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The response of embedded strain sensors in concrete beams subjected to thermal loading

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HIGHLIGHTS

- Strain sensors used in structural engineering applications are commonly affected by temperature changes.
- We examined the responses of four types of strain sensors under controlled temperature changes.
- The variance between strain measurements from different sensors are 25–30%.
- Temperature compensation methods and calibration factors used are the two main issues to cause uncertainties.

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ABSTRACT

A wide range of commercially available sensors are frequently used to record the response of civil engineering structures that may be subjected to unexpected loading scenarios, changes of environmental conditions or material deterioration. However, a common problem faced when using these sensors is to distinguish strain changes experienced by the structure due to a temperature change from strain changes that occur due to other causes. Temperature effects on strain sensors are usually accommodated by allowing for temperature effects (temperature compensation); however, there is limited research in the literature that investigates the performance of strain sensor measurements when subjected to temperature change. Understanding the temperature effect on strain sensors will greatly enhance the ability of civil engineers to monitor the performance of structural materials. In this paper, different types of commonly used and advanced strain sensors have been installed in a reinforced concrete beam to measure the thermal strain response of concrete under different temperature conditions. The experimental results demonstrated a 25–30% difference in strain measurements from the different sensors. It is shown in this paper that this difference is due to the combined effects of sensor inaccuracy, uncertainties related to the testing conditions and uncertainties associated with the temperature compensation methods.

1. Introduction

Structural Health Monitoring (SHM) relies on the use of sensors to measure physical parameters. The strain change of structures is one of the most commonly assessed quantities in SHM to investigate the performance of structures under loading. There are three categories of commercially available strain sensors: (i) discrete strain sensors, (ii) quasi-distributed strain sensors and (iii) highly distributed strain sensors. Discrete sensors measure localised strain at the point where the sensor is installed while the highly distributed strain sensors measure the complete strain profile along the entire length of the sensor. Quasi-distributed strain sensors are discrete sensors connected in series. Measurements from these sensors are adversely affected by the surrounding environment such as temperature change which induces a thermal component in the sensor strain measurement. This is due to the different thermal expansion properties of the materials that constitute the sensor itself and the structural material in which the sensor is installed. Many civil engineering structures are subjected to repeated temperature changes on a very frequent basis hence it is important to understand how the thermal effects influence the strain measurements so that the mechanical strain induced by any unexpected loading scenarios or rapid material deterioration can be more accurately derived.

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The effect of temperature on different sensors (conventional and advanced) has been researched by a number of researchers in the past. The following sections will briefly discuss some of the most significant research that has been done previously. Neild et al. [9] conducted theoretical calculations to express the relationship between the measurements of Vibrating Wire Strain Gauges (VWSG) and the thermal deformation of a test specimen. Based on the results obtained, they argued that an unstrained VWSG (i.e. free from structural material deformations but under the same environmental conditions as the test specimen) should be used as a dummy gauge to compensate the temperature effect. However, they also found that if the sizes and geometries of the test specimens and the control samples were significantly different, they would be affected differently by temperature. This may have a significant implication, particularly in cases where such sensors are embedded in massive concrete structures like bridges for example. Sreeshyiarn et al. [13] reported a temperature calibration factor of 2.19 με/°C for an embedded VWSG and 4.32 με/°C for a surface mounted gauge on a concrete specimen. They expressed concern that, due to the varied thermal expansion coefficient of concrete from one case to another, an individual calibration test was required for each VWSG.

