Arch-bridge Lift Process Monitoring by Using Packaged Optical Fibre Strain Sensors with Temperature Compensation

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Abstract. This paper presents a novel sensor design and packaging, specifically developed to allow fibre grating-based sensors to be used in harsh, in-the-field measurement conditions for accurate strain measurement, with full temperature compensation. After these sensors are carefully packaged and calibrated in the laboratory, they are installed onto the paragrid of a set of flat-packed concrete units, created specifically for forming a small-scale, lightweight and inexpensive flexi-arch bridge. During the arch-bridge lifting process, the sensors are used for real-time strain measurements to ensure the quality of the construction. During the work done, the sensors have demonstrated enhanced resilience when embedded in concrete structures, providing accurate and consistent strain measurements during the whole installation process and beyond into monitoring the integrity and use of the structure.

1. Introduction

Fibre Bragg gratings (FBGs) are well established as important sensing elements for the measurement of strain, temperature, and a wide range of other parameters. In the civil engineering sector, this is primarily attributed to the fact that the sensing signals from such fibre Bragg gratings are wavelength encoded, thus making them well suited for multiplexing: this allows multiple sensing points to be included within a single length of fibre, thus showing advantages over using a large number of conventional strain gauges for large-scale structural monitoring. However, FBG sensors can suffer a significant limitation in real engineering applications due to their cross-sensitivity to several parameters, especially strain and temperature. To overcome this limitation, a number of techniques have been reported, such as dual-wavelength superimposed gratings [1], hybrid Bragg grating/long-period gratings [2], dual-diameter FBGs [3], FBGs super-imposed with polarisation-rocking filters [4], FBGs combined with EDFAs [5], FBG/Fabry-Perot cavities [6], the use of long-period gratings [7], FBGs inscribed on the splice joint between two different fibres [8], and a chirped Bragg grating fabricated in a fused fibre taper [9]. Most of
these designs are based on modifying the fibre gratings structurally or physically, which imposes additional complexity in the fabrication process for the resultant sensor head and thus increases the overall system cost and complexity. Additionally, bare FBGs can easily be damaged when being handled improperly or subjected to harsh working conditions. Therefore, it is necessary to protect the FBGs in a way that allows for use under normal working conditions. In this paper, a special sensor packaging is reported, developed for a specific and novel application in structural health monitoring, to enable discrimination between strain and temperature while still providing enhanced mechanical resilience for an important sensing application.

2. Sensing principle
Fibre Bragg Gratings (FBGs) [10] reflect light centred at a particular wavelength, termed as the Bragg wavelength, which is equal to twice of the product of the effective refractive index of the fibre core and of the grating period. Consequently, a change in temperature and/or in strain can cause a shift in the reflected wavelength through effects such as mechanical and thermal expansion, the photoelastic and the thermo-optic effects. By having two independent fibre gratings exposed to the same surroundings, the strain and temperature can be distinguished by solving the following matrix [11],

\[
\begin{bmatrix}
\Delta T \\
\Delta \varepsilon
\end{bmatrix} = \begin{bmatrix}
D & K_{T2} \\
-K_{T2} & K_{T1}
\end{bmatrix} \begin{bmatrix}
\Delta \lambda_{B1} \\
\Delta \lambda_{B2}
\end{bmatrix}
\]

(1)

where \( K_{ei} \) is the effective strain coefficient, \( K_{Ti} \) is the effective temperature coefficient for the fibre gratings, \( i = 1,2 \) referring to gratings 1 and 2, \( D = K_{T1}K_{s2} - K_{s1}K_{T2} \) and \( \Delta \lambda_{Bi} \) is the Bragg wavelength shift. These coefficients can be determined experimentally as they are related both to the optical fibre glass materials and to the influence of the packaging medium which is used to protect the gratings.

3. Experimental setup and results

3.1. Sensor Fabrication and Packaging
The authors and other have demonstrated the use of optical fibre Bragg gratings in a number of applications to civil engineering structures [12] but in this work the aim was to provide a suitably packaged grating that could readily be installed on a structure exposed to considerable strain during the arch lifting process. Thus the aim of the packaging process for the gratings employed was to create a sensor system that would allow independent measurement of strain and temperature and be ruggedized for use in-the-field, employable during the construction and evaluation of a novel arch bridge design. To achieve this, as shown in figure 1 (a), two adjacent fibre Bragg gratings (set 30mm apart) were inscribed in a piece of a B/Ge co-doped photosensitive fibre before being sandwiched between two plastic slabs (polypropylene) by means of cyanoacrylate adhesive. To enable one grating to measure temperature only (and thus allow for correction for temperature effects on the grating measuring temperature and strain), a special packaging scheme was developed in which one fibre grating is slightly bent in order to prevent strain transfer from the package. The grating was enclosed by a thin metal envelope to protect and isolate the grating from any transverse mechanical stresses and lateral strain surge. By contrast, the other grating was glued to the package material to sense both strain and temperature so that the combined signal can be used to separate strain from temperature by using equation (1). The actual construction of the sensor is shown in figure 1(b). The length of the package was 80mm and the width of the sensing length was 6mm. The ends of the package are intentionally made slightly wider to function as anchors on the structure.
3.2. Sensor calibration

The effective strain and temperature coefficients for both sensors were obtained by measuring separately the wavelength shifts when they are subjected to controlled strain or temperature variations. To achieve this, the strain calibration was performed by using a purpose-built calibration rig with a 1µm-resolution and the temperature calibration was performed by using a climatic chamber (Binder, KBF 115 (E2)). The individual strain and temperature coefficients of both sensors, used together in the packaging discussed, were obtained through calibration and are shown in figure 2. The differences in the coefficients between the paired gratings were clearly evident.

