segments of the optical fiber, local spectral shifts can then be calibrated and assembled to form a distributed strain or temperature measurement. The typical accuracy of Rayleigh based sensing technique OBR are±0,2°C in temperature and ±1µm/m in strain with a spatial resolution less than 2cm. The range measurement is approximately 70m with a measurement time less than 10s according to specifications provided by the manufacturer of the device. This technique is limited to static tests up to now.



(a) (b)

Figure 1. OBR tracking showing both successfully embedded optical fiber (a) as well as a failed one during pultrusion (b)

Figure 1a shows the signals before and after embedment of an optical fiber into a pultruded profile that show that the optical sensor has not experienced any damage and was positively inserted. On the reverse, when an optical fiber is broken, the OBR is a perfect indicator, where the failure of the optical fiber is clearly shown (Figure 1b).

MONITORING OF THE DEFORMATION OF THE SPECIMEN DURING MECHANICAL CHARACTERIZATION

The prototype will be working in bending configuration. Thus, for maximum approach to the actual loads, bending tests were considered only.

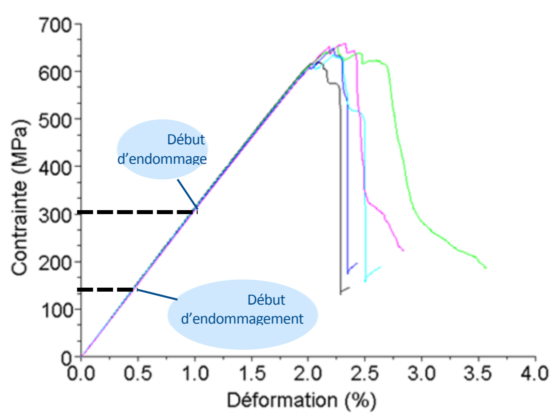


Figure 2. Stress-strain curve in 3-point bending for a set of composite specimens. The onset of damage as well as the proportional limit are indicated.

The distance between lower spans is 260 mm. First quasi-static tests (Figure 2) with a cross-head speed of 1 mm/min allowed the determination of the composite Young's modulus as 31 GPa. Moreover, the proportional limit is estimated as 300 MPa, while keeping in mind that for a material with a behavior very close to the brittle behavior, it is difficult to rigorously establish this value. Finally, using acoustic emission testing, the early damage appearing was estimated at about 130 MPa.

Fiber-Bragg-Gratings (FBG) were also used to monitor strain during quasi-static and fatigue loadings under 3-point-bending. A FBG is photo-inscribed grating in the core of the optical fiber with a given pitch. At each FBG corresponds to a Bragg wavelength λ_B. When there is thermal expansion or deformation of the fiber, the Bragg wavelength is modified. By studying the shift of the wavelengths, strain can be measured. It is also possible to multiplex an optical fiber with more FBG whose wavelengths of Bragg are sufficiently separated. Embedded Fiber-Bragg Gratings (FBG) were used to get the deformation trigged during quasi-static flexure loading, as well. Figure 3 shows Bragg wavelength shift. This result shows clearly that there is an increase of the wavelength (thus, the strain) when increasing the load.

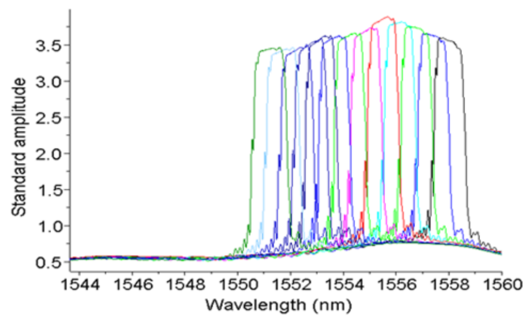


Figure 3 Bragg wavelength shift during3 point bending load of a composite specimen.

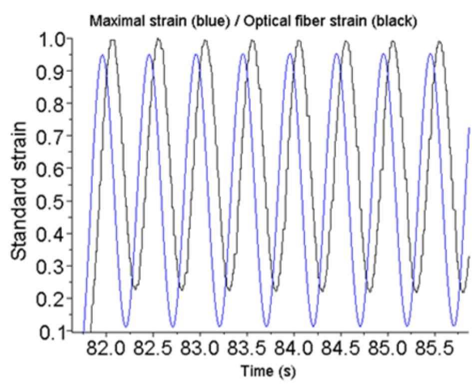


Figure 4 Comparison of strain values delivered by FBG and the mechanical testing machine.

Figure 4 shows the strain recorded by both FBG and mechanical testing machine. To enable an easy comparison between the two signals, a lag phase was introduced. As shown on the Figure, the strain measured using FBG is smaller than the one displayed by the mechanical testing machine. This is simply the result of the difference between the strain measured by the mechanical testing machine at the extreme of the area under tension and the position of the optical fiber inserted into the heart of the area under tension, but closer to the neutral axis. To get a match between the 2 signals, it is of a prime importance to run some additional mechanical calculation that help to figure out the accurate position of the FBG.

This study demonstrates several very positive results about the insertion of optical fiber in a composite beam, since no ruptures of the fibers was recorded during the pultrusion of fiber. In addition, this kind of sensor show low intrusivity and good reliability at high strain.

CONCLUSIONS

The instrumentation by optical fiber give a alarm signal in the event of excessive deformation and the measure is very accurate. This study demonstrates several very positive results about the insertion of optical fiber in a composite beam: no ruptures of the fibers during the pultrusion of fiber, low intrusivity and good reliability at high strain

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