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Structural health monitoring of concrete cylinders using protected fibre optic sensors

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Abstract

Two kinds of sensor protection system for fibre optic sensors (FOS), an embedded type and a surface-mountable type, have been developed in the work described this paper. Extrinsic Fabry–Perot interferometric (EFPI) and fibre Bragg grating (FBG) sensors protected by the designed protection systems have been used to monitor the cure progress and structural health status of concrete cylinders. Experimental results indicate that the sensor protection systems for the FOS perform adequately and effectively in a concrete environment. The protected fibre optic sensors are suitable for achieving structural health monitoring in practice. It is also revealed that there is excellent correlation between the results obtained from the protected FOS and reference electrical resistance strain gauges.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In-service structural health monitoring (SHM) is very important and is a requirement for safer working of engineering structures such as concrete structures. This task is very difficult to carry out using conventional methods. New reinforced concrete constructions would benefit greatly from *in situ* structural monitors that could detect a decrease in performance or imminent failure, for example variation in strain, temperature, corrosion or crack formation. The ability to interrogate numerous sensors multiplexed along a single fibre permits an entire structure to be outfitted with sensors with a manageable number of leads routed to central access points. In response to this increased need, various techniques are being developed and some of the most promising are based on the use of fibre optic sensors (FOS) [1].

Fibre optic smart structures are enabling technology that will allow engineers to add a 'nervous system' to their designs, providing damage assessment, vibration damping and many other capabilities to structures that would be very difficult to achieve by other means. The potential market for the application of smart civil structures could be quite large. The most probable candidates will be smart civil structures such as smart buildings and skyscrapers, smart bridges, dams, bridge decks etc. FOS can offer many potential advantages for applications in civil structural systems. In fact, many FOS have been developed for using in smart civil structures such as polarization FOS, extrinsic Fabry–Perot interferometric (EFPI) and fibre Bragg gratings (FBGs), multimode FOS, etc [1–8]. These FOS have already been successfully used to monitor the structural health status of composite and concrete structures [9–16].

However, the inherent vulnerability of FOS makes it difficult to protect the fibres from the concrete aggregate during the pouring phase and the following term of service. So these unprotected FOS can be easily damaged and corroded during long-term practical applications as the FOS will normally be in direct contact with cement and aggregates. This disadvantage

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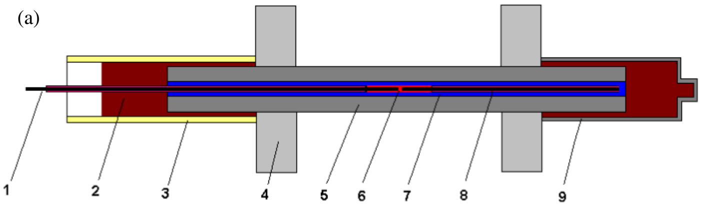
(a)



1 - Optical fibre 2- Silicone rubber 3- Thick PTFE tube 4 -Steel flange 5 - Steel tube 6 - FP sensor

7 - Epoxy adhesive 8 - Thin PTFE tube 9 - Fixed steel tube

(b)

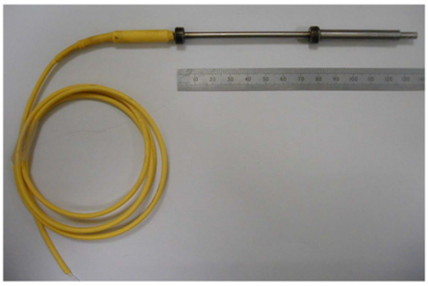


Figure 1. (a) Schematic illustration of the steel tube-based ESPS. (b) Photograph of the steel tube-based ESPS.

really limits the application of FOS in concrete structures. Thus, sensor protection systems are certainly demanded for the application of FOS in civil engineering. Previously, other researchers have developed some protected FOS and used them in concrete structures to perform mechanical measurements [17–19].

In this paper we describe the development of two kinds of protection system for FOS—surface-mountable and embedded protection systems. The cure process of a concrete cylinder has been monitored using protected EFPI and FBG sensors. Furthermore, experimental validation of concrete cylinders with embedded and surface-mountable protection system with EFPI and FBG sensors has also been done.

