Engineering Structures 33 (2011) 539–548

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Analysis of the strain transfer in a new FBG sensor for Structural Health Monitoring

Benjamin Torres, Ignacio Payá-Zaforteza*, Pedro A. Calderón, Jose M. Adam

ICITECH, Departamento de Ingeniería de la Construcción, Universidad Politécnica de Valencia. Camino de Vera s/n, 46071 Valencia, Spain

ARTICLE INFO

Article history:
Received 19 May 2010
Received in revised form
2 September 2010
Accepted 2 November 2010
Available online 30 November 2010

Keywords:
Fiber Bragg grating sensors
Fiber optic sensors
Strain transfer
Structural Health Monitoring

ABSTRACT

Structural Health Monitoring (SHM) is a topic of great interest in structural engineering due to the ageing of the built infrastructures and the growing use of innovative structural systems and construction materials. Although several sensing technologies have been developed for use in SHM systems, fiber optic sensors, especially Fiber Bragg grating sensors (FBGs), are now attracting much attention due to their advantages over other types of sensors.

This paper presents a new FBG strain sensor with an unsymmetrical packaging configuration designed to be fixed to the surface of the monitored structure. A 3D Finite Element numerical analysis of the sensor, packaging and adhesive used to fix the system to the host structure was conducted to study the influence of (1) the thickness and mechanical properties of the adhesive, and (2) the configuration of the packaging on the accuracy of the sensor. The results obtained from the numerical models show that the strains measured by the proposed system and the actual strains in the host structure differ by less than 2.5% due to the fact that the packaging contains only one layer of composite material in an unsymmetrical configuration. The proposed design can thus be said to be an improvement compared to the typical configurations of optical fiber surface strain sensors.

1. Introduction

Structural Health Monitoring (SHM) has been defined by Li et al. [1] as the *use of in situ, continuous or regular (routine) measurement and analyses of key structural and environmental parameters under operating conditions, for the purpose of warning of impending abnormal states or accidents at an early stage, as well as giving maintenance and rehabilitation advice*. Although the formal establishment of this discipline is fairly recent (the International Society for Structural Health Monitoring of Intelligent Infrastructure was created in 2003 and the first journal devoted exclusively to this field appeared in 1993) the history of systems to monitor the behavior of bridges and buildings is much older, as engineers such as Torroja and Nervi monitored some of their innovative designs during the first half of the XXth century (see [2,3] respectively).

A monitoring system is composed of three elements (see [1,4–6]): a sensor system, a data processing system and a health evaluation system. Sensors that detect the transmission of electrical signals have traditionally been used in SHM, but in recent years the use of fiber optic sensors (FOSs) has attracted a great deal of attention in research and development, as reflected in both review and application articles [1,7–12]. The main reasons for this interest are the falling prices of FOSs added to their advantages over conventional sensors. These advantages relate mainly to their flexibility, embeddability, multiplexity, small size and immunity to electrical or magnetic interference (see [4,13]). FOSs detect variations in the properties of light travelling through the optical fiber. The fiber usually consists of three layers: the core, which is a thin glass fiber, the cladding that confines the propagation of the light within the fiber core, and an outer coating or jacket that provides the fiber mechanical strength and protects it from damage and moisture absorption. Although there are three different FOS technologies (point, long gauge and distributed sensors), the most frequently used system at the present time is the Fiber Bragg grating (FBG) point sensor [8].

FBG sensors cannot be installed bare in a structural element as they are very fragile and the harsh environment of a construction site and building structures would affect their durability and behavior. Therefore several encapsulation or packaging techniques have been developed to protect them (see [4,8,14]). It is common practice to assume that the strain values recorded by FBG sensors are the actual strains in the host structure, but this is not always the case. In the common case of sensors that are first embedded in a material or fixed to a plate and then glued to the surface of the host structure, a discrepancy appears related to the thickness of the embedding material or fixing plate and the thickness and mechanical properties of the adhesive.

* Corresponding author. Tel.: +34 963877562; fax: +34 963877568.
E-mail addresses: bentorgo@upvnet.upv.es (B. Torres), igpaza@cst.upv.es (I. Payá-Zaforteza), pcaldero@cst.upv.es (P.A. Calderón), joadmar@cst.upv.es (J.M. Adam).

0141-0296/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2010.11.012

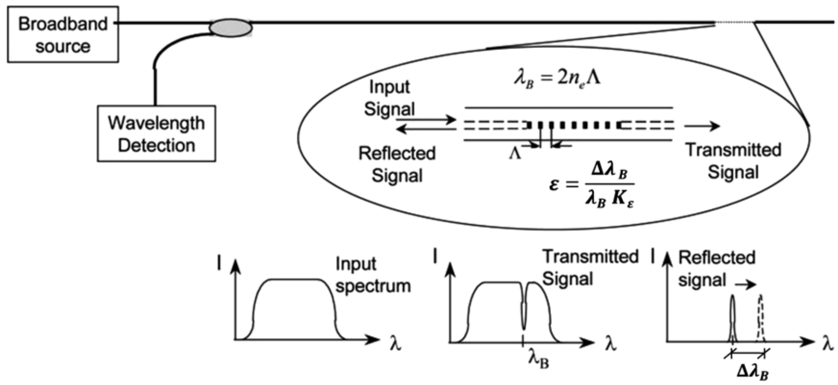

Fig. 1. Basic Bragg grating-based sensor system with transmissive or reflective detection options.
Source: [11]. Reproduced with the kind permission of the authors.

