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## Method for Independent Strain and Temperature Measurement in Polymeric Tensile Test Specimen Using Embedded FBG Sensors

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### Abstract

A novel method to obtain independent strain and temperature measurements using embedded Fibre Bragg Grating (FBG) in polymeric tensile test specimens is presented in this paper. The FBG strain and temperature cross-sensitivity was decoupled using two single mode FBG sensors, which were embedded in the specimen material with a certain angle between them. It is demonstrated that, during temperature variation, both FBG sensors show the same signal response. However, for any applied load the signal response is different, which is caused by the different levels of strain acting in each sensor. Equations to calculate independently the strain and temperature are presented in the article, together with a measurement resolution study.

This multi-parameter measurement method was applied to an epoxy tensile specimen, tested in a unidirectional tensile test machine with a temperature controlled cabinet. A full calibration procedure (temperature and strain) was performed to this material-sensor pair, where a calibration error < 1% was achieved. This was followed by a strain-temperature test case, where multiple two loading/strain stages of  $\varepsilon = 0.30\%$  and  $\varepsilon = 0.50\%$  were applied during a continuous variation of temperature, from  $40^{\circ}C$  to -  $10^{\circ}C$ .

The consistency of the expected theoretical results with the calibration procedure and the experimental validation shows that this proposed method is applicable to measure accurate strain and temperature in polymers during static or fatigue tensile testing. Two different calibration protocols are presented and analysed.

Keywords: Fibre Bragg Grating Sensors; Strain and Temperature Measurement; Polymer Embedded Sensors; FBG Multi-Parameter Measurement

#### Notation

$\lambda_b$	reflected wavelength peak;
$\lambda_b^A$	reflected wavelength peak of the FBG <sub>A</sub> ;
$\lambda^B_b$	reflected wavelength peak of the $FBG_B$ ;
$\Delta \lambda_b$	wavelength shift;
$n_{eff}$	effective refractive index for unstrained condition;
$\Lambda_0$	nominal period of the refractive index modulation for unstrained condition;
$p_e$	optical fibre photo-elastic coefficient;
$\alpha_h$	thermal expansion coefficient of the host material;
ξ	thermo-optic coefficient of the optical fibre;
θ	angle between $FBG_A$ and $FBG_B$ ;
$\mathcal{E}_1$	strain in the longitudinal direction of the optical fibre;
$\mathcal{E}_{\chi}$	strain in the x axis direction of the specimen;
$\varepsilon_y$	strain in the y axis direction of the specimen;
$arepsilon_L$	specimen strain caused by the uniaxial loading;
Т	specimen temperature (K);
$\Delta T$	specimen temperature variation;
Ε	Young's modulus of the host material;
$v_{12}$	Poisson's ratio of the host material;
$\varepsilon_L^{resolution}$	method strain resolution
$\varepsilon^{resolution}_{Hardware}$	signal acquisition hardware resolution

#### **1. Introduction**

Improving measurement techniques to obtain more accurate strain measurements is a central research topic in the material characterization field. Specifically in the polymeric materials field, some authors have developed new methods to perform strain measurement, and improved current techniques to obtain more accurate and reliable strain measurement. Zike et al.[1], have developed a procedure to correct the gauge factor for strain gauges used in polymer composite testing. Jerabek et al.[2] and Crupi et al.[3] have developed digital image correlation techniques to evaluate the strain during shear and static/fatigue tensile testing.

Fibre Optic Bragg grating (FBG) sensors are considered a promising alternative to the conventional strain measurement techniques. Due to its small diameter, 125  $\mu$ m, it is possible to embed the sensor in the specimen without compromising the material resistance. Additionally, the fact that the FBG is embedded improves the strain transfer between the host material and the sensor, increasing the measurement accuracy. The FBG measured information is encoded as a light resonance wavelength,

giving this system unique properties, such as immunity to optical/power fluctuation, insulation and immunity to electromagnetic fields [4]. However, strain and temperature cross-sensitivity, limited measuring range, expensive hardware and difficulties in handling the sensors are some of the drawbacks of this technology.

