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Development of fiber Bragg grating sensors for monitoring civil infrastructure

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Abstract

The concept of structural health monitoring has been the subject of research over the last few years, particularly in civil and structural engineering where ageing infrastructure is of major concern. These studies have led to initiatives towards the development and deployment of new sensing technologies. Owing to the harsh environments found in the construction industry, and the large size of civil engineering structures, such sensors should be robust, rugged, easy to use and economical. Fiber Bragg grating (FBG) sensors offer a viable such sensing approach with a number of advantages over traditional sensors. These include immunity to electromagnetic interference, light weight, small size, multiplexing capabilities, ease of installation and durability. This paper reports some results from a multi-disciplinary research program on FBG sensors involving the School of Civil and Structural Engineering and the School of Electrical and Electronic Engineering at Nanyang Technological University in Singapore. Novel FBG strain sensors have been developed and deployed on highway bridges to measure dynamic strain, static strain, and temperature. Results of these studies indicate that, if properly packaged, FBG sensors can survive the severe conditions associated with the construction environments of civil infrastructure.

Keywords: Fiber optic sensors; Fiber Bragg grating sensors; FBG strain sensors; FBG temperature sensors; Structural health monitoring

1. Introduction

Socio-economic pressure to install structural health monitoring (SHM) systems on civil infrastructure in order to improve safety, and to optimize maintenance strategies, is growing. The demand for SHM systems has largely been driven by deficiencies in structural performance arising from ageing phenomena, and the need to increase the load-carrying capacity of structures to enable them to cope with increased loading regimes. By continuously or periodically measuring structural response to live loading and environmental changes such as stress, strain, temperature, and vibration, and applying relevant data analysis procedures, one can detect anomalies in structural behaviour and performance. Anomalies include, and are often defined as, deterioration and damage resulting from changes in material properties, geometric properties, boundary conditions, system connectivity and the loading environment of the structure.

A typical SHM system comprises an array of sensors, sensor excitation hardware, a host computer and communication hardware and software. Sensors play the important role of providing information about the state of strain, stress and temperature of the structure. Their selection for a particular application is governed by application, sensor sensitivity, power requirements, robustness and reliability. Most SHM systems reported in the literature have focused on traditional sensing technologies such as electrical resistance train sensors, vibrating wire strain gauges and piezoelectric accelerometers. While the traditional sensors are robust and strong enough for civil engineering applications they often

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require many cables to support them, and for long distance monitoring these cables suffer from electromagnetic interference (EMI). Also only sparse populations of electrical resistance (ER) sensors can be installed due to costs. In recent years there have been a number of research initiatives towards the development and deployment of fiber Bragg grating sensors (FBG) for sensing applications in civil and structural engineering [1–3]. The interest in FBG sensors as a viable sensing approach for civil infrastructure has been motivated by the advantages they offer over traditional sensors. FBG sensors are: immune to electromagnetic interference, lightweight, small in size, easy to install, corrosion resistant, durable and can be multiplexed. The multiplexing capabilities of FBG sensors mean that many sensors can be installed on a structure with minimum wiring. However these sensors are fragile and their packaging should ensure that the sensors are robust and rugged enough to withstand the harsh environment found in the construction industry. A number of FBG based strain monitoring programs have been reported in the technical literature. Todd [4] demonstrated the sensing capabilities of FBG sensors by installing a number of sensors on a steel girder in a bridge. Schulz [5] reported the application of long gauge FBG sensors for monitoring civil structures. The performance of FBG sensors has also been demonstrated in the laboratory [6–8]. Most of these studies focus on sensing and multiplexing capabilities of FBG sensors. Little attention has been paid to the packaging of these sensors for application in civil engineering where conditions are harsh. This paper reports the design and experimental evaluation of FBG sensors carried out at Nanyang Technological University (Singapore), with particular emphasis on packaging of sensors for applications in concrete structures.

