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# RTM process monitoring and strain acquisition by fibre optics

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**Abstract**

The development of Resin Transfer Moulding technology for advanced applications requires a detailed analysis and control of the process. Fibres optics and Fibres Bragg Gratings are useful tools to investigate composite structures during their lifetime service. They are here employed for the monitoring of manufacturing phase and the acquisition of strains during product usage in service. The adopted monitoring procedure allows to follow all the stages of the production process, evidencing their possible influences over final laminate characteristics. Resin injection, curing and cooling, mould extraction, sensor position, deformation control during mechanical testing are analysed on the basis of the signal output from fibre optic sensors embedded in a model component.

*Keywords:* RTM process monitoring; strain measurament; FBG sensors; fibre optic sensors.

## 1. Introduction

In recent years aeronautic industry has shown an increasing request to produce light and efficient structures, with high standards of performance and safety. The possibility of employing a monitoring system to have a direct control during laminate composite manufacturing can remarkably improve the quality level of produced parts. The most common technique used in the production of composite structures for aerospace applications is the vacuum bagging, with a manual lamination of each ply; however, techniques based on resin infusion, such as resin transfer moulding (RTM) and vacuum assisted RTM (VaRTM), have shown many advantages, particularly in the production of complex shape components with stringent tolerances [1]. In addition, RTM technologies operate with dry fabrics, which are cut in the right shape and are layered inside the mould to make a preform. The preform is then compacted when the mould is closed; next the mould is heated up to the infusion temperature and the

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resin is injected or flowed under vacuum at high temperature. Mould filling is very important because, it remarkably influences the final quality of the composite product; partial impregnation of the fibre bed creates voids in the part and as a result reduces mechanical properties. For these reasons the percentage of defects formed during resin infusion must be reduced. After infusion, the resin is cured and, when the curing process is completed, the mould is cooled down and the composite part is extracted [2].

In this work, a practical methodology is presented to implement a monitoring system, able to follow all the production made with VaRTM technique. The monitoring system should respond to some characteristics like: resistance to the processing temperature (180°C), capacity to record the resin front position during infusion, ability to measure temperature variations and to measure the extent of deformations within the laminate. Sensors embedded in the composite layup were also used in the after-production testing and service of the component, thanks to their capacity to work as a deformation transducer; they can be considered as a health monitoring system [3]. In order to respond to all the requirements, a monitoring system based on fibre optic sensors was developed, which guarantee a minimum embedding problem and a resistance to high temperature. Two different types of sensors were employed: simple fibre optics, able to detect the resin front during the infusion, and Fibre Bragg Grating sensors (FBG). These sensors work as deformation transducers; they are able to record deformations due to temperature variations and mechanical deformations which arise inside the laminates during the production. The application of FBG sensors, as deformations transducer, is due to the dependence of some of its characteristics from the geometrical variation, created by deformations or by an increase in temperature. These sensors are able to measure deformations with an accuracy of 3-5με, so they are competitive with traditional strain gauges. The use of these sensors is an important improvement to obtain smart-materials and smart-structures [4]. In order to reliably monitor the strain, the exact position of the sensor must be localized. This paper demonstrates how the use of measuring systems based on FBG can give valuable improvements over classical strain gauge techniques in structure deformation monitoring.

## 2. Experimental

### 2.1. Materials

Materials employed during the testing were characterized, in particular the epoxy resin RTM6 (Hexcel) and two carbon fabrics, CC420 and CC600, produced by Seal SpA (Table 1). The viscosity curves of the resin at different temperatures, and, thus, the variation of curing time with the process temperature, were measured by a torsional reometer (Rheometrics RDAII). The viscosity measurement was performed by applying a torsional deformation with constant strain rate and was repeated at different rates and temperatures. Results shows that when the degree of cure is less than 30%, the resin can be considered as a liquid, moreover, at this stage, it behaves like a Newtonian fluid showing a viscosity independent of strain rate (1).

$$\eta = 0.0053 \cdot e^{\frac{293.14}{T}} \tag{1}$$

Table 1. Properties of CC420 and CC660 fabrics.

| Fabric | Fibre (tex) | | Threads x *cm* | | weight [*g/m²*] | Thickness [*mm*] |
|--------|-------|-------|------|------|------|------|
| | warp | weft | warp | weft | | |
| CC420 | HS12K | HS12K | 2.6 | 2.5 | 416 | 0.38 |
| CC600 | HS12K | HS12K | 3.8 | 3.8 | 600 | 0.60 |

The permeability of the reinforcements was determined by measurements of flow rate along the principal directions of the fabrics according to one-dimensional Darcy's law (2). Figure 1 shows measured permeability for different fibre volume fraction.

