Smart design for temperature-strain measurement using distributed fiber-optic embedded in laminated composites

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Abstract
A smart structure embedding an optical fiber in laminated composites is proposed for distributed temperature and strain measurements. The sensing structure is manufactured embedding a standard single-mode optical fiber in carbon fiber reinforced polymer (CFRP), thus providing mechanical protection to the optical fiber, which can be interrogated by a distributed optical fiber sensing technique. While some optical fiber sections are loosely embedded inside the CFRP packaging, thus enabling strain-free temperature measurements, other fiber sections are tightly glued inside the packaging, allowing for simultaneous temperature-strain sensing. A linear strain response of the smart CFRP packaging is experimentally verified using a distributed sensor based on optical frequency domain reflectometry (OFDR). Experimental results are compared and validated with theoretical values and measurements using traditional strain gauges, indicating only small discrepancies. The layout of free optical fibers and adhesive fibers can be designed according to the application itself, enabling a correct temperature and strain discrimination in the designed CFRP structure. The proposed smart CFRP packaging is good candidate for structural health monitoring, thus providing mechanical protection to the optical fiber and allowing for an efficient strain transfer.

Keywords: Carbon fiber reinforced polymer (CFRP), Distributed optical fiber sensors, Temperature and strain measurement, Structural health monitoring (SHM)

1. Introduction

With the development of materials science and technology, carbon fiber reinforced polymers (CFRPs) have been developed for a wide range of applications, such as for forming parts of aviation structural components of aircraft and aerospace structures, among many others. CFRPs help in reducing the weight of the aircraft, while providing sufficient strength, stiffness and flexibility. Although the large number of demonstrated advantages of CFRPs, there are still some concerns about the performance of lightweight materials in widespread use. Thus, adding a sensing element into CFRP structures has become an important necessity for studying their properties during material development and in-service operational monitoring [1,2]. In this context, fiber-optic sensing has been proved as a highly compatible technology to be embedded into CFRP laminated structures, thus providing a reliable solution for real-time structural health monitoring (SHM) [1,2]. The most common fiber sensing technology for SHM is based on fiber Bragg gratings (FBGs), however FBGs allow the monitoring of only discrete pre-defined positions along the fiber, leaving unmonitored areas over big structures. Another approach more in demand for large structures is to use distributed optical fiber sensing technologies [2], in which a given physical variable (e.g. strain) can be monitored along an entire optical fiber. Unfortunately, optical fibers are very small and brittle, so that embedding them directly into a thermosetting structure often results in very low survival rates. In order to meet the requirements of engineering practical applications, the optical fiber must be ideally embedded and protected in an effective packaging. As the composite is solidified, the embedded optical fiber will be bonded to the CFRP, providing possibilities for temperature and strain monitoring. In most of practical applications of composite materials (e.g. operating wind turbines and aircraft structures), a simultaneous monitoring of the temperature and strain is favorable and
important for the diagnosis and identification of structural damage and failures in a timely way. Unfortunately most fiber sensing techniques for SHM are sensitive to both temperature and strain, leading in many cases to an unwanted cross-sensitivity between these two physical variables. One of the easiest approaches used for strain-temperature discrimination is to adopt different hybrid sensing techniques, such as combining FBG sensors with other sensing methods [1]. However, difficulties in real-field scenarios, especially for implementing continuous (distributed) temperature-strain discrimination, have prevented further developments from using discrete sensing techniques [3].

In this paper, a new smart structure based on distributed fiber-optic sensing embedded in laminated composites is proposed for temperature and strain simultaneous measurements. The sample has been manufactured and experimentally characterized. Making use of a distributed fiber sensor based on optical frequency-domain reflectometry (OFDR) [4], the strain response of the embedded optical fiber has been characterized under static loading tests. Since the OFDR sensor is sensitive to both strain and temperature, the CFRP packaging has been designed with the optical fiber placed within compressed and loose sections, thus allowing for temperature and strain discrimination. After temperature compensation, the OFDR sensor shows to have a linear response with respect to the applied load and induced strain. The proposed smart CFRP packaging embedding an optical fiber for simultaneous distributed temperature and strain sensing has great market potential for future SHM applications in composite structures.