2. Principle of FBG sensors

A Bragg grating is a periodic structure fabricated by exposing photosensitized fiber core to ultraviolet light (Fig. 1). When light from a broadband source interacts with the grating a single wavelength, known as the Bragg wavelength, is reflected. The Bragg wavelength is related to the grating period, Λ, and the effective refractive index of the fiber by

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

Both the effective refractive index and the grating period vary with changes in strain, ε, temperature, T, and pressure P, imposed on the fiber. An applied strain and pressure will shift the Bragg wavelength through expansion or contraction of the grating periodicity and through the photoelastic effect. Temperature affects the Bragg wavelength through thermal expansion and contraction of the grating periodicity and through thermal dependence of the refractive index. These effects are well understood and, when adequately modelled, provide a means for predicting strain, pressure and temperature. If only the dominant linear effects of these three factors on an FBG are considered, neglecting higher-order cross-sensitivities, then the amount of Bragg wavelength shift is given by [9]

$$\Delta\lambda_B = K_\varepsilon \varepsilon + K_T \Delta T + K_P P \tag{2}$$

where K_ε, K_T and K_P are coefficients of wavelength sensitivity to strain, temperature and pressure (force per unit area) for an FBG given by

$$K_\varepsilon = [1 - 0.5n_{\text{eff}}(\rho_{12} - \nu(\rho_{11} - \rho_{12}))]\lambda_B \tag{3}$$

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

$$K_P = \left[-\frac{1-2\nu}{E} + \frac{n^2}{2E}(1-2\nu)(2\rho_{12} + \rho_{11})\right]\lambda_B \tag{5}$$

where ρ_{11} and ρ_{12} are the components of the fiber optic strain tensor and ν is Poisson's ratio for the fiber, ξ is the fiber thermo-optic coefficient, E is Young's modulus for the fiber, n is the refractive index of the fiber. Most of these properties are known experimentally and remain fairly constant for the different fibers. For a common bare FBG, they are $K_\varepsilon = 1.15$ pm/με, $K_T = 11$ pm/°C and $K_P = -3.0$ pm/MPa, respectively, at 1.55 μm wavelength.

3. FBG sensing systems

Installation of bare FBG sensors on components of civil structures may result in a high rate of sensor failure owing to the fragile nature of the glass fiber and the harsh environment of the construction industry. Also handling problems resulting from the small physical size of the fiber add to the difficulties associated with attaching bare FBG sensors to structural components. As noted above, a bare FBG sensor is sensitive to temperature, strain and pressure. An ideal sensor should be sensitive to only one parameter and be immune to others. Thus there is a need to develop techniques for minimizing cross-effects in FBG sensors. The elimination of cross-sensitivity may be achieved by measurements at two different wavelengths or two different optical modes, for which the strain and temperature responses are different [10–13]. Fernández-Valdivielso et al. [14] proposed temperature discrimination based on an FBG sensor and a thermochromic material where the strain is measured through the variations of the FBG wavelength while the temperature is measured using the change in optical power reflected by the thermochromic material. However these techniques suffer from system complexity, limited measurement range and limited multiplexing capabilities. A simpler way to correct a strain measurement for the effect of temperature is using physically separated sensors, where the one for temperature compensation is isolated from the strain field. The following sections describe novel strain FBG sensors and temperature FBG sensors designed for application in civil and structural engineering. The important aspect of the design of these FBG sensors is their packaging for civil engineering applications.

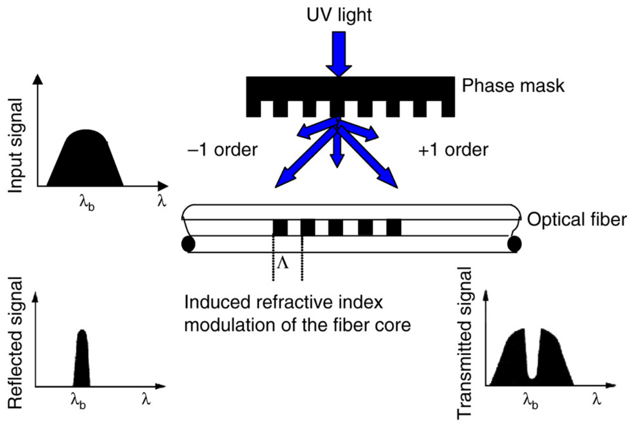

Fig. 1. FBG fabrication process.

Fig. 2. FBG temperature sensor.