Strain and temperature cross-sensitivity is especially problematic for long tests, where external variation of temperature can occur. On the other hand, during dynamic tests, such as fatigue testing, the material self-heating can generate a strain caused by thermal expansion. A simple solution to decouple the strain from the temperature measurement is by embedding two gratings in the material, one of which is isolated with a glass or a metallic sleeve [5][6]. However, the sleeve used to isolate the grating will increase the sensor diameter, which becomes more intrusive to the material and can lead to a decrease in the measured mechanical strengths. Moreover, the optical fibre needs to be cut to introduce the sleeve, which makes having several gratings in the same fibre optic (multiplexing) impossible. Other authors propose an indirect measurement method that can be used for simultaneous measurement of the bending force and temperature. This is done by drilling a hole in the material, near the grating location, which will create a change in the width of the standardised sum of the transmission spectra, and consequently a decoupling of strain from the temperature [7]. However, as this technique requires a hole to be drilled near the grating, the material strength is reduced, compromising the results of the material testing. Within the optical fibre sensors field, new techniques and sensors have been developed for multi-parameter measurement, such as a dual grating in the same location using a standard FBG and a Long Period Grating (LPG) [8], chirped FBG and Fabry-Perot [9], different FBG sensor diameter [10], FBG with a thermochromic material [11]. However, these techniques require more advanced and costly technology, skilled operators, and some cases are not commercial available. In this article, a simple approach for multi-parameter measurement is presented, where the strain and temperature can be measured independently in a tensile test specimen using commercially available technology. This method can be used in static testing, but it was developed especially for fatigue/dynamic testing where the specimen can experience temperature variation.

The article is divided into four sections: *FBG Working Principle*, where the sensor response to strain and temperature is shown; *Strain and Temperature Independent Measurement Method*, the independent strain and temperature method is discussed, and its impact to the measurement resolution is studied; *Experimental Procedure and Validation*, the calibration procedure is performed, and the strain and temperature are independently measured in a tensile specimen under thermal and strain loading; and *Proposed Calibration Protocol*, where two different measurement protocols, with or without calibration, are presented and analysed.

### 2. Fibre Bragg Grating Working Principle

A Fibre Bragg Grating is formed by a permanent periodic modulation of the refractive index along a section of an optical fibre[12]. This is made by exposing the optical fibre to an interference pattern of intense ultraviolet light, which will increase the photosensitivity of the silica. Then, when the optical fibre is illuminated by a broadband light source, a narrow wavelength band is reflected back, as showed in Figure 1.



**Figure 1**- Fibre Bragg Grating working principle: spectral response of a homogeneous FBG. The parameter  $\lambda_b$  is the wavelength of the reflected peak, and  $\Lambda_0$  is the constant nominal period of the refractive index modulation.

The spectral response of a homogeneous FBG is a single peak centred at the wavelength  $\lambda_b$ , described by the Bragg condition (Equation (1)),

$$\lambda_b = 2n_{eff}\Lambda_0 \tag{1}$$

where the parameter  $n_{eff}$  is the effective refractive index at the location of the grating, and  $\Lambda_0$  is the constant nominal period of the refractive index modulation [13]. Any external load or temperature variation affecting the grating region will change the effective index of refraction and/or the period of modulation, which will create a shift in the wavelength reflected peak. Tracking this wavelength peak shift is the sensing principle of the FBG sensor, giving an indirect measurement of strain and/or temperature in the structure.

#### 2.1. Embedded FBG Response to Strain and Temperature Variation

If perfect strain transfer between the embedded FBG sensor and the host material is assumed. The wavelength shift  $(\Delta \lambda_b)$  caused by the load induced strain in the longitudinal direction of the optical fibre ( $\varepsilon_1$ ), and temperature change ( $\Delta T$ ), is given by Equation (2).

$$\frac{\Delta\lambda_b}{\lambda_h} = (1 - p_e)\varepsilon_1 + (1 - p_e)\alpha_h\Delta T + \xi\Delta T$$
<sup>(2)</sup>

The parameter  $p_e$  is the optical fibre photo-elastic coefficient,  $\alpha_h$  is the thermal expansion coefficients of the host material and  $\xi$  is the thermo-optic coefficient [14]. The effect of the optical fibre to the overall specimen stiffness is very small, because the FBG cross section << specimen cross section. Thus, it can be assumed that the FBG measurements represent the true material behaviour and the FBG thermal expansion contribution to the Equation (2) can be neglected.