2. Principles of distributed optical fiber sensors for SHM

Distributed optical fiber sensors make use of a conventional optical fiber as a distributed linear sensing element, and exploit the natural light scattering generated in the fiber, such as Rayleigh, Raman and Brillouin scattering, to interrogate the surrounding environment. Those scattering phenomena are sensitive to environmental variables, allowing for the interrogation of physical variables such as temperature and strain along the optical fiber. There exist basically two interrogation approaches, which are based on either optical time-domain reflectometry (OTDR) or optical frequency-domain reflectometry (OFDR). The time-domain approach typically enables distributed sensing over of several kilometers of optical fiber with spatial resolutions in the meter scale; whilst the frequency-domain approach allows for much better spatial resolutions (down to sub-millimeter scale) but over a reduced sensing range (e.g. up to few meters). In the field of SHM, distributed fiber sensors based on either Brillouin [3] or Rayleigh [6] scattering can be employed to monitor strain over large civil structures. In these two cases, the strain affecting the structure can be transferred to the sensing fiber, resulting in a spectral shift of the sensor response. However, Brillouin and Rayleigh scattering are both sensitive not only to strain changes in the fiber but also to temperature variations, resulting in an unwanted cross-sensitivity that makes almost impossible to discriminate temperature from strain in a single position of the sensing fiber. In general, the Brillouin and Rayleigh sensor responses \( \Delta f(z) \), as a function of the fiber position \( z \), can be written as \( \Delta f(z) = C_T \Delta T(z) + C_\varepsilon \Delta \varepsilon(z) \), where \( \Delta T(z) \) and \( \Delta \varepsilon(z) \) represent local temperature and strain changes, and \( C_T \) and \( C_\varepsilon \) are the temperature and strain coefficients of the sensor. In the case of a Brillouin sensor \( C_T = 1 \) MHz/K and \( C_\varepsilon = 0.05 \) MHz/\( \mu \varepsilon \), whilst in a Rayleigh-based sensor \( C_T = 1.3 \) GHz/K and \( C_\varepsilon = 150 \) MHz/\( \mu \varepsilon \). Another important aspect of distributed fiber sensors to consider for SHM is the capability of performing dynamic strain measurements. Conventional Brillouin sensing techniques are typically limited to quasi-static measurements; and even though dedicated interrogation methods exist for fast dynamic Brillouin sensing [5], their implementation with sub-meter spatial resolution capabilities becomes very challenging. Rayleigh-based OFDR
techniques [6], on the other hand, can allow simultaneous mm-scale resolution and dynamic strain measurements up to a few hundred Hz range, within short sensing ranges. The CFRP package system proposed here for distributed sensing applications in SHM is a kind of module design with standard fiber jumper interfaces, which can make use of either Brillouin or Rayleigh-based sensing techniques independently.

3. Fabrication of the smart CFRP package embedding optical fibers

The manufactured smart CFRP packaging is based on T700 carbon fiber prepregs, peel plies and Teflon rods. The used pre-impregnated (prepreg) tape has a unidirectional ply orientation, and therefore the optical fiber used for sensing has been embedded along the carbon fiber direction to maximize strain transfer. The positioning of the optical fiber has been divided into three sections, as depicted in Fig. 1a. Sections A and C correspond to areas where the optical fiber has been remained loose inside the packaging, enabling strain-free temperature sensing; while the optical fiber in section B has been tightly pressed inside the carbon fiber laminates, enabling simultaneous temperature and strain sensing. Measurements in Sections A and C can then be used to compensate the temperature effect measured in Section B, thus obtaining temperature-independent strain measurements.

In order to prepare the CFRP packaging, two pieces of 800 mm × 100 mm carbon fiber prepregs are used together with an aluminum foil of the same dimensions. The optical fiber inside Sections A and C is placed within two short Teflon rods and two pieces of release clothes, so that some space for the optical fiber is created between two plies of carbon fiber prepreg during CFRP hot pressing. The optical fibers segments in these spaces remain free of adhesion, enabling temperature measurements with no impact of strain. On the other hand, the fiber segments in Section B are aligned with regular intervals and parallel to the direction of the carbon fiber. The fiber segments in Section A and C are bent with a reasonably large curvature radius to avoid large optical losses in the embedded fiber, which could affect the performance of the sensing system/interrogator).