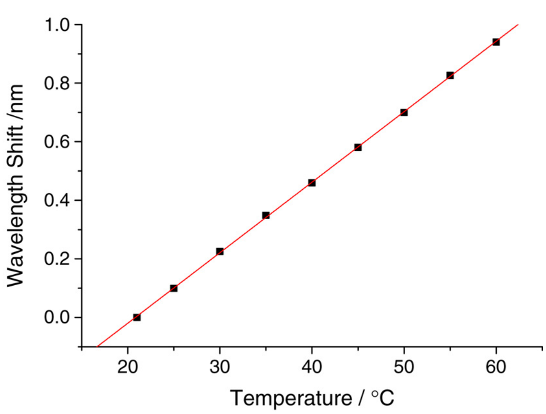

Fig. 3. Calibration of a temperature sensor.

3.1. Temperature sensor

The temperature sensor consists of an FBG sensor packaged into a 35 mm long metal tube (Fig. 2). The metal tubing protects the FBG from external stress and increases the temperature sensing range and sensitivity by enhancing the FBG dilation [15]. The Bragg wavelength shift of the FBG temperature sensor is only related to the change of ambient temperature. A typical calibration curve for the temperature sensor is shown in Fig. 3. The wavelength–temperature coefficient is 25 pm/°C, with a sensitivity of 0.04 °C, and the accuracy is 0.2 °C.

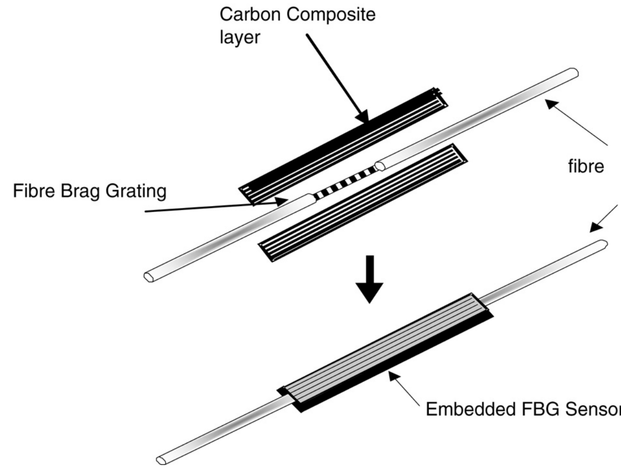

Fig. 4. Embedded FBG strain sensor.

3.2. FBG strain sensor

The embedded strain sensor consists of an FBG sandwiched between layers of carbon composite material (Fig. 4) and is about 50 mm long and 0.5 mm thick. The accuracy and sensitivity of the sensor are dependent upon the optical interrogation system. The function of the optical interrogating system is to detect the wavelength shift in relation to external perturbation and to deduce the measurands using Eq. (2). The interrogating system used for strain measurements described here had a sensitivity of 1 με and an accuracy of 5 με. It should be noted that the strain sensor is not immune to temperature variations and would therefore indicate strain due to thermal expansion. The sensor described in Section 3.3 allows for minimization of strains related to temperature change.

3.3. Temperature compensated FBG strain sensor

The temperature compensated sensor consists of two FBGs written in close proximity. One FBG is encased in a metal tube to form a temperature sensor while the other is sandwiched in carbon composite as described above. The assembly of the two sensors is then encased in a specially designed dumb-bell (Fig. 5). The sandwiched sensor is bonded to the dumb-bell using an epoxy glue and the temperature sensor is left loose. The design of the dumb-bell is such that the strain sensor is isolated from pressure effects. This sensor was designed for strain and temperature measurements in mass concrete.

4. Experimental evaluation of FBG sensors

Embedding the FBG sensors in carbon composite material or encasing the FBG in a metal tube alters its sensitivity coefficients making it necessary to calibrate the sensors. To this end experiments were carried out where the embedded FBG strain sensors were installed alongside

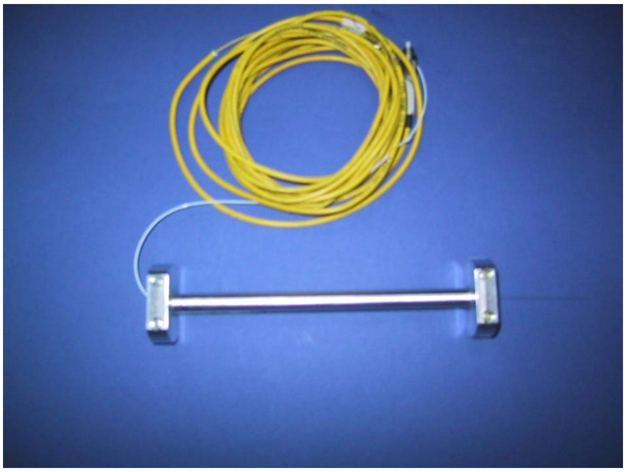

Fig. 5. Temperature compensated strain sensor.