2. The sensor protection system and fibre optic sensors

In order to protect the FOS from the concrete aggregate and corrosion *in situ* a FOS protection system is certainly demanded. Two kinds of sensor protection system (SPS) for FOS, surface-mountable and embedded protection systems, are described here. Figure 1(a) shows the embedded sensor protection system (ESPS) made of a stainless steel tube with two flanges and relevant sealing materials. The adhesive materials were carefully selected to obtain better strain transfer between the FOS, which are located inside the steel tube and outside flanges. The flange shape was optimized by finite-element methods (FEM). To avoid damage to the FOS at the end of the steel tube, highly flexible polytetrafluoroethylene (PTFE) and nylon tubes are used to protect the fibres at the entrance to minimize the risk of fibre breakage due to sharp turning or other unexpected damage. Water-resistant silicon rubber and epoxy were used to seal the tube in order to protect the sensors from humid environments. A demonstration of the ESPS is shown in figure 1(b).

A surface-mountable sensor protection system (SSPS) has been developed for FOS used for ageing engineering structures. The construction of a SSPS can use existing techniques and procedures that have been developed for surface mounting of electrical resistance strain gauges. These devices can be mechanically fastened or bonded to the concrete structure.

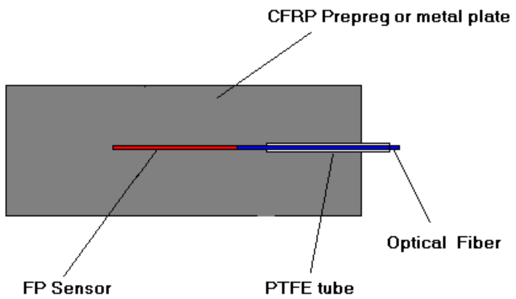
The surface-mounted protection system can be made of a wide variety of materials such as metal, plastic or composite materials, and in different shapes to fit the shape of the surface of the engineering structure according to the practical requirements. However, the option of using a fibre-reinforced plastic (FRP) composite is considered predominantly in this paper due to the ease of manufacture and corrosion resistance via the composite prepreg. A schematic illustration of a SSPS for a FOS is shown in figure 2(a). This protection system is made from composite prepreg with different materials such as glass/epoxy, carbon/epoxy, as shown in figure 2(b).

2.1. The EFPI sensor

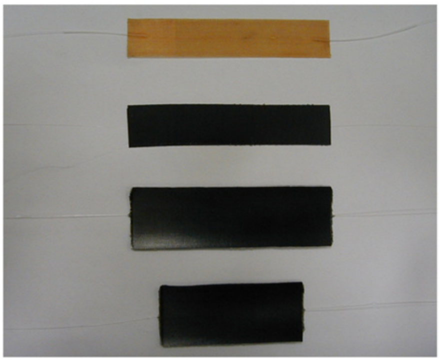
The basic principle of the EFPI sensor is based on the multireflection Fabry–Perot interference between two reflecting mirrors. The schematic configuration of an EFPI sensor is shown in figure 3. The cavity length between the two optical fibre surfaces is changed when an external load is applied to this sensor. This can be measured by a CCD spectrometer through a 3 dB 2×2 fibre coupler. The strain of the sensor is given according the following equation [6]:

$$\varepsilon = \frac{\Delta d}{L} \tag{1}$$

where Δd is the change in the cavity length and L is the gauge length that is the distance between the two fusion spliced points on the microcapillary.



(a)



(b)

Figure 2. (a) Schematic illustration of composite-based SSPS. (b) Photograph of composite-based SSPS made using carbon fibre reinforced plastic (CFRP) and glass fibre reinforced plastic materials.