For the fabrication of the packaging, a carbon fiber prepreg is first laid on top of an aluminum foil and gently flattened. Two pieces of release cloth are then placed near the ends of the long side of the rectangular prepreg. A 19.6 m-long standard single-mode optical fiber is then placed in repeated "S" shapes over the entire area used for sensing, as shown in Fig. 1a. The optical fiber is carefully placed to secure that fiber segments are located in straight and parallel lines within Section B (denoted as I, II, III, IV, V and VI in Fig. 1a), while U turns with long enough bending radius are placed on release clothes at both ends (marked as ①, ②, ③, ④ and ⑤ in Sections A and C). While the optical fiber sections in Section B are temporarily fixed by a
roller pressing, two Teflon rods are placed on a release cloth along both sides of the carbon fiber prepreg long edges (Sections A and C). Then, the bent fibers in Section A and C are covered with the release cloth, while an upper carbon fiber prepreg is placed on the top and flatten with a pressing roller to ensure a uniform surface without bubbles. The last step is to hot press the entire structure at 120°C on a hot-pressing machine for 30 minutes, at a constant temperature and pressure (0.08 MPa). The CFRP structure is then cooled down for another 30 minutes, keeping the same pressure as before. Note that in order to avoid uneven curing residual stress in the embedded optical fiber, a pre-designed fiber clamper has to be used to make the optical fiber in Section B always in a pre-stressed state during the whole hot pressing process.

The packaged optical fibers are then connectorized in both ends. This allows us not only to connect the structure to a distributed optical fiber sensor interrogator, but also to connect consecutive smart CFRP packages in a large structure. Indeed, the prepared sample (see Fig. 1b) with embedded optical fibers before hot press can also be considered as a new piece of "prepreg" (smart skin or middle layer) for co-curing applications with other structural composite components.

4. Characterization of the strain response of the CFRP packaging using distributed optical fiber sensing

To characterize the distributed fiber sensor response embedded in the CFRP package, the experimental layout shown in Fig. 2 has been used. The fabricated CFRP package has been affixed to a metallic cantilever beam by gluing the aluminum foil substrate to the surface of the beam, over which different weights are applied. The base of the aluminum foil in the CFRP packaging provides a tight connection with the metallic cantilever, enabling an efficient transfer of the strain induced by the cantilever bending into the CFRP packaging. The cantilever beam has a varying cross-section but the same strength, thus securing a uniform strain over the CFRP package as a consequence of the applied load. This way, the same amount of strain is expected to be transferred to the six parallel optical fiber segments (within Section B) for strain monitoring.

For this characterization, a Rayleigh-based OFDR distributed fiber sensor has been used for interrogation. The OFDR system allows for measurements over the entire 19.6 m-long optical fiber with a spatial resolution of 5 mm, thus providing 3920 independent sensing points over the CFRP package. The dynamic sampling rate of the OFDR sensor is limited by our instrumentation to 100 Hz, thus enabling reliable dynamic strain monitoring with frequency components of up to 50 Hz. Furthermore, in order to better validate the design of the CFRP package, 3 traditional strain gauges have also been placed in the cantilever beam thus providing reference measurements for comparison.

![Figure 2. Schematic diagram of the strain sensing loading test](image-url)
The experiment has been carried out by using different loads, ranging from 1 kg up to 11 kg. Fig. 3 shows the response of the OFDR sensor as a function of distance for different applied loads. Note that since the OFDR response is very sensitive the temperature changes and measurements are obtained in different (consecutive) instants, temperature compensation has been performed to obtain reliable strain measurements. This compensation has been carried out by setting the OFDR response of the fiber sections ①, ②, ③, ④, and ⑤ to zero. Note that those fiber segments are only affected by temperature changes (since they are not compressed inside the CFRP packaging) and therefore variations in the OFDR response within those sections can be only associated to temperature changes, which can be used to compensate the entire measured trace. Results in Fig. 3 demonstrate that the OFDR response is essentially the same for the six fiber segments affected by strain (I to VI). This is expected due to the uniform strain distribution provided by the cantilever shape, but also demonstrates a uniform strain transfer to the CFRP package and to the embedded optical fibers.