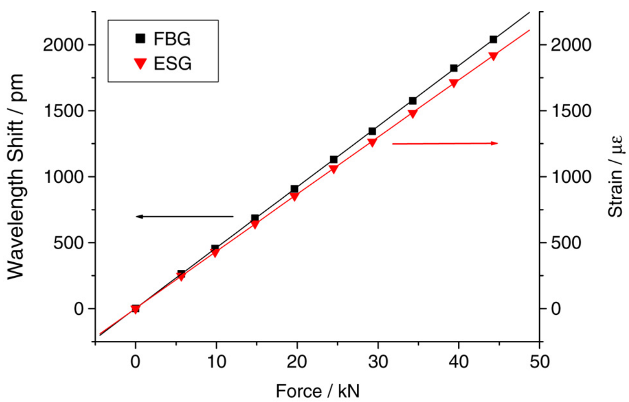

Fig. 6. Tensile test load–strain curve.

conventional foil strain gauges and then subjected to various kinds of loads. In addition experimental evaluation sought to establish simple procedures for installing FBG sensors in concrete structures.

4.1. Tensile tests

Tensile tests were performed on a steel rebar instrumented with both FBG sensors and electrical resistance strain gauges (ERS) attached to the rebar in close proximity. Fig. 6 shows the load–strain curves for both FBG and electrical strain gauges. Clearly there is a linear variation between electrical FBG sensor strains and electrical resistance strains. The correlation between FBG sensor strains and electrical resistance strains was about 0.99. On the basis of the tensile experiments, the wavelength–strain coefficient of the embedded FBG strain sensor was found to be 1.06 pm/με (Fig. 6).

4.2. Static tests on concrete beams

The objective of this experiment was to study the performance of FBG sensors in quantifying strains. Another aim of the experiment was to establish a simple procedure for installing FBG sensors in concrete structures. Important issues considered were: bonding sensors to rebars, protecting sensors during casting and isolating pressure effects.

Two 3000 mm long, 300 mm deep and 150 mm wide doubly reinforced concrete beams were used (Fig. 7). Each beam was instrumented with six FBG strain sensors alongside ERS gauges on top and bottom rebars and at mid-spans and quarter-spans. All FBG sensors survived concrete pouring and compaction.

The beams were simply supported and first loaded to the serviceability limit state and then to failure. Test results show good linearity (Fig. 8) between FBG sensor strains and electrical resistance strains.

4.3. Monitoring the curing process of a concrete beam

Two FBG temperature sensors described in Section 3.1 were attached to top and bottom rebars of the 3000 mm, 300 mm deep, 150 mm wide reinforced concrete beam described in Section 4.2 alongside FBG strain sensors. The process of curing of the beam was monitored over a few days. Fig. 9 shows the temperature changes from the FBG temperature sensors attached to top and bottom rebars together with air and concrete surface temperature changes (measured using a thermistor) during the curing process. The temperature increased rapidly and reached a maximum at approximately 8 h after casting. The maximum temperatures recorded for the top and bottom rebars are 39.3 °C and 40.2 °C respectively.

4.4. Dynamics tests

A reinforced concrete beam 5500 mm long, 150 mm deep and 300 mm wide was used for these vibration experiments (Fig. 10). Six strain FBG sensors were installed in the beam. Minimum protection was provided for a set of three sensors. Of these sensors only one was damaged during casting. A set of four FBG sensors and four demountable electrical strain gauges was installed on the surface of the beam. The beam was excited using an instrumented impulse hammer and signals acquired by relevant interrogating systems. The sampling rates for the sensors were FBG sensors at 17.5 Hz, dynamic strain gauges (DSGs) at 100 Hz. The natural frequency of the beam was then extracted from the strain signals.

The maximum amplitude of the dynamic strain recorded by DGSs at beam mid-span is 58 microstrains while the FBG sensor recorded 55 microstrains (Fig. 11). This slight difference can be attributed to the low sampling rate used for FBG sensors. The power spectrum density of all signals shows very close agreement with the maximum power at about 7.9 Hz (Fig. 12).