#### 3. Strain and Temperature Independent Measurement Method

Multi-parameter measurement is an important topic within the fibre measurement field, allowing parameter discrimination in situations where cross-sensitivity is a critical issue. In the following section

a technique to perform independent strain and temperature measurements in a polymeric tensile specimen with embedded optical fibres is presented.

#### 3.1. Strain and Temperature Cross-sensitivity Decoupling

For a single FBG sensor configuration, it is impossible to measure independently the temperature and strain variation if both happen at the same time. By analysing Equation (2), the load induced strain ( $\varepsilon_1$ ), the temperature induced strain/ thermal expansion ( $\alpha_h \Delta T$ ) and the thermal-optic dependency ( $\xi \Delta T$ ) creates the same sensor response, a wavelength shift of the reflected peak  $\Delta \lambda_b$ . Thus, it is impossible to determine each phenomenon contribution to the wavelength shift.

To overcome this problem, the authors propose a new sensor configuration during tensile testing, as presented in Figure 2.



**Figure 2-** FBG sensors configuration for independent strain and temperature measurement. The FBG sensors are placed parallel to the *xy* plan, being the FBG-A in the middle-plan and the FBG-B 1 mm ahead.

The tensile specimen is instrumented with a pair of embedded FBG sensors, aligned in different directions; one FBG sensor is aligned with the loading direction (*FBG-A*), and the other is tilted with a certain angle ( $\theta$ ). With this configuration, the FBG sensors will have a distinct response to temperature variation and to strain, as shown schematically in Figure 3.



**Figure 3-** Schematic representation of the FBG sensors signal response under strain ( $\varepsilon_y$ ) or temperature variation ( $\Delta T$ ). The solid line represents the FBG-A wavelength shift, and the dashed line the FBG-B wavelength shift.

Assuming that the specimen material has isotropic thermal expansion, i.e. it expands or contracts with the same magnitude in all directions, both sensors will experience the same deformation under temperature variation; however, when the specimen is loaded (direction y and FBG A), the sensors will have a different response from each other. This is caused by the different level of strain that is acting along each sensor longitudinal direction. While the FBG-A will measure the maximum strain caused by the load, the FBG-B will measure a smaller strain that is dependent on the angle  $\theta$  and the specimen Poisson's ratio.

Herewith, by knowing the angle ( $\theta$ ) between the FBG-B and the loading direction, and the difference in the sensors response it is possible to calculate directly the specimen strain by extracting the temperature effect.

#### 3.2. Strain-angle relationship between the FBG sensors

As previously mentioned, the magnitude of strain measured by each sensor will depend on the angle between the FBG sensors. Considering the directions shown in Figure 4, the transformation matrix from xy coordinate system to x'y' coordinate system is given by the Equation (3).

$$[T]_{xy \to x'y'} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$
(3)

The parameter  $\theta$  is the angle between the two coordinate systems (FBG sensors longitudinal direction). The strain tensor in the *xy* coordinate system is described by equation (4), where  $\varepsilon_x$  and  $\varepsilon_y$  are the strain components in the direction *x* and *y*. As this measurement method was developed for unidirectional tensile tests, the shear strain component does not contribute ( $\gamma_{xy}$ =0).

$$[\varepsilon]_{xy} = \begin{bmatrix} \varepsilon_x & 0\\ 0 & \varepsilon_y \end{bmatrix}$$
(4)

The strain tensor in the x'y' coordinate system can be calculated by the Equation (5).

$$[\varepsilon']_{x'y'} = [T][\varepsilon][T]^T$$
(5)

Finally, the strain in the longitudinal direction of the optical fibre (sensor measurement direction) for any given angle is given by Equation (6).

$$\varepsilon_{\theta} = \varepsilon_{\nu} \cos(\theta)^2 + \varepsilon_{\nu} \sin(\theta)^2 \tag{6}$$



**Figure 4-** Coordinate system transformation from FBG-A to FBG B. The parameter  $\theta$  is the angle formed between the FBG sensors.

