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Simultaneous measurement of strain and temperature using fiber Bragg grating sensors embedded in hybrid composite laminates

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Abstract
The use of fiber Bragg grating sensors embedded in hybrid composite laminates for simultaneous measurement of strain and temperature is proposed. The hybrid structure, formed by a pre-impregnated thermoset and thermoplastic composites, contains one single fiber Bragg grating embedded in each material, connected in series with each other. A different response is observed when the smart composite laminate is subjected to strain and to temperature. This is expected due to the distinct properties presented by each material. The rms deviation obtained for a temperature range between 20 and 60 °C is ± 0.97 °C and for a strain range from 0 to 1100 $\mu\varepsilon$ is ± 13.04 $\mu\varepsilon$.

Keywords: optical fiber sensors, smart composite materials, thermoset and thermoplastic materials

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Over the last two decades, there has been a growing interest in research and development of fiber optic sensors, namely fiber Bragg gratings (FBGs) and their applications. Optical sensors of this type present interesting properties, such as reduced dimensions, high resistance to corrosion and fatigue, electrical isolation and immunity to electromagnetic fields, wide bandwidth operation and wavelength multiplexing capability [1–4].

Several techniques have been presented for simultaneous measurement of strain and temperature, such as the use of different types of FBG [5], superstructure FBG [6], FBG imprinted in a bow-tie fiber [7], normal and reverse index FBG [8], combined short and long FBGs [9], and the use of FBGs written in microstructured fibers [10].

Smart composites can be defined as structures that may respond to changes in their conditions by monitoring themselves and/or their environment [11]. Due to the previously mentioned characteristics, the employment of FBGs in the fabrication of smart composite materials is very attractive, since they can be used not only for *in situ* process monitoring and health checks, but also for measurement of the characteristics of the smart composite itself. The incorporation of FBGs in composite materials has been reported by several researchers. Vieira *et al* [12] studied the influence of the FBG length and its coating on embedded FBGs in polymers. Biswas *et al* [13] investigated the use of FBGs embedded in concrete structures, and Park *et al* [14] used them to study the peak wavelength interrogation of FBGs during impact events.

Tanaka *et al* [15] firstly introduced the concept of a hybrid sensor, constituted by a carbon fiber reinforced plastic (CFRP) and glass fiber reinforced plastic connected

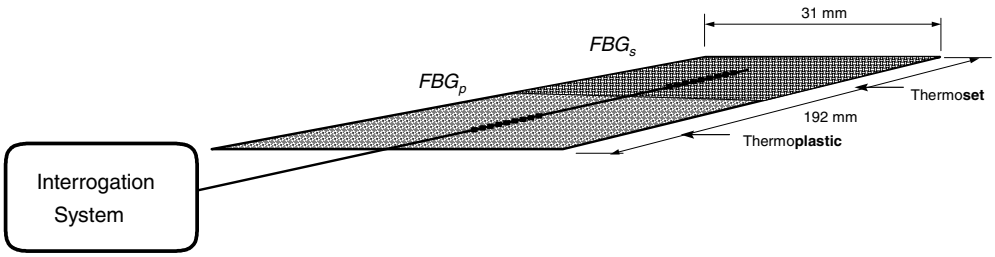

Figure 1. Geometry of the sensing head.

Table 1. Physical characteristics of the composite materials.

	Thermoplastic	Thermoset
Commercial designation	208-C200(1)/45% (TEPEX® *dynalite*—BOND LAMINATES)	CC206 ET443 (Advanced Prepreg TEXIPREG®—SEAL)
Fabric	Carbon twill 2/2	Carbon twill 2/2
Polymer	TPU (thermoplastic polyurethane)	ET443 (epoxy resin)
Density laminate	1.47 g cm^{-3}	1.2 g cm^{-3}
Fiber content	45% vol.	n.a.
Tensile modulus	48.5 GPa	68 GPa
Tensile strength	710 MPa	812 MPa
Tensile elongation	1.5%	n.a.
Poisson's ratio	0.3	0.07
Flexural modulus	42.5 GPa	60 GPa
Flexural ultimate stress	745 MPa	750 MPa

in series. With such a hybrid structure, they were able to make temperature-compensated strain measurements. On the other hand, Jung *et al* [16] studied the residual stress developed in the interply hybrid carbon/phenolic composite using an embedded FBG sensor during the curing process. Recently, a smart laminate composite was proposed using FBG sensors embedded between the different layers of CFRP [3].

The aim of this work is to demonstrate the simultaneous measurement of strain and temperature using two FBGs embedded in a hybrid composite laminate. Due to the different responses obtained, it is possible to use a simple matrix method in order to discriminate strain and temperature.