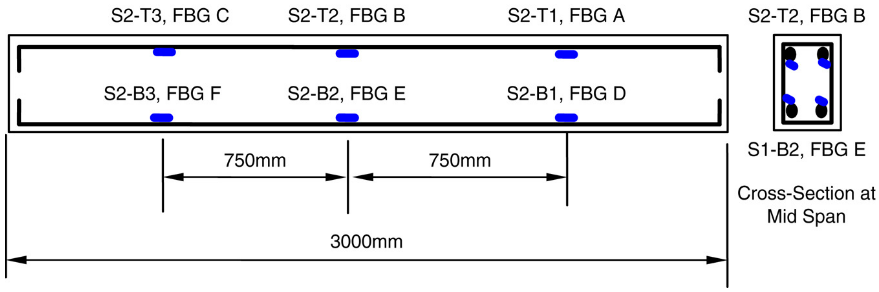

Fig. 7. Reinforced concrete beam sensor arrangement.

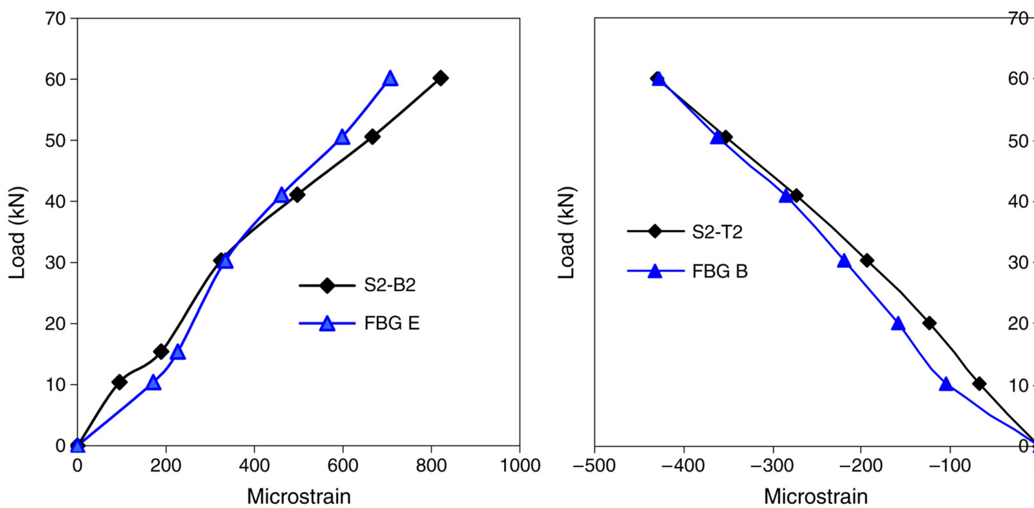

Fig. 8. RC beam load–strain curves at beam mid-span.

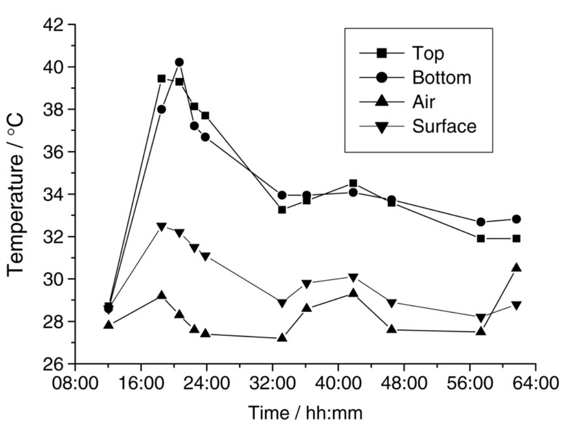

Fig. 9. Monitoring concrete curing process.

Fig. 10. Dynamic test set-up.

4.5. *Tests on a temperature compensated sensor*

The temperature compensated FBG sensor was placed in an oven and temperature increased from 22 to 85 °C. The wavelength shift was measured every 5 °C change (Fig. 13). The sensitivities of the strain and temperature sensors were found to be 13.74 pm/°C and 11.67 pm/°C respectively. The sensor was embedded in a concrete cylinder and tested in compression. Fig. 14 shows the response to the compression load of the temperature compensated sensor. Clearly, only the strain sensor indicates a change in wavelength of the FBG with increasing compression.

