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Embedded compaction pressure sensor based on Fiber Bragg Gratings

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ABSTRACT

A new optical fiber sensor for monitoring the compaction pressure of a composite material during the molding process is designed and experimentally demonstrated. The sensor is based on a Fiber Bragg Grating embedded into a composite material, and it is able to measure the compaction pressure during the manufacturing process and the strain information while the structure is in operation. The proposed design has been characterized before its embodiment, showing a logarithmic response to the pressure. The sensor also exhibits a linear response to both strain and temperature, making it suitable for structural health monitoring applications.

1. Introduction

Ensuring the final performance of a composite structure implies a perfect control of the manufacturing process. Some manufacturing parameters such as the curing temperature or the compaction pressure need to be accurately set to achieve the material top performance. This is significantly relevant in Vacuum-assisted Resin Infusion (VaRI) or in Vacuum-assisted Resin Transfer Molding (VaRTM) [1], where the structure is molded using a rigid mold and a thin flexible membrane over the fiber that compress it against the mold surface due to the outer atmospheric pressure. Regarding this process the strict control of the compaction pressure is a critical point. As shown in [2], a pressure variation during the VaRTM may lead to a different thickness within the structure, so the monitoring of this parameter will ensure a better behavior of the structure. This strict control becomes more important for larger structures where thicker composites are required (reaching several centimeters) such as vessels or wind turbine blades.

There are lots of reported applications where different manufacturing parameters have been monitored. Examples such as the monitoring of the resin flow with artificial vision [3] or with electrical arrays [4] or measuring the inner strains or temperatures by optical means [5] have been successfully tested. Optical fiber sensors [6] and particularly Fiber Bragg Gratings (FBGs) [7] have been proved as a highly compatible technology with composite materials [8]. Their light weight, small size and electromagnetic immunity, make optical fibers highly compatible with composite materials to be embedded into the structure. This kind of sensors have been successfully employed to characterize the manufacturing process by analyzing the curing reactions using florescence [9] or by recording the inner strain and temperature during the curing process [10]. However, by embedding optical fiber sensors during the manufacturing process [11], it is also possible to obtain a sensor network capable of providing information during the structure operation. There are many examples where

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strain and temperature measurements are obtained with embedded optical fiber sensors [12,13] but, by combining these data with processing schemes, more complex artifacts can be detected such as cracks or damages [14], thus preventing a structure malfunction.

In this work, an optical fiber sensor to measure the compaction pressure during the manufacture process is designed and tested. The proposed sensor is embedded into the composite material during the manufacturing process, recording the pressure during the molding. This process can be critical for large composite structures where thickness of several centimeters must be achieved. Once it has been embedded, the sensor is also able to obtain strain or temperature measurements of the hosting structure under working conditions without degrading its mechanical behavior. Several characterization steps have been also performed to obtain the sensor response to pressure, strain and temperature, exhibiting a great sensitivity and repeatability.

2. Sensor design

The sensor design is based on a plastic block with an embedded Fiber Bragg Grating. The central section, where the FBG is embedded, is arc-shaped to be compressed when a transversal load is applied (Fig. 1). Surrounding the arc-shaped section, two straight glass fiber filaments were included to limit the central section compression after being installed. The proposed design is oriented to be embedded into a composite structure during its manufacturing process, so it has to be small enough to avoid the modification of the structural mechanical response, but solid enough to withstand the fabrication process.

In a simple way, a Fiber Bragg Grating (FBG) is a periodic variation of the refractive index in the optical fiber core that reflects particular wavelengths. Reflected wavelengths are centered around the Bragg wavelength that is defined by $\lambda_{Bragg} = 2n_{eff}\Lambda$, where n_{eff} is the effective index (constant) of the fiber core and Λ is the period of the variation of the refractive index. By stretching or compressing the FBG, Λ is modified and, therefore the central wavelength (λ_{Bragg}). This implies that, by measuring the central wavelength, the deformation of the structure where the FBG is attached can be also obtained. This deformation obtained by the Bragg wavelength has to be scaled by some value (fixed for a given scenario) to deal with model deviations such as the embodiment process or the strain-optic effect.

Once the sensor is embedded into the composite material, the central section is compressed as the transversal pressure increases. The compression can be measured using the wavelength shift of the embedded FBG, while the dimensions of the central arc determine the sensitivity of the sensor to the pressure. However, the arc cannot be excessively abrupt, enhancing the pressure sensitivity, because it will create a non-uniform deformation along the FBG, that would deform its spectral shape complicating the peak determination. A correct behavior of a FBG relies on a uniform deformation of its periodic variation and, consequently, any odd artifact close to the FBG can limit its final performance.

The arc shape of the central section is maintained by two surrounding glass fiber reinforcements that also help to limit the sensor compression, by establishing a minimum thickness. Once the composite structure has been manufactured, the sensor remains compressed inside the material maintaining the FBG orientation parallel to both sensor surfaces so further strain measurements can be also performed employing the same sensor. A simplified version of the proposed design has been simulated using the Abaqus Finite Element Analysis (FEA) software (Dassault Systemes Inc.). Simulated model just reproduces central section using the proposed arc dimensions and has been employed to obtain the qualitative sensor response, validating the chosen dimensions. The central block has been considered as a homogeneous resin block under distributed pressure over its surface. Despite the surrounding glass fiber reinforcements have not been included in the model, the mechanical response of the sensor must be similar.

The simulated mechanical response and the FEA model are depicted in Fig. 2. At lower pressure, the arc is easily deformed and, consequently, the achieved sensitivity at lower pressures is better than at higher pressures. However, after the sensor has been compressed, its sensitivity becomes very low following a logarithmic trend as can be noticed in Fig. 2 (right).

3. Manufacture and embodiment process

The sensor is built in epoxy resin using two glass fiber filaments of 0.6 mm of diameter as reinforcements. To obtain the desired shape, a mold is manufactured using non-stick silicone from a plastic (PMMA) CNC mechanized male. Some alignment points are included in the sensor design to accurately place the FBG and the glass fiber

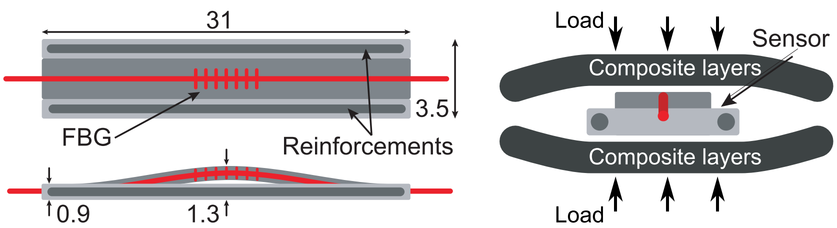

Fig. 1. Sensor design (left) and embodiment scheme (right). The arc-shaped section is compressed while a transversal load is applied. Dimensions are in millimeters.