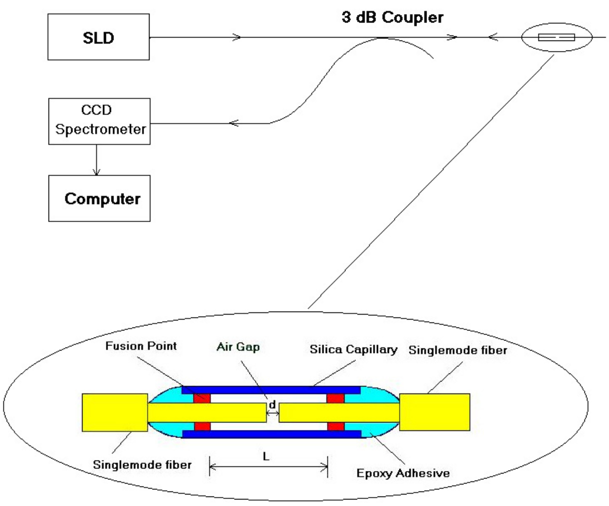


Figure 3. Schematic configuration of an EFPI sensor.

2.2. The FBG sensor

A uniform FBG includes a segment of optical fibre with a periodic modulation of the core refractive index as shown in figure 4. Usually, an in-fibre FBG can be fabricated on a photosensitive (Ge-doped or hydrogen loaded) single-mode optical fibre by using a UV laser source of wavelength 240–248 nm. Basically, the principle of the FBG sensor is based on the measurement of changes in the reflective signal, which is the centre wavelength of back-reflected light from a Bragg

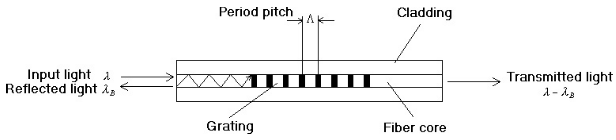


Figure 4. Schematic illustration of a FBG sensor.

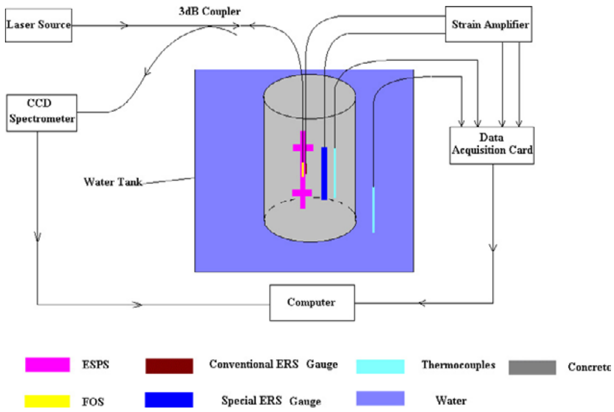


Figure 5. Schematic diagram of cure monitoring of concrete cylinders with an embedded FOS.

grating, and which depends on the effective refractive index of the core and the periodicity of the grating. According to the Bragg condition, the Bragg wavelength can be expressed as [20]

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

3. Experimental validation and discussions

3.1. Cure monitoring of a concrete cylinder using EFPI and FBG sensors

A schematic diagram of the experimental system of concrete cylinders with embedded EFPI and FBG FOS for cure monitoring is shown in figure 5. The FOS are packaged in the ESPS and investigated by an Ocean Optics S-2000 CCD spectrometer. A conventional electrical resistance strain (ERS) gauge is surface bonded to the outside of steel tube to compare the strain transfer. Special water-resistant adhesive also been used to protect the strain gauge from the harsh environment during long-term curing of the concrete materials. A commercial special embedment ERS gauge from the Measurement Group, normally used to monitor the cure of concrete materials, is also embedded in the cylinder as a reference measurement. Thermocouple temperature sensors are put in the concrete cylinder and water tank to monitor the environmental temperature. Before being embedded into concrete cylinders, the thermocouple temperature sensors are packaged with PTFE tubing and calibrated with a standard temperature sensor. A photograph of the experimental set-up is shown in figure 6.

All sensor data are automatically captured by programmed Labview software through a 16-channel data acquisition card from National Instruments. The dimensions of the concrete cylinder are 200 mm (length) × 100 mm (diameter).

Figure 6. Photograph of experimental set-up for cure monitoring of concrete cylinders.