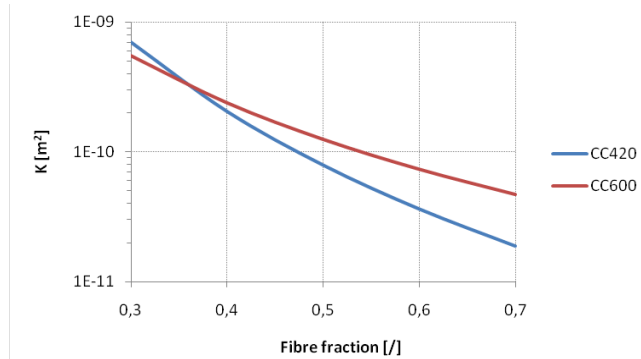$$v_x = -\frac{K_x}{\eta\phi}\frac{\partial P}{\partial x} \tag{2}$$



Fig. 1. Measured permeability for CC420 and CC660 fabrics.

### 2.2 *Laminate fabrication*

In this work plane laminates were produced and monitored. The total thickness was 7 mm and a symmetric lamination sequence composed of 6 CC600 + 6 CC420 laminae, in order to have a fibre volume fraction of 50%, was selected. Thanks to the optical fibres connected to the laser source and the power meter, the infusion rate could be experimentally checked. When the resin reaches the top of an optical fibre the variation of the refractive index is detected by the power meter. The correct infusion rate can be evaluated if the actual position of each fibre optic is known and the time interval between each decrease of reflected power is measured.



(a)                                                            (b)
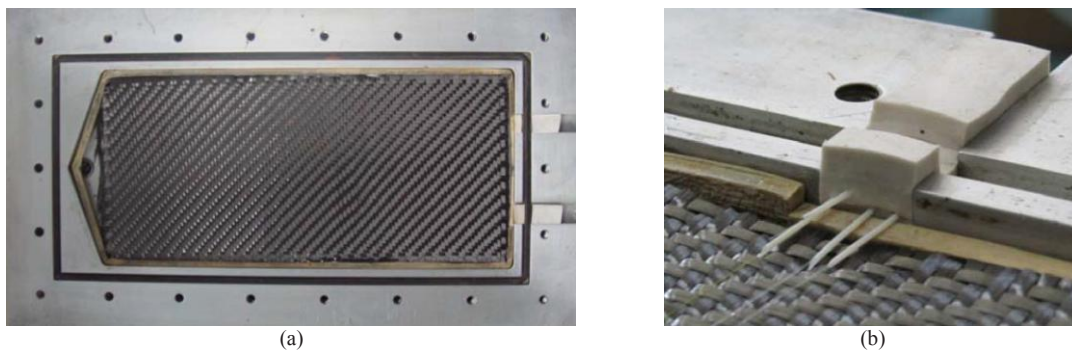
Fig. 2. Preform in the mould (a) and details of FO entry (b).

The monitoring system consists of a laser source connected to FO and to a FBG sensor, a Power Meter used to measure the laser power reflected by the end of FO and an optic interrogator, able to detect every

minimum variation of Bragg wavelength $\lambda_B$ [5]. In both laminates 6 FO were embedded at different positions; FBG sensor was also embedded to monitor strain and temperature (Fig. 2). During these tests all the production phases were monitored, from the first step in which the preform was placed inside the mould until the extraction of the product from the mould, passing through the different stages: layup, heating, infusion, curing, cooling and mould opening.

## 2.2. FO and FBG individuation

To view the path of the optical fibres, X-Ray radiography of the plate were made, by selecting optimal parameters in order to obtain sharp images. From these images it is possible to determine the path of the optical fibre in an exact way (Fig. 3).
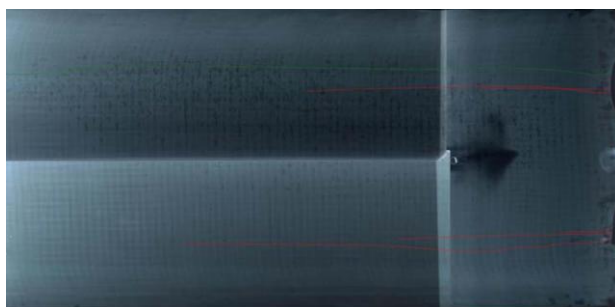
Fig. 3. Position of FO's evidenced by radiographic images.

Radiographs also allowed to observe the arrangement of warp and weft of the fabric in different layers of carbon fibres. In the central part of the laminate, fibres are placed perfectly perpendicular, as expected. The results could also evidence defects such as the areas next to edges where edge effects, i.e. curvature of the fabric due to non-homogeneous resin flow front, were evidenced. The exact location of FBG sensor along the fibre was determined by recording signal time and amplitude following temperature pulses applied in different positions of the FBG area.

## 2.3. Mechanical tests

The use of FBG, as deformation transducer, is based on the variation of the Bragg wave-length $\lambda_B$. Any change in the spacing of the grating, inside the FBG sensor, due to some deformations, determines a variation of the Bragg wavelength. The deformation state of FBG can be reconstructed by analysing the variation of the Bragg wavelength. Four points bending test was selected to stress the specimen with a constant bending moment in defined area. An independent measure of deformation by strain gauges glued on the specimen surface was used as check. Figure 4 illustrates the dimension of the specimens and the position of strain gauges.