5. Concluding remarks

The results of these studies demonstrate that, if properly installed, FBG sensors can survive the severe conditions associated with the construction of concrete structures and yield accurate measurements of strains and temperature. The potential applications for these FBG sensors include

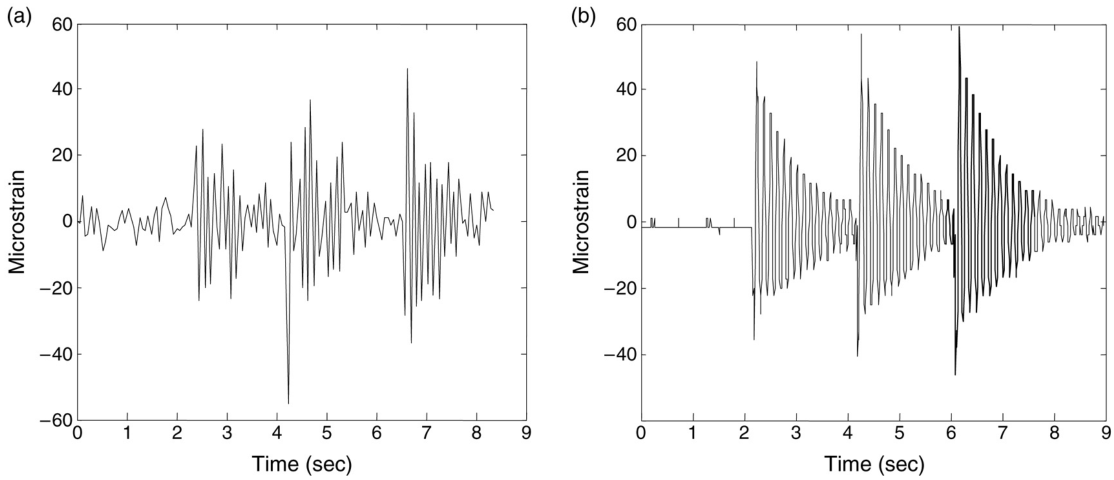

Fig. 11. Dynamic strains: (a) dynamic strain signal recorded by the FBG; (b) dynamic strain signal recorded by the DSG.

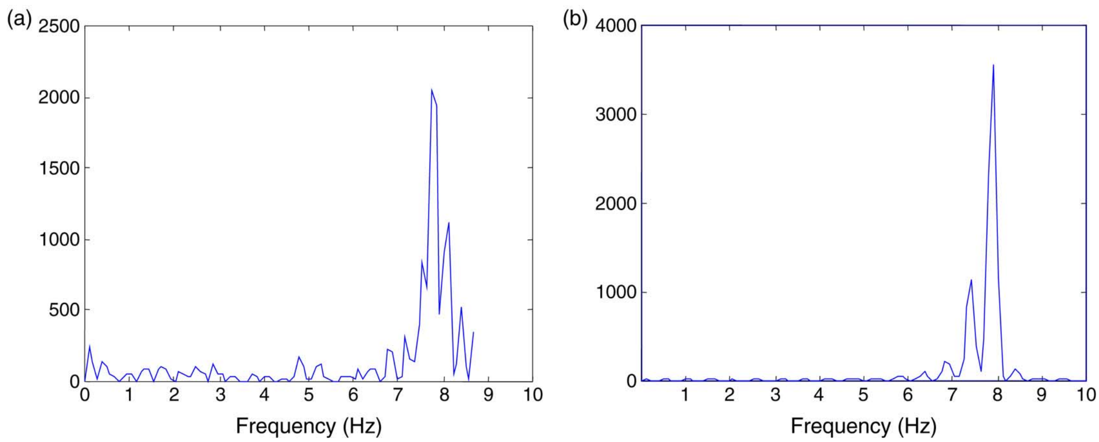

Fig. 12. Beam natural frequency based on strain signals: (a) FBG signal power spectral density; (b) DSG signal power spectral density.