#### *3.3. Temperature Measurement* ( $\varepsilon_L = 0$ )

Both FBG sensors will measure the same wavelength shift during any temperature variation. Thus, if we consider that no load/strain is applied to the specimen during temperature variation, the wavelength shift measured by the FBG can be described by Equation (7).

$$\frac{\Delta \lambda_b^A}{\lambda_b^A} = \frac{\Delta \lambda_b^B}{\lambda_b^B} = [(1 - p_e)\alpha_h + \xi]\Delta T$$
<sup>(7)</sup>

However, Equation (7) only remains valid if the temperature in the two FBG sensors is the same, which is true if the gratings are close enough to each other.

#### *3.4. Strain Measurement (\Delta T = 0)*

For the specimen configuration presented in Figure 2, loaded in the specimen y direction, the parameter  $\varepsilon_L$  represents the strain caused by the loading the specimen. Thus, the strain in the xy coordinate system can be described by Equation 8,

$$\varepsilon_y = \varepsilon_L \; ; \; \varepsilon_x = -\nu_{12}\varepsilon_L \tag{8}$$

where the strain  $\varepsilon_y$  is equal to the strain caused by the loading and  $\varepsilon_x$  is caused by the Poisson's effect. Therefore, the wavelength shift measured by each FBG sensor can be obtained by combining Equations (6), (8) and (2). G.Pereira/ Independent Strain and Temperature Measurement Using Embedded FBG Sensors

$$\frac{\Delta \lambda_b^A}{\lambda_b^A} = (1 - p_e)\varepsilon_L \tag{9}$$

$$\frac{\Delta \lambda_b^B}{\lambda_b^B} = (1 - p_e)(\cos(\theta)^2 - \nu_{12}\sin(\theta)^2)\varepsilon_L$$
<sup>(10)</sup>

#### 3.5. Strain and Temperature Independent Measurement Method

For a simultaneous strain and temperature variation, the wavelength shift measured by each grating are shown in Equation (11) and (12).

$$\frac{\Delta\lambda_b^A}{\lambda_b^A} = (1 - p_e)\varepsilon_L + [(1 - p_e)\alpha_h + \xi]\Delta T$$
<sup>(11)</sup>

$$\frac{\Delta\lambda_b^B}{\lambda_b^B} = (1 - p_e)(\cos(\theta)^2 - \nu_{12}\sin(\theta)^2)\varepsilon_L + [(1 - p_e)\alpha_h + \xi]\Delta T$$
(12)

As can be observed, the effect of temperature as a wavelength shift is identical in both FBG sensors. Therefore, the difference between the two responses is caused by the strain in the specimen ( $\varepsilon_L$ ) without the temperature effect, as demonstrated by equation (13).

$$\varepsilon_L = \left(\frac{\Delta\lambda_b^A}{\lambda_b^A} - \frac{\Delta\lambda_b^B}{\lambda_b^B}\right) \frac{1}{(1 - p_e)(1 - \cos(\theta)^2 - \nu_{12}\sin(\theta)^2)}$$
(13)

Finally, the temperature change ( $\Delta T$ ) can be calculated by subtracting the strain contribution to the wavelength shift measured. Reorganizing equation (11), the temperature variation is given by:

$$\Delta T = \frac{\frac{\Delta \lambda_b^A}{\lambda_b^A} - (1 + p_e)\varepsilon_L}{(1 - p_e)\alpha_h + \xi}$$
(14)

#### 3.6. Measurement Resolution

The strain resolution of this method strongly depends on the angle between the FBG sensors ( $\theta$ ) and the material Poisson's ratio, as demonstrated in equation (15). The parameter  $\varepsilon_{Hardware}^{resolution}$  is the resolution given by the signal acquisition hardware, typically around 1µ $\epsilon$ .

$$\varepsilon_L^{resolution} = \varepsilon_{Hardware}^{resolution} \frac{1}{(1 - \cos(\theta)^2 - v_{12}\sin(\theta)^2)}$$
(15)

The angle between FBG sensors ( $\theta$ ) has a big impact on the strain resolution, as shown in Figure 5. For an angle  $\theta$  around 90°, the resolution is actually improved, benefiting from the Poisson's effect. However, for some cases, the FBG sensors angle is limited by the tensile specimen width (*specimen*<sub>width</sub> > *FBG*<sub>length</sub> *sin*( $\theta$ )).