Through eq. 3 it is easy to calculate the effective deformation of the embedded FBG:

$$\varepsilon = \frac{\Delta \lambda_B}{(1 - p_e) \cdot \lambda_B} \tag{3}$$

where $p_e$ takes into account, through the Poisson's ratio and Pockel's coefficient, effect of stress on the index of reflection.
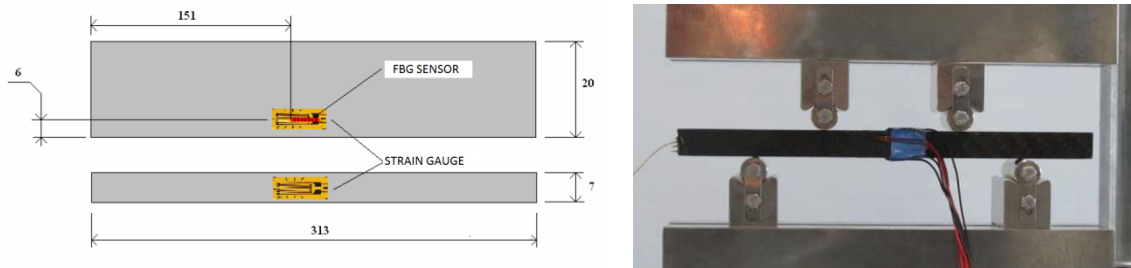
Fig. 4. Position of strain gauges and FBG in the specimens.

## 3. Results

The investigations allowed to check the efficiency of the embedding procedure and to verify the ability of the monitoring set up to record the resin front. In the infusion stage the resin flow rate was increased by regulating the resin inlet valve. Both FO and FBG were recorded during infusion. Figure 5 shows the signal representation of the optical fibres as a function of time.

For a better analysis of the deformation evolution recorded by FBG the whole processing cycle was subdivided into four different stages:

- carbon fabrics lamination and mould closure;
- resin infusion at high temperature;
- further mould heating, resin curing and cooling;
- mould opening and laminate extraction.

Lamination by stacking each carbon ply inside the mould was followed by compaction of the preform and mould closure at room temperature. During infusion, the resin at 80 °C flowed in the mould and in the preform, which were maintained at 120 °C. At the beginning of the infusion stage the FBG sensor did not show any modification, while it marked clearly when the resin front reached it: a substantial reduction of Bragg wavelength when the resin, at 80 °C, reaches the sensor, at a temperature of 120 °C was recorded.
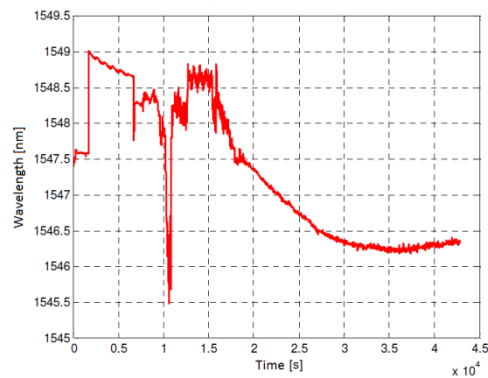


Fig. 5. Evolution of the wavelength during the production process.

When the infusion was completed, the mould was heated up to the curing temperature, i.e. 180°C. An increase in temperature corresponds to a constant increase of $\lambda_B$. The curing, at a constant temperature of 180°C required two hours; during this stage the FBG sensor did not record substantial variations of $\lambda_B$.

The monitoring continued during the cooling stage; a contraction was recorded due to mould and laminate shrinkage, evidenced by a wavelength variation with time; part of this deformation was recovered during the mould opening and laminate extraction.

Successfully completed the investigation as to determine the exact position of the FBG sensor in the laminate a verification of the functionality in quantitative terms was needed. To achieve these goals mechanical tests were performed on samples extracted from the laminates. A specimen with FBG placed at a distance of 4 mm from neutral axis was cut, and a strain gauge was glued at the bottom side (Fig. 4). As reported in Fig. 6, the accordance between recorded and expected signal was remarkable.
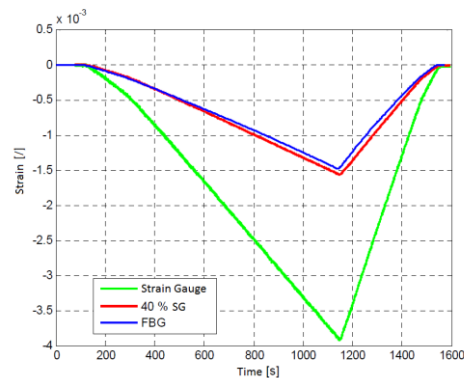


Fig. 6. Comparison between FBG sensor and strain gauge measurements.

## 4. Conclusions

This work demonstrates the capabilities of FO and FBG in monitoring either during components production and life cycle. Remarkable is the use of the same FBG sensor for both applications obtaining significant results, similar to those achievable using traditional measuring systems like strain gauges. This way of measuring represents an interesting characteristic for structural health monitoring systems.

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