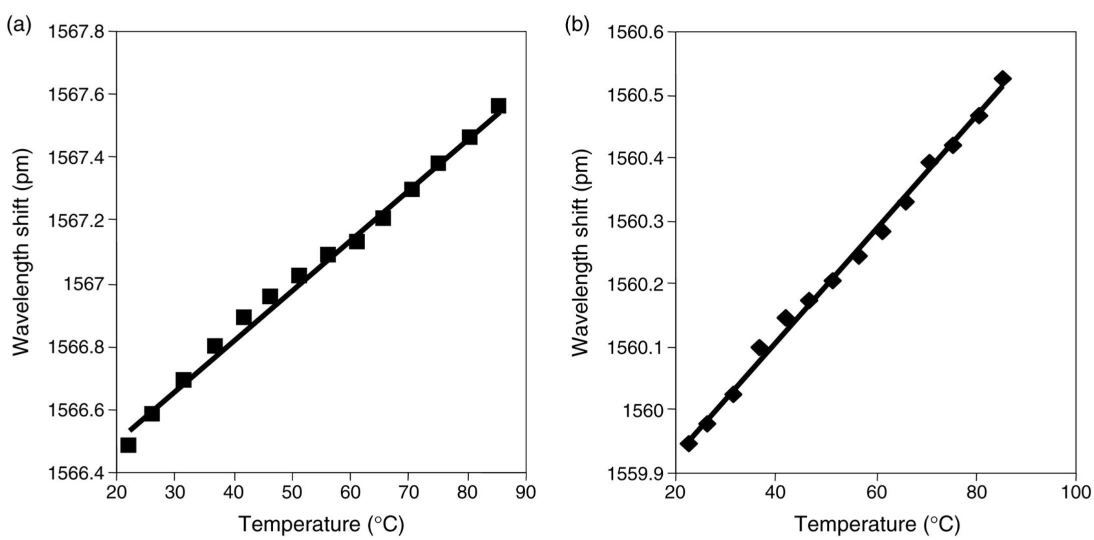

Fig. 13. Thermal response of temperature compensated FBG sensor: (a) thermal response of strain sensor; (b) thermal response of temperature sensor.

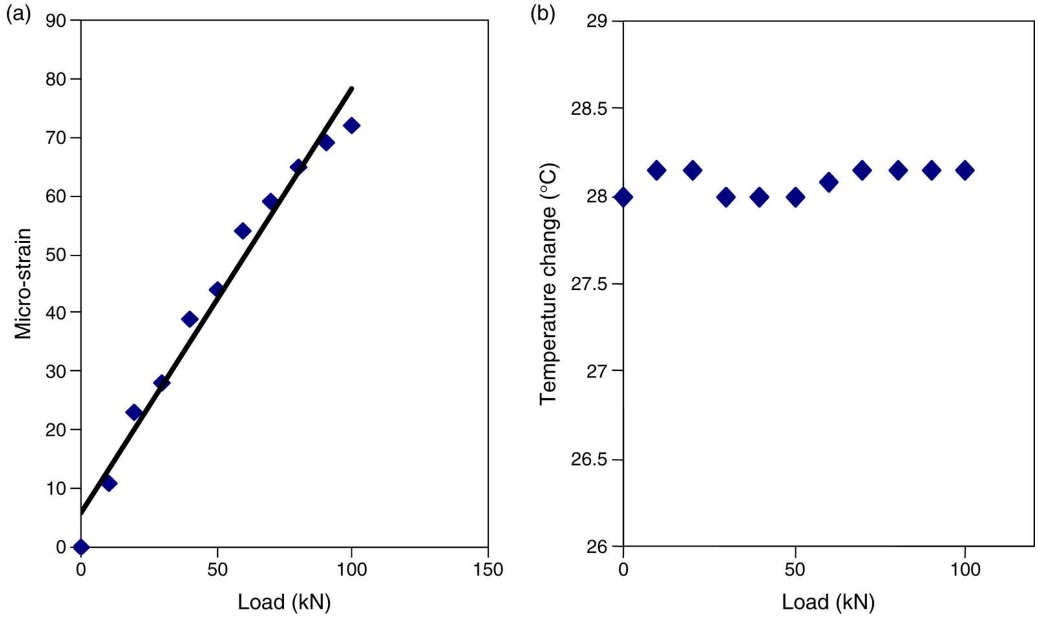

Fig. 14. Response of temperature compensated sensor to loading: (a) strain sensor response to compression; (b) response of temperature during load testing.

long term structural health monitoring, short term condition assessment of structures, vibration and seismic response structures and traffic loading assessment on bridges. The deployment of these sensors is currently limited by lack of portable, rugged data acquisition systems with low power consumption.

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