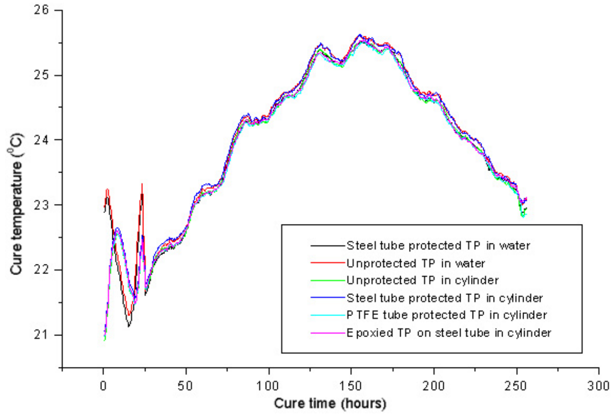


Figure 8. Temperature records during the cure using thermocouples (TC).

Figure 7. Concrete cylinder with embedded sensors.

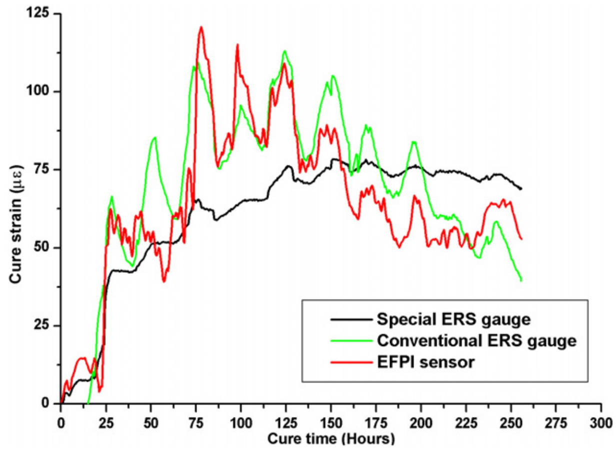


Figure 9. Cure monitoring of a concrete cylinder using EFPI sensors.

The concrete has a water/cement ratio of 0.52 and an aggregate/cement ratio of 6. Figure 7 shows a concrete cylinder with various embedded sensors. Experimental temperature records for the concrete cylinder during the 10 days of the cure period measured using protected and unprotected thermocouples (TC) are shown in figure 8. There are a few kinds of protected TC and unprotected TC used in both water tank and concrete cylinders to monitor the temperature development.

It can be seen that the temperatures in the concrete cylinder and water tank are different in the early cure period and then trend to nearly the same track. It emerged that a chemical reaction of cement with water occurred during the early cure period and led to the increasing temperature in the concrete cylinder. Temperatures in both the concrete cylinders and the water tank change slightly during the cure period from 21 to 26 °C, as shown in figure 8. There are also periodical changes in temperature which can be explained as due to alternation from day to night. The cure development of concrete cylinders measured using EFPI sensor is shown in figure 9. It can be seen that the cure strain is increased to 60 $\mu\varepsilon$ during the first 48 h at an early curing stage. Then the cure strain is trending to constant with certain periodical perturbations during the following 10 days. It can be speculated that the periodical perturbations are caused by the change in ambient temperature from day to night during the cure period. Thus, this leads to additional deformation of the cement mortar due to material shrinkage. As we can see, the perturbations given by EFPI and conventional ERS sensors are much bigger than those from the commercial special strain gauge. The reason for this is that the ESPS are strongly held within the surrounding cement and transfer the cure strain more effectively. At the same time, the perturbations also prove that the protected EFPI and FBG sensors are more sensitive to changes in environmental temperature than the commercial special strain gauges due to the special design of the ESPS. It also emerged that the early stage deformation is much greater and normally comprises thermal deformation (swelling and shrinkage), endogenous shrinkage, carbonation shrinkage and evaporation shrinkage. The deformation due to autostressing provoked by stiffness of the formwork can be considered negligible [21].