2. Experimental results

The composite materials that constituted the sensing head were two carbon fiber twills (the laminates are crossply $90/0_{(s)}$): one in a thermoplastic polyurethane matrix and the other in an epoxy resin, whose physical properties can be seen in table 1.

Both pre-impregnated thermoplastic and thermoset composites were united, with an overlap of 22 mm. The resultant hybrid laminate composite was composed of three superimposed layers of this slab, with two Bragg fibers embedded in them. The FBG sensors were written in a standard single mode fiber (SMF-28); the grating had a reflectivity of 50% and a length of 10 mm. They were placed in series, 108 mm apart from each other, one centered in the thermoset composite and the other one in the thermoplastic composite. The center wavelength of each grating was 1545.0 and 1550.0 nm, respectively. Once ready, the hybrid laminate was put in a hot plate press, for 1.5 h, at a temperature of 130 °C and a pressure of 20 bar. The geometry of the sensing head, with an interrogation system, is presented in figure 1. A commercial interrogation system (Fibersensing) with an accuracy of 2 pm was used.

After processing, the sensing head behavior toward strain and temperature variations was studied. Regarding strain measurements, made at a constant temperature ($T = 25$ °C), a test machine INSTRON (mod. 4208) was used. The distance between grips, load cell and displacement rate were 140 mm, 5 kN and 0.05 mm min^{-1}, respectively. For the temperature measurements, the sensing head was placed in a tubular oven, which permitted an error associated with temperature reading smaller than 0.1 °C. The interrogation system included an optical spectrum analyzer (ANDO AQ 6330), with a maximum resolution of 10 pm, an erbium broadband optical source (PHOTONETICS) with a bandwidth of 80 nm, and a computer data acquisition system.

Figure 2 presents the responses of the sensing head when subjected to strain variation. The measurands used were λ_{BP} and λ_{BS}, corresponding to the Bragg wavelength in the region of the thermoplastic composite and thermoset composite, respectively. The sensitivities are different for each composite material, being 1.08 pm $\mu\varepsilon^{-1}$ for the thermoplastic and 0.26 pm $\mu\varepsilon^{-1}$ for the thermoset. This difference is expected, since the studied polymers belong to different classes. In the case of thermoplastics, their molecular chains are either linearly connected or branched. So, when strain is applied, the chains tend to slip, thus influencing the sensitivity, which will be higher. On the other hand, thermosets present heavily cross-linked chains, which will give rise to a dense three-dimensional network. So they are normally rigid and less sensitive than thermoplastics. Besides, the Poisson ratio has a higher value for the thermoplastic (0.3) than for the thermoset

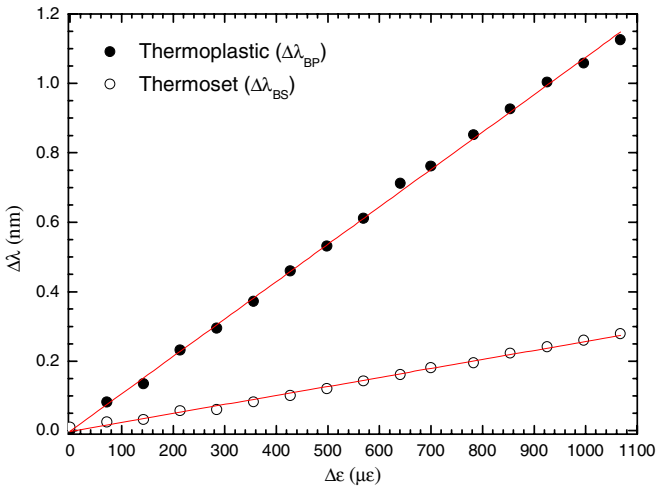

Figure 2. Response of the sensing head to strain variation.

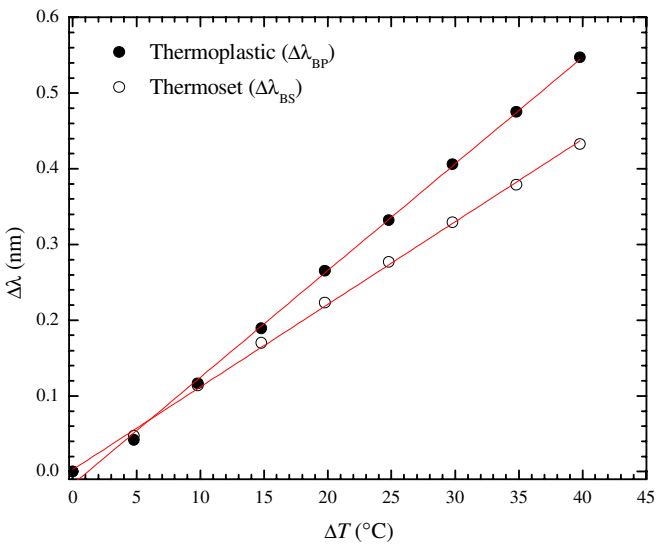

Figure 3. Response of the sensing head to temperature variation.