**Figure 5-** Strain resolution for different FBG angles ( $\theta$ ) and Poisson's ratio ( $v_{12}$ ). The different lines represent different Poisson's ratios ( $v_{12}$ ).

#### 4. Experimental Procedure and Validation

Two tensile test specimens were manufactured with the dimensions presented in Figure 2 using an epoxy system based on *Araldite LY 1564* and *Aradur 3486*. Two uncoated single mode FBG sensors, with a grating length of 10 mm, were embedded in each specimen; both gratings were placed parallel to the *xy* plan, being the FBG-A in the middle plan and the FBG-B *1 mm* ahead. The FBG-A was aligned with the load/y direction, and the FBG-B was aligned with an angle  $\theta$  of 37.5°. The test was performed in a tensile testing machine, *Instron 8802*, where the head displacement speed was set to 0.02 mm/s. A tensile testing cabinet from *Weiss* was used to perform a controlled temperature variation testing. Two side mounted extensometers were used to monitor the specimen strain and to calibrate the FBG sensors, as shown in Figure 6. The FBG sensor signal was acquired using a *FS2200-Industrial BraggMeter* supplied by *FiberSensing<sup>TM</sup>*, and synchronized with the strain measured by the extensometers.



Figure 6- Experimental set-up apparatus. Epoxy tensile specimen with two embedded FBG sensors and two side mounted extensometers.

The optical fibre parameters, material properties and specimen geometry used are presented in Table 1.

<b>Table 1-</b> Optical fibre parameters, material properties, and specimen geometry.					
Specimen Geometry		Epoxy Properties (Manufacture Data Sheet)		Fibre Optic Parameters	
Thickness	5 mm	Young's modulus (E)	3.3 GPa	Photo-elastic coefficient $(p_e)$ [13]	0.22
Width	25 mm	Poisson's ratio ( $v_{12}$ )	0.35	Thermo-optic coefficient $(\xi)$ [13]	8.3E-6
FBG angle $(\theta)$	37.5°	Thermal expansion coefficient $(\alpha_h)$ [15]	8.3E-5 ε/k	Wavelength peak FBG- A $(\lambda_b^A)$	1566.65 nm
				Wavelength peak FBG-B $(\lambda_b^B)$	1553.75 nm

#### 4.1. Measurement Calibration

A calibration procedure was performed to determine accurately the material and fibre optic parameters, and to minimize any measurement errors.

The calibration procedure was divided in two parts:

- Strain calibration: calibration of the photo-elastic coefficient  $(p_e)$ , using the strain measured • by the surface mounted extensometers;
- Temperature calibration: calibration of the thermo-optic coefficient ( $\xi$ ) and the host • material thermal expansion coefficient  $(\alpha_h)$ , by a controlled variation of temperature in the

environmental chamber;

#### 4.1.1. Strain Calibration

To perform the strain calibration three loading/strain stages of 0.15, 0.30, and 0.50  $\varepsilon$ (%) at a constant temperature were applied.



**Figure 7-** Strain calibration procedure; a) Machine measurement of temperature and strain; b) FBG wavelength shift  $\Delta \lambda_b$ .

The strain measured by the extensioneters and the temperature from the environmental chamber are shown in Figure 7a). The wavelength shift  $\Delta \lambda_b$  response of each sensor is different, as can be observed in Figure 7b), which proves the authors' statement that the sensors have different responses during loading.



**Figure 8-** Strain and temperature measured independently by the FBG sensors. The lines show the strain and temperature measured by the machine, and the symbols the strain and temperature obtained by the developed method using the FBG sensors measurement.

The strain without thermal effect was calculated using Equation (13), and good agreement between the applied strain and FBG measured strain was found, as shown in Figure 8. This material-geometry pair was calibrated for strain measurement with a maximum error of 0.9%. The calibrated parameters are presented in Table 2.