The same phenomena can be validated in figure 10 when a protected FBG sensor is used to monitor progress of the curing. It can be seen that the FBG sensors can be used to monitor the cure strain and show very good agreement with conventional strain gauge sensors. This means there is very good strain transfer between the FOS inside the steel tube and the strain

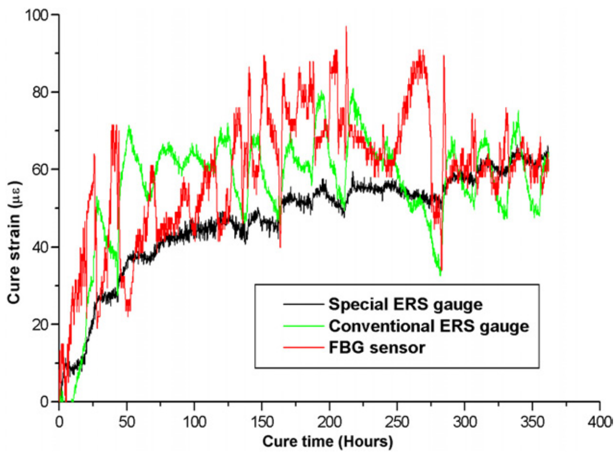


Figure 10. Cure monitoring of a concrete cylinder using FBG sensors.

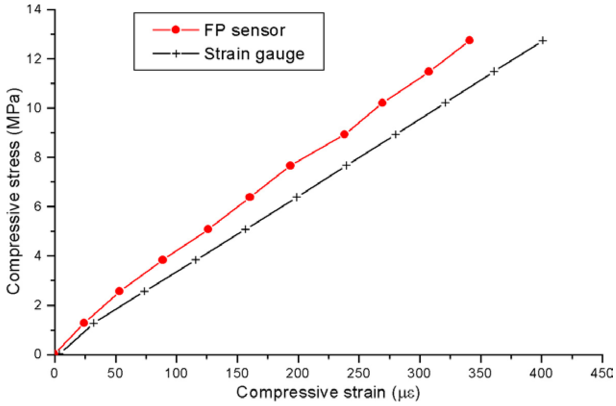


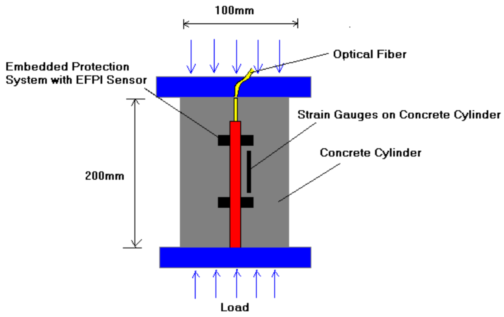
Figure 12. Experimental results of compression testing of a concrete cylinder using an ESPS with an EFPI sensor compared with a strain gauge.

gauge mounted on the surface of the steel tube. Thus, the cure strain can be transferred more effectively through the fibre sensor protection systems.

3.2. Compression test of a concrete cylinder with embedded and surface mounted EFPI and FBG sensors

The concrete cylinders with embedded and surface-mountable FOS have also been investigated in a compression test. A schematic illustration of the experimental set-up of the compression test of a concrete cylinder with an embedded FOS is shown in figure 11(a). Figure 11(b) shows the FOS during the pouring of the concrete. In fact, the FOS still works properly even after pouring and shaking of the concrete cement. This also proves the right design for the ESPS. Strain gauges of length 60 mm are bonded on the surface of the concrete cylinder after surface treatment using AE-10 adhesive from the Measurement Group. The ESPS was already calibrated before being embedded into the concrete cylinder. The compression test was carried out in an INSTRON 1195 structural testing system. A special groove was made on the top steel clamp to prevent breakage of the fibre cable. The experimental results of the compression test of a concrete cylinder with an embedded EFPI sensor compared with the results from ERS gauges are shown in figure 12. One can note that the results from EFPI sensors are in good agreement with those of the reference ERS sensors. The experimental results also show that the compressive strain measured with the embedded EFPI sensor is a little smaller than that from the ERS results. It is speculated that the strain transfer is not 100% from concrete materials to the protection system. This should be improved in the future. Furthermore, an FBG sensor has also been embedded in a concrete cylinder and its compression properties have been investigated. Figure 13 shows the compressive stress–strain curves obtained using FBG and ERS sensors. The results show good consistency and linearity.

In order to monitor an ageing concrete structure that is difficult to embed with FOS, composite prepreg-based SSPS of different shapes and