(0.07), which means that it is harder to induce a change in the volume of the thermoset than the thermoplastic.

The sensing head behavior toward temperature shows a linear tendency, as can be seen in figure 3. The sensitivity is 14.1 and 10.9 pm °C^{-1}, for the thermoplastic and thermoset, respectively. The difference is due to the properties of each polymer. Thermoplastics are in general more sensitive to temperature, and by heating they can be molded and remolded. Thermosets, on the other hand, cannot melt on heating, decomposing when the temperature is high enough. Since both polymers exhibited different sensitivities toward the measurands, it is possible to use this sensing head for simultaneous measurement of strain and temperature variation. Hence, through the measurands' variation, it is possible to obtain the Bragg wavelengths of the gratings embedded in the thermoset and in the thermoplastic, according to the following equation:

$$\Delta\lambda_{Bi} = K_{Ti}\Delta T + K_{\varepsilon i}\Delta\varepsilon \tag{1}$$

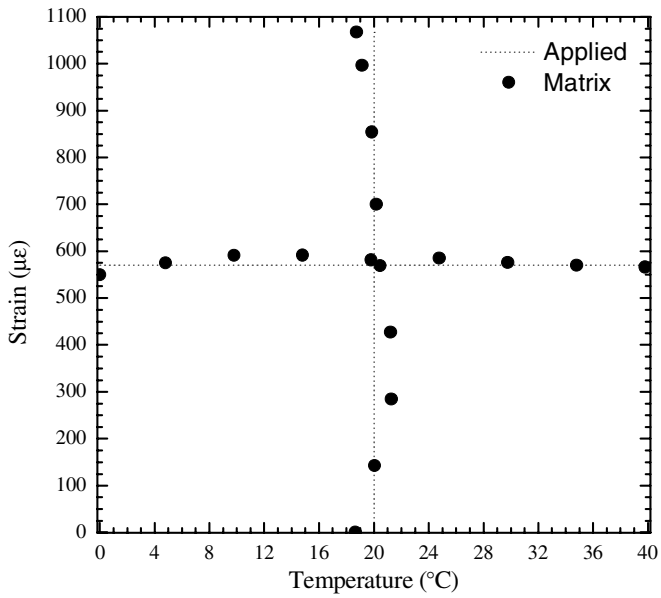

Figure 4. Resolution of the sensing head for applied strain at constant temperature and temperature variation at constant strain.

where i stands for the grating embedded in the thermoplastic (P) and in the thermoset (S); K_{Ti} and $K_{\varepsilon i}$ correspond to the sensitivity due to temperature and strain of each Bragg grating, respectively; ΔT and $\Delta\varepsilon$ are the temperature and strain variations, respectively. This equation can be written as a matrix, and through simple algebraic manipulation, one obtains

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} = \frac{1}{D}\begin{bmatrix} \kappa_{\varepsilon P} & -\kappa_{\varepsilon S} \\ -\kappa_{TP} & \kappa_{TS} \end{bmatrix}\begin{bmatrix} \lambda_{BP} \\ \lambda_{BS} \end{bmatrix} \tag{2}$$

where $D = \kappa_{TS}\kappa_{\varepsilon P} - \kappa_{\varepsilon S}\kappa_{TP}$ is the matrix determinant. In this case, the materials present different sensitivities in relation to deformation and temperature, which makes the matrix method quite stable. This is evaluated through the matrix determinant: the higher its value, the more accurate are the results [17]. Using the sensitivity coefficients previously calculated, the following matrix can be written:

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} = \frac{1}{8.133}\begin{bmatrix} 1.08 & -0.26 \\ -14.1 & 10.9 \end{bmatrix}\begin{bmatrix} \lambda_{BP} \\ \lambda_{BS} \end{bmatrix}. \tag{3}$$

The resolution of the sensing head is illustrated in figure 4. The graphic is obtained by fixing one measurand and varying the other one, in both cases. The dotted lines indicate the applied values, and the dots represent the variations of the measurands, obtained by the matrix equation (3). Ideally, an agreement between these values should be expected. The rms deviations obtained were ±0.97 °C and ±13.04 $\mu\varepsilon$ for temperature and strain measurements, respectively.