Table 2- FBG strain calibration: calibrated parameters

Calibrated Parameters		
Photo-elastic coefficient $(p_e)$	0.21±0.05	
Poisson's ratio ( $v_{12}$ )	$0.35 \pm 0.07$	
Calibration Error	0.9 %	
$(\varepsilon_{machine} - \varepsilon_{FBG})/\varepsilon_{machine}$		

#### 4.1.2. Temperature Calibration

To perform the temperature calibration, three temperatures stages (25°C, -10°C and 40°C) controlled by the environmental chamber were applied. No load or displacement constrains were applied to the specimens, which allows them to expand or contract freely. The temperature was kept constant for 60 min at each stage to ensure a complete temperature homogenisation in the specimen and, consequently, in the FBG sensors.



**Figure 9-** Temperature calibration procedure; a) Machine measurement of temperature and strain; b) FBG wavelength shift  $\Delta \lambda_b$ .

The strain measured by the extensioneters and the temperature from the environmental chamber are shown in Figure 9a). As previously described, both FGB sensors have the same response to temperature variation, as can be observed in Figure 9b). However, a small difference in the sensor response is observed every time the temperature changes. This is because FBG-B is closer to the specimen surface, which makes it experience the temperature change first.



**Figure 10-** Strain and temperature measured independently by the FBG sensors during temperature calibration. The lines show the strain and temperature measured by the machine, and the symbols the strain and temperature obtained by the developed method using the FBG sensors measurement.

The strain without thermal effect and temperature were calculated using Equations (13) and (14), as shown in Figure 10. Good agreement between the predicted and measured temperature was found. However, the small difference in the sensor response observed in Figure 9b) caused an error in the strain measurement, which disappears once the temperature homogenised inside the specimen. Thus, the distance between the sensors can be problematic for the strain measurement accuracy and it should be as small as possible to minimize this effect.

The temperature calibrated parameters are presented in Table 3.

Table 3- FBG temperature calibration: calibrated parameters

Calibrated Parameters			
Thermo-optic coefficient ( $\xi$ )	8.3E-6		
Thermal expansion coefficient ( $\alpha_h$ )	6.1±0.03 E-5		
Calibration Error	0.05 %		
$(T_{machine} - T_{FBG})/T_{machine} (K)$			

#### 4.1.3. Simultaneous Strain and Temperature Measurement

As a final test, a continuous variation of temperature from -10°C to 40°C was applied to the specimen and, at the same time, the specimen was cyclically loaded with two strain stages of  $\varepsilon = 0.30\%$  and  $\varepsilon = 0.50\%$ , as shown in Figure 11a).



**Figure 11-** Simultaneous strain and temperature measurement; a) Machine measurement of temperature and strain; b) FBG wavelength shift  $\Delta \lambda_b$ .

However, in order to compare both measured strains without the thermal effect, the machine strain was converted using the load applied by the tensile machine ( $\varepsilon_{noThermal} = F/(A_{section}E)$ ; E=4.4 GPa).

The wavelength shift  $\Delta \lambda_b$  of each FBG sensor can be observed in Figure 11b) and, as expected, the signal global behaviour follows the specimen temperature variation in both sensors, and the difference in the sensor response  $\left(\frac{\Delta \lambda_b^A}{\lambda_b^A} - \frac{\Delta \lambda_b^B}{\lambda_b^B}\right)$  increases as the strain in the specimen increases.



**Figure 12**- Strain and temperature measured independently by the FBG sensors during a tensile test with simultaneous temperature and strain variation. The lines show the strain and temperature measured by the machine, and the symbols the strain and temperature obtained by the developed method using the FBG sensors measurement.

The strain and temperature measured independently by the FBG sensors during the tensile test are shown in Figure 12. The strain in the specimen caused by the loading without the thermal expansion

effect was successfully measured with a maximum error of 2.4%. This measurement error can be justified by the mismatch in temperatures acting in each sensor, as this error is only observed during large temperature variation. This problem can be solved by minimizing the distance between sensors. Nevertheless, the error value achieved is acceptable, and in common tests or application this magnitude of temperature variation will not happen.

The observed difference between the two measured temperatures is caused by fact that the machine temperature is measured in the environmental chamber, and the FBG temperature is measured inside the specimen. Therefore, the specimen needs more time to homogenise its temperature, creating a delay in the measurement.