It was verified through a series of experiments carried out that the fibre grating used for temperature measurement in the metal envelope exhibits no response at all to the applied strain. This enables it to act as a temperature-only sensor, one which is immune to the influence of strain when the sensor package is used. The calibrated data from the temperature sensor is subsequently utilized to remove the temperature effect from the dedicated strain sensor (i.e. the other fibre grating) by using equation (1).

![Figure 1.](image)

**Figure 1.** (a) Schematic diagram, and (b) photograph, showing the actual construction of the special sensor packaging design.

![Figure 2.](image)

**Figure 2.** The response of packaged sensor for (a) strain calibration, and (b) temperature calibration.
3.3. Sensor installation in a model arch bridge

The above sensor package had been designed specifically for use on an arch bridge to allow strain to be determined when the bridge was being constructed and subsequently when loaded. The arch bridge is designed for convenience of movement to a site for construction and figure 3 shows a ‘flat pack’ assembly, comprising a number of concrete units, connected by a paragrid layer on the top. In this work, a total of 10 fibre optic sensors was specially packaged and then installed on the paragrid, following which the flexi-arch was formed from the ‘flat pack’ by lifting the concrete units. The sensors are constructed both to survive vigorous handling in the process of arch formation and to allow the measurement of strains in real time during the lifting process.

![Figure 3](image)

**Figure 3.** Flat pack assembly for arch bridge construction, which is ready for lifting to form an arch bridge

This is a unique application of fibre Bragg grating based sensors and, as may be expected, a number of the sensor package connections were broken during the initial phases of construction and lifting of the arch: in the end 3 fibre-optic sensors, as shown in figure 4, survived until the end of the experiment. One of the reasons for the failure of the sensor link was due to an unexpected forceful breakage of the screed layer during the arch formation and the avoidance of this problem should be planned into future installations. However in spite of the level of breakage, there proved to be a sufficient number of sensors to gain valuable data on the bridge and to establish a protocol for future tests to limit the level of breakage of the sensors and their network connections.

![Figure 4](image)

**Figure 4.** The arrows indicate the positions of fibre-optic sensors along the paragrid of the flexi-arch bridge, and the inset shows the placement of the fibre-optic sensors underneath the paragrid.
As shown in figure 4, the sensors were fixed to the paragrid by using cyanoacrylate adhesive, which has proved in previous work to be highly successful in achieving a good level of strain transfer and stability. The top surfaces of the sensors were then covered loosely by the same paragrid material in order to decouple the sensors from the screed layer, while their anchor points were intentionally exposed to be attached to the screed material.

4. Experimental results obtained
As indicated in figure 4, in this initial test only three sensors, i.e. L2, L4 and L5 survived the entire construction and lifting process; therefore as the flexi-arch was lifted, the strain was measured at 3 different locations and the measurement data obtained are presented as a function of the vertical height of the one-third point. Figure 5 shows the results obtained from sensor L2, located at the middle of the flexi-arch bridge, where the necessity for enhanced temperature compensation is illustrated.

**Figure 5.** Strain measurement on the paragrid at the centre of the flexi-arch bridge during lifting by the middle sensor with and without temperature compensation.

**Figure 6.** Overlay of two different sets of strain measurement on paragrid during lifting by three fibre-optic sensors at various joint locations.
Two tests were undertaken sequentially, allowing two sets of measurement data for all three fibre-optic sensors on the paragrid at various joint locations to be obtained. Figure 6 shows the two sets of strain measurement data obtained from the three fibre-optic sensors at various joint locations, as shown in figure 4, during process of lifting the arch into position. The results obtained have confirmed that the sensors have not just been able to survive the harsh conditions of construction and lifting but also to provide consistent readings of the strains experienced during the experiments, with the temperature effect being fully compensated.

5. Discussions and conclusion
The work has uniquely tackled an application of measurement of strain on the arch as it is both lifted into place and has shown the value of the specially designed package of a combined strain/temperature sensor. This has been demonstrated in a challenging application to a new type of light weight arch bridge which has significant potential in construction processes. To do so, a compact design for the temperature compensated fibre grating-based strain sensors has been demonstrated and shown to achieve enhanced mechanical resilience and to allow the accurate strain/temperature measurement data required, both through laboratory calibration and field tests. The work, undertaken by civil and electrical engineers working together on developing, placing and installing the packaged fibre grating sensors has shown that they could be successfully installed on the paragrid of a model flexi-arch bridge and tested extensively for strain/temperature measurements, even though a number were broken on this initial trial. Based on the positive experimental results obtained, it can be concluded that the novel sensor system has been successfully integrated into the concrete material and the performance of the sensors has been validated through a series of successful tests of the sensors installed in the paragrid of the arch model bridge when it is lifted. The novel design of the packaging helps the sensors to survive harsh handling both during the sensor installation and during the bridge tests, and even when embedded in concrete.

On-going work will tackle the issues of enhanced survivability of the sensor package and allow the testing and evaluation of the packaged sensors ‘in-the-field’ on a larger version of the arch bridge on a commercial site.

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