3. Conclusion

In summary, the simultaneous measurement of strain and temperature using two FBGs embedded in a hybrid composite laminate was demonstrated. By embedding the FBG, a

protection from high strain conditions is guaranteed. In this work, conventional fibers were used, and the two gratings were manufactured in the same way; only their center wavelength is different.

The thermoplastic and thermoset exhibited different responses, the thermoplastic being 76% and 23% more sensitive than the thermoset in strain and temperature measurements, respectively. The discrepancy is due to the physical properties of each material. As a consequence of the results obtained, it was possible to use a simple matrix method in order to discriminate temperature and strain. The rms deviations obtained for strain and temperature measurements were $\pm 13.04\ \mu\varepsilon$ and $\pm 0.97\ ^{\circ}$C, for a range of 0–1100 $\mu\varepsilon$ and 20–60 °C, respectively.

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References

[1] Kuang K S C, Kenny R, Whelan M P, Cantwell W J and Chalker P R 2001 Embedded fibre Bragg grating sensors in advanced composite materials *Compos. Sci. Technol.* **61** 1379–87

[2] Capoluongo P, Ambrosino C, Campopiano S, Cutolo A, Giordano M, Bovio I, Lecce L and Cusano A 2007 Modal analysis and damage detection by fiber Bragg grating sensors *Sensors Actuators* **133** 415–24

[3] Frazão O, Oliveira R and Dias I 2009 A simple smart composite using fiber Bragg grating sensors for strain and temperature discrimination *Microw. Opt. Technol. Lett.* **51** 235–9

[4] Kersey A D, Davis M A, Patrick H J, LeBlanc M, Koo K P, Askins C G, Putnam M A and Friebele E J 1997 Fiber grating sensors *J. Lightwave Technol.* **15** 1442–63

[5] Shu X W, Liu Y, Zhao D H, Gwandu B, Floreani F, Zhang L and Bennion I 2002 Dependence of temperature and strain coefficients on fiber grating type and its application to simultaneous temperature and strain measurement *Opt. Lett.* **27** 701–3

[6] Guan B O, Tam H Y, Tao X M and Dong X Y 2000 Simultaneous strain and temperature measurement using a superstructure fiber Bragg grating *IEEE Photon. Technol. Lett.* **12** 675–7

[7] Urbanczyk W, Chmielewska E and Bock W J 2001 Measurements of temperature and strain sensitivities of a two-mode Bragg grating imprinted in a bow-tie fibre *Meas. Sci. Technol.* **12** 800–4

[8] Park S O, Jang B W, Lee Y G, Kim C G and Park C Y 2010 Simultaneous measurement of strain and temperature using a reverse index fiber Bragg grating sensor *Meas. Sci. Technol.* **21** 035703

[9] Triollet S, Robert L, Marin E and Ouerdane Y 2011 Discriminated measures of strain and temperature in metallic specimen with embedded superimposed long and short fibre Bragg gratings *Meas. Sci. Technol.* **22** 015202

[10] Frazão O, Carvalho J P, Ferreira L A, Araujo F M and Santos J L 2005 Discrimination of strain and temperature using Bragg gratings in microstructured and standard optical fibres *Meas. Sci. Technol.* **16** 2109–13

[11] Culshaw B 1996 *Smart Structures and Materials* (Norwood, MA: Artech House)

[12] Vieira A, Oliveira R, Frazão O, Baptista J M and Marques A T 2009 Effect of the recoating and length on fiber Bragg grating sensors embedded in polymer composites *Mater. Des.* **30** 1818–21

[13] Biswas P, Bandyopadhyay S, Kesavan K, Parivallal S, Arun Sundaram B, Ravinsankar K and Dasgupta K 2010 Investigation on packages of fiber Bragg grating for use as embeddable strain sensor in concrete structure *Sensors Actuators* A **157** 77–83

[14] Park C, Peters K, Zikry M, Haber T, Schultz S and Selfridge R 2010 Peak wavelength interrogation of fiber Bragg grating sensors during impact events *Smart Mater. Struct.* **19** 045015

[15] Tanaka N, Okabe Y and Takeda N 2003 Temperature-compensated strain measurement using fiber Bragg grating sensors embedded in composite laminates *Smart Mater. Struct.* **12** 940–6

[16] Jung K, Kang T J, Lee B and Kim Y 2007 Estimation of residual strain and stress in interply hybrid composite using fiber Bragg grating sensor *Fibers Polym.* **8** 438–42

[17] Jin W, Michie W C, Thursby G, Konstantaki M and Culshaw B 1997 Simultaneous measurement of strain and temperature: error analysis *Opt. Eng.* **36** 598–609