Recently developed measurement technologies, such as fibre optic sensors, have been used to measure strain and/or temperature changes of structures whether embedded internally or attached externally. The advantages of these sensors over conventional sensors (e.g. VWSGs) include: they are not affected by electro-magnetic fields, longer sensing lengths and the potential to provide a long term reliable monitoring solution [2]. Two types of fibre optic sensors are most commonly adopted in practice: (a) the Fibre Bragg Grating sensors (FBG) and the distributed optical fibre cables (FO). The former are quasi-distributed sensors where individual FBGs can be placed at numerous locations on one cable (providing simultaneous multiple points sensing) while the latter have the advantage of providing highly-distributed continuous strain profiles along the entire length of the optical fibre cables and are believed to have potential for long term monitoring with less implementation costs [4]. The particular FO technique discussed in this paper uses the Brillouin backscattering technique [1]. Published case studies in the literature where temperature compensation is discussed in detail are very limited. Rodrigues et al. [11] presented a study on FBG sensors where the FBG sensors were initially fixed onto steel tubes before they were embedded in the concrete deck of the Lezíria Bridge in Portugal. For temperature compensation in particular, the paper mentioned briefly that a direct calculation could be applied with known temperature measurements at the location of the FBG sensors, taking into account the characteristics of the FBGs and the material of the structure that was being monitored. However, no further detail was given for the accuracy and reliability of measurements after applying such a temperature compensation method. Mohamad [7] discussed the use of dummy temperature optical fibre cables alongside the active FO sensing cables to carry out temperature compensation for distributed FO measurements. The design of the temperature optical fibre cable allows the cables to be used for temperature compensation. The fibre core in the FO dummy temperature cable can expand freely in a gel-filled tube and hence is isolated from any strains transmitted to the outer sheath of the cable. The "temperature strain" measured by the temperature cable is then subtracted from the total strain measured by the active FO sensing cable to calculate the mechanical strain. Mohamad [6] argued that using such a method is much cheaper and simpler than other approaches, particularly when temperature coefficients relating to different types of optical fibres can be easily estimated. Field case studies conducted recently [14,12] discussed the installation of FO temperature and strain cables in a number of pre-stressed concrete bridge beams and cast in-situ concrete pile foundations at the Nine Wells Bridge near Cambridge, UK. Schwamb [12], who reported the pile foundation sensing results, pointed out that the accurate interpretation of the measurements, including temperature compensation, is highly dependent on the geometric alignment of the strain and temperature cables; a small mis-alignment of 5 cm resulted in significantly inaccurate results. Webb [14] adopted the same temperature compensation method as suggested by Mohamad [6] and compared the temperature compensated FO measurements to the theoretical strain prediction and found that the two were correlated well in larger scale.

In summary, SHM schemes have been used to monitor the performance of a number of civil engineering structures, however, in most cases the sensors employed in these SHM schemes are likely to be subjected to and affected by temperature changes. In most studies in the literature, measurements from different independent instruments would normally be introduced to allow cross calibration and comparison, however there is still little quantitative evidence available on the reliability of the different sensors when subjected to temperature changes. Understanding the effect of the temperature changes on the different strain sensors plays a significant role in understanding the performance of the structures under conditions such as unexpected/extreme loading scenarios and rapid material deterioration. The research presented in this paper provides quantitative information about the effect of temperature on some of the most commonly used strain sensors such as the VWSGs and FBGs, as well as some of the promising new strain sensors such as distributed FO sensors.

2. Experiment design

Since the vast majority of commonly used strain sensors are affected to some extent by temperature, the reliability of their output measurements needs careful calibration and validation. Therefore, a thorough study of the effect of temperature on strain measurements is needed. The research presented in this paper examined the performance of strain sensors from two main perspectives:

(1) How reliable is the sensor calibration and what is the accuracy of the measurements?
(2) What role does temperature compensation play in the accuracy of measurements?

To investigate the questions above, an experimental programme was conducted in which a reinforced concrete beam, instrumented with four types of strain sensors, was subjected to varied temperature conditions without external mechanical loading. The beam was 3.5 m in length with cross-section dimensions of 25 cm in depth and 20 cm in width as shown in Fig. 1. It had a cylinder compressive strength of 32 MPa at 28 days. Four Grade 500B reinforcement steel bars with a diameter of 12 mm were used as longitudinal reinforcement while 8 mm diameter shear links were used (at a spacing of 15 cm towards the supports 50 cm elsewhere) along the beam. The concrete cover was 20 mm from the surface of the beam to the surface of shear links. The beam was simply supported at each end with the roller bearings allowing free expansion in the longitudinal direction. Four types of sensors were installed: a conventional foil electrical resistance strain gauge (ERS), a Vibrating Wire Strain Gauge (VWSG), Fibre Bragg Grating sensors (FBG) and distributed Brillouin backscattering optical fibre sensor (FO). The four types of strain sensors were located so that the point sensors (ERS, VWSG and FBG) could be used to compare results with those obtained with the distributed fibre optic sensor (FO). The location of the different sensors in the beam is shown in Fig. 1c and d. Temperatures inside the beam were monitored by thermocouples (type K) and distributed optical fibre (FO) temperature cable. Thermocouples were installed at the same locations as each of the discrete strain sensors (ERS, VWSG and FBG) and also at the mid-height of the beam at a number of locations along the beam as shown in Fig. 2a and b.

The experiment was divided into two parts; firstly, the whole beam was enclosed in an insulated box where all external surfaces of the beam were uniformly heated (from room temperature up to a maximum of 40 °C in 1 °C increments) as shown schematically in Fig. 3a. In this case, the thermal strains measured from all instruments were expected to be the same given the beam was allowed to expand freely. In the second part of the experiment, the same concrete beam was used however, this time only the top surface of the beam was exposed to rising temperature inside the temperature box (Fig. 3b), thus creating a temperature gradient through the depth of the beam. The bottom was uncovered and exposed to ambient air temperature. The ends of the beam were wrapped with