This paper describes the design and experimental evaluation of a new surface FBG strain sensor system developed at the Universidad Politecnica de Valencia (UPV). Unlike many commonly used strain sensors in which the strain perceived by the sensor may differ from that on the surface on which it is placed, the packaging of the new sensor has been designed in such a way that the discrepancy between the recorded and real strain values is negligible. Following a description of the basic principles of FBG sensors, this paper explains the main features of the proposed packaging and describes the numerical studies carried out to evaluate its behavior and compare it to other similar systems. Finally, conclusions are drawn on the behavior of the packaging system, based on the previous analyses.

2. Principle of FBG sensors

An FBG is a reflector built in a short segment of the core of an optical fiber by exposing the fiber to an intense UV light. This exposure creates periodic alterations in the index of refraction of the fiber core, known as *Bragg gratings*, and makes the FBG (1) reflect only particular narrowband light wavelengths, of light known as *Bragg wavelengths*, and (2) transmit all others (see Fig. 1). The Bragg wavelength condition is given by Eq. (1), where λ_B is the wavelength of the FBG, n_{eff} is the effective refractive index of the fiber core, and Λ is the Bragg grating period or distance between two consecutive alterations of the fiber core.

$$\lambda_B = 2n_{\text{eff}}\Lambda. \tag{1}$$

As external perturbations such as strains (ε) and temperature (T) changes induce modifications in the Bragg grating period Λ, they also induce a shift $\Delta\lambda_B$ in the Bragg wavelength. This shift is given by Eq. (2), when only the dominant linear effects of ε and T on an FBG are considered and higher order cross-sensitivities are neglected (see [15]).

$$\frac{\Delta\lambda_B}{\lambda_B} = K_\varepsilon \Delta\varepsilon + K_T\,\Delta T. \tag{2}$$

In Eq. (2), K_ε and K_T are the coefficients of wavelength sensitivity to strain and temperature for an FBG whose values are given by:

$$K_\varepsilon = [1 - 0,5n_{\text{eff}}\,(\rho_{12} - \upsilon\,(\rho_{11} - \rho_{12}))]\;\lambda_B \tag{3}$$

$$K_T = [1 + \xi]\,\lambda_B \tag{4}$$

where ρ_{11} and ρ_{12} are the components of the fiber optic strain tensor and ν is the fiber Poisson's ratio, ξ is the fiber thermo-optic coefficient and n_{eff} is the refractive index of the fiber (see [15,16] for more details).

K_ε and K_T are obtained experimentally, K_T being dependent on the material of the host structure. Once K_ε and K_T are known, it is possible to obtain the values of the increments in strains and temperatures corresponding to a certain shift of the Bragg wavelength by using Eqs. (5) and (6) (see [17]). It should be pointed out that two sensors must be used when measuring to avoid strain misreading due to thermal effects. One of them is tightly fixed to the structure and is therefore affected by both strains and temperature changes, while the second is designed in such a way that it is only affected by temperature changes. In Eqs. (5) and (6), subscript 1 relates to the optical fiber sensor that is fixed to the structure and subscript 2 relates to the sensor that only measures temperature changes.

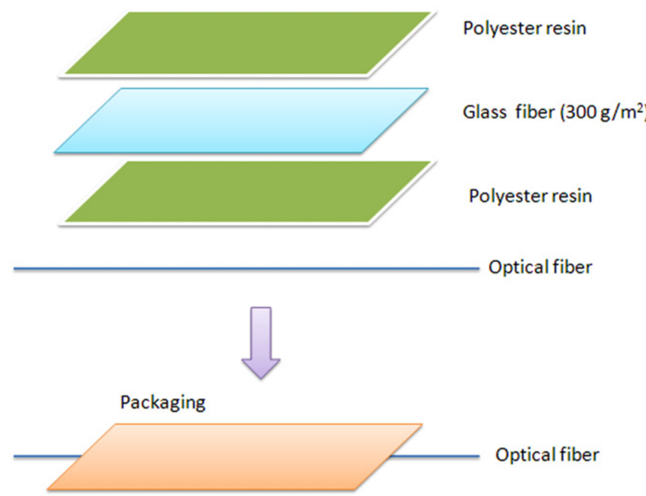

Fig. 2. UPV sensor. 3D view of the FBG and the packaging.

$$\Delta\varepsilon = \frac{1}{K_\varepsilon}\left(\frac{\Delta\lambda_{B1}}{\lambda_{B1}}\right) - \frac{K_{T1}}{K_{\varepsilon 1}\;K_{T2}}\left(\frac{\Delta\lambda_{B2}}{\lambda_{B2}}\right) \tag{5}$$

$$\Delta T = \frac{1}{K_{T2}}\left(\frac{\Delta\lambda_{B2}}{\lambda_{B2}}\right). \tag{6}$$

For the FBG strain sensor described in Section 3, $K_{\varepsilon 1}$ is equal to 1.15 pm/$\mu\varepsilon$ whereas K_{T1} is equal to 17.5 pm/°C or 20.5 pm/°C, depending on whether the host structure is made of concrete or steel, respectively, as explained in [16,18]. K_{T2} depends on the specific sensor used to measure temperature changes and is equal to 8 pm/°C for the system used in this study.

3. FBG strain sensor

The FBG strain sensor consists of an FBG protected by layers of composite material made of glass fiber reinforced polyester resin with a weight of 300 g/m^2 (see Fig. 2). The sensor system is