In summary, these results showed that by using this method it is always possible to determine the strain without the thermal effect within a reasonably low error, even for a complicated temperature-loading case.

#### 5. Proposed Calibration Protocol

A calibration procedure is required before any measurement can be made. The two calibration options are:

- Full calibration or using already calibrated parameters; this is the most accurate method but it is time consuming.
- Strain/partial calibration; it is faster to perform but the temperature can't be measured.

#### 5.1.1. Measurement with Full Calibration

The full calibration procedure allows more parameters to be measured; it is possible to measure the specimen strain and temperate independently, and also to measure the material Poisson's ratio ( $\nu_{12}$ ) and thermal expansion coefficient ( $\alpha_h$ ). The full calibration procedure requires the following steps:

- a) Strain calibration:
  - 1. Load/Unload the specimen and maintain the temperature constant during the test;
  - 2. Measure the wavelength shift from both FBGs,  $\Delta \lambda_b^A$  and  $\Delta \lambda_b^B$ ;
  - 3. Measure the specimen strain using the surface mounted extensioneters; this strain is considered the reference strain ( $\varepsilon_{ref} = \varepsilon_{extensometer}$ );
  - 4. Calibrate the photo-elastic coefficient  $(p_e)$  using Equation (16);

$$\frac{\Delta\lambda_b^A}{\lambda_b^A} = (1 - p_e)\varepsilon_{ref} \tag{16}$$

5. Calibrate the Poisson's ratio  $(v_{12})$  using the Equation (17); Use the calibrated  $p_e$  value;

$$\varepsilon_{ref} = \left(\frac{\Delta\lambda_b^A}{\lambda_b^A} - \frac{\Delta\lambda_b^B}{\lambda_b^B}\right) \frac{1}{(1 - p_e)(1 - \cos(\theta)^2 - \nu_{12}\sin(\theta)^2)}$$
(17)

- b) Temperature calibration:
  - 1. Apply a controlled variation of temperature, ensuring that no load or any displacement constrains are applied to the specimen;
  - 2. Measure the wavelength shift from both FBGs,  $\Delta \lambda_b^A$  and  $\Delta \lambda_b^B$ ;

- 3. Measure the chamber temperature variation; This temperature is considered the reference value ( $\Delta T_{chamber} = \Delta T_{ref}$ )
- 4. Calibrate the thermo-optic coefficient ( $\xi$ ) and the host material thermal expansion coefficient  $(\alpha_h)$  using the Equation (18); Use the calibrated  $p_e$  value;

$$\frac{\Delta\lambda_b^A}{\lambda_b^A} = \frac{\Delta\lambda_b^B}{\lambda_b^B} = [(1 - p_e)\alpha_h + \xi]\Delta T_{ref}$$
(18)

c) This material-sensor calibrated parameters:  $v_{12}$ ;  $p_e$ ;  $\xi$ ;  $\alpha_h$ 

Note that this was the protocol used in the section 4.

#### 5.1.2. Measurement with strain/partial calibration

If the thermal expansion coefficient  $(\alpha_h)$  is unknown and the full calibration was not performed, the temperature of the specimen can't be measured by the developed method. However, it is still possible to measure the strain without the thermal effect by executing a strain/partial calibration.

This calibration method is faster to execute and it does not requires surface mounted extensometers or an environmental chamber, which makes it a good calibration alternative (for measurements where the temperature is not a requirement). The strain/partial calibration procedure requires the following steps:

- a) Strain/partial calibration:
  - 1. Load/Unload the specimen and maintain the temperature constant during the test;
  - a. Measure the wavelength shift from both FBGs,  $\Delta \lambda_b^A$  and  $\Delta \lambda_b^B$ ;
  - b. The strain measured by the FBG-A is considered the reference strain ( $\varepsilon_{ref} =$

$$\frac{\Delta\lambda_b^A}{\lambda_b^A}\frac{1}{(1-p_e)}\bigg)$$

- c. Assume the parameter  $p_e$  as the value provided by the manufacture (in this case  $p_e = 0.22$ ); d. Calibrate the Poisson's ratio ( $v_{12}$ ) using Equation (17);
- b) Execute the tensile test, and calculate the strain without the thermal expansion effect using equation (13) and the calibrated Poisson's ratio.