![Figure 3. Distributed OFDR strain response of the CFRP packaging for different loads.](image)

Fig. 4a shows the OFDR strain response of the CFRP package as a function of the applied load. Note that the measured value shown in the figure for each applied load corresponds to the mean strain value obtained by the OFDR sensor within the fiber sections I to VI (mean value calculated within longitudinal windows of 100 points centered in each respective fiber segment). A linear response of the embedded sensor can be verified as a function of the applied load, showing a load-to-strain conversion factor equal to 8.49 με/kg. Similar response has also been measured with the strain gauges directly attached to the cantilever, as shown in Fig. 4b, but having a slightly higher load-to-strain conversion factor equal to 8.85 με/kg. The small difference is basically attributed to the attenuation of the CFRP material itself and to the adhesive between the cantilever and CFRP packaging. Note that the strain gauges are directly glued on the surface of the cantilever, and therefore they secures slightly better strain transfer.
Figure 4. Strain response versus applied load for (a) OFDR sensor with embedded optical fibers in the CFRP packaging, and (b) conventional strain gauges.

Measurements obtained by these two sensors have also been compared with theoretical values. For this comparison, the bending-induced strain in the cantilever has been calculated as a function of the applied load using the following well-known expression:

\[ \varepsilon = \frac{6WL}{Ebh^2} \]  

where \( W = mg \) is the applied weight in Newton (using loads ranging from \( m = 1 \text{ kg} \) up to \( 11 \text{ kg} \), and \( g = 9.8 \text{ m/s}^2 \)), \( L = 1104.6 \text{ mm} \) is the cantilever length, \( E = 200 \text{ GPa} \) is Young’s modulus of the metallic cantilever, \( b = 400 \text{ mm} \) is the width of the cantilever fixed-end, \( h = 9.5 \text{ mm} \) is the thickness of the cantilever.

Table I compares the results obtained by the OFDR sensor and traditional strain gauges (average values) with the theoretical values. As described before, small discrepancies can be observed, being mainly due to the different load-to-strain factors determined by the gluing and positioning of the gauges and CFRP packaging. Note that Table I also shows the relative strain efficiency of the OFDR system compared to the theoretical and gauge measured values. Results indicate an average OFDR strain efficiency of \(~94.6\%\) and \(~96.4\%\) with respect to theoretical and gauge values, respectively.

Table 1. Comparison between measured strain values using an OFDR-based fiber sensor and traditional strain gauges with respect to the theoretical values obtained by Eq. (1)

<table>
<thead>
<tr>
<th>Load (kg)</th>
<th>Theoretical value (με)</th>
<th>Strain gauges (με)</th>
<th>CFRP package w/OFDR (με)</th>
<th>OFDR efficiency vs. Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.00</td>
<td>8.7</td>
<td>8.35</td>
<td>92.77 %</td>
</tr>
<tr>
<td>3</td>
<td>26.99</td>
<td>26.6</td>
<td>25.58</td>
<td>94.78 %</td>
</tr>
<tr>
<td>5</td>
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<td>44.8</td>
<td>43.20</td>
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</tr>
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<td>62.98</td>
<td>61.2</td>
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<td>94.86 %</td>
</tr>
<tr>
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<td>80.1</td>
<td>77.34</td>
<td>95.52 %</td>
</tr>
<tr>
<td>11</td>
<td>98.96</td>
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<td>92.90</td>
<td>93.88 %</td>
</tr>
</tbody>
</table>

5. Conclusion

In this paper, a smart structure embedding optical fibers inside a CFRP packaging has been proposed and experimentally characterized for distributed sensing in large structures. The
optical fiber positioning, making use of loose and tightly glued fiber sections, allows for temperature and strain discrimination. The modular structure offers two main advantages for structural health monitoring applications, by offering distributed sensing enabling strain-temperature discrimination and mechanical protection to the optical fiber. Indeed, it is important to point out that the design of the optical fiber placement can be customized to the requirements of specific applications by changing the length, shape and covered area of the different sections of the embedded fiber. Furthermore, by choosing an appropriate substrate, a good matching with the monitored structural material can be achieved, thus facilitating the adhesion and strain transfer between the monitored structure and the smart CFRP packaging with embedded fibers. It is expected that the proposed smart CFRP structure can be used as a modular and flexible building block to monitor large civil structures (e.g. aircrafts), providing distributed sensing capabilities and protection to the optical fibers.

References