A comparison between the two calibration methods, full calibration and strain/partial calibration, is presented in Appendix A.

#### 6. Summary and Conclusions

The FBG sensors have a strain and temperature cross-sensitivity, making them inaccurate for tests where the temperature can change. A temperature variation in the specimen will create an additional strain, caused by the thermal expansion. A simple measurement method to decouple this crosssensitivity, enabling independent and accurate measurement of strain and temperature, was developed in this article. This technique was developed especially for polymeric tensile test specimens, and it can be accomplished by using two single mode FBG sensors embedded in the material.

Equations describing this method, which allows strain and temperature calculation from the FBGs

signal, were derived from the general FBG work principle. It was demonstrated that, during temperature variation, both sensors will measure the same amount of wavelength shift  $\Delta \lambda_b$ , caused by the material thermal expansion. However, during loading, the sensor response will have a different evolution, which gives information about the strain in the material. Moreover, the angle between FBG sensors ( $\theta$ ) has a big impact on the strain resolution. For an angle  $\theta$  around 90°, the resolution is actually improved, benefiting from the Poisson's effect.

Two different calibration protocols were presented; one, fast that allows measuring the strain without the thermal effect, sacrificing temperature measurement and accuracy; other, more time consuming but that allows accurate measurement of strain and temperature. Nevertheless, the authors suggest that for each material-sensor configuration the full calibration procedure should be performed, in order to tune the parameters used by the method.

This multi-parameter measurement method was applied to an epoxy tensile specimen. The full calibration protocol was performed and achieved a calibration error smaller than 1%. Then, multiple two loading/strain stages of  $\varepsilon$ = 0.30% and  $\varepsilon$ = 0.50% during a continuous variation of temperature, from 40°C to -10 °C, were applied to the specimen. The consistency of the expected/theoretical results with the calibration procedure, and the experimental validation, suggests that this proposed method is applicable to measure accurate strain and temperature in a wide range of polymer materials during tensile testing, being specially promising for polymer fatigue test specimens.

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# **Appendix A. Comparison Between The Two Calibration Methods: Full And Strain/Partial Calibration**

In this appendix the two calibration methods, full and strain/partial calibration, are compared. To simulate the case where only the strain/partial calibration was performed, only the FBG data measured during tests is considered (without included the strain measured by the surface mounted extensometers).

The parameters obtained after preforming the calibration protocols are shown in Table A.1.

Parameters	Full Calibration	<b>Strain/Partial Calibration</b>
Photo-elastic coefficient $(p_e)$	0.21±0.05	0.22 (given by manufacturer)
Poisson's ratio ( $v_{12}$ )	0.35±0.07	0.35±0.04
Thermo-optic coefficient ( $\xi$ )	8.3E-6	8.3E-6 (given by manufacturer)
Thermal expansion coefficient $(\alpha_h)$	6.1±0.03 E-5	Not possible to obtain

**Table A.1-** Calibrated and assumed parameters used. Comparison between the two calibration methods, full and strain/partial calibration

The comparison between the strain and temperature measured by the two methods are shown in Figure A.1 and the maximum strain measurement error obtained is presented in Table A.2. The measurement where full calibration was performed shows a lower strain measurement error, but it requires a more time consuming procedure.

On the other hand, the measurement where only strain/partial calibration was performed shows an error slightly larger; however it does not allow any temperature measurement.

In any case, both options will give accurate measurement of strain without the thermal effect.



**Figure A.1-** Strain and temperature measured independently by the FBG sensors during a tensile test with simultaneous temperature and strain variation: Comparison between the two calibration methods, full and strain/partial calibration. The line represents the control strain and temperature measured by the machine, the cross symbol the strain and temperature measured by the full calibration method, and the square symbol the strain measured by the strain/partial calibration method.

**Table A.2-** Maximum strain measurement error obtained during the test: Comparison between the two calibration methods.

	Full Calibration	<b>Strain/Partial Calibration</b>
Maximum Strain error	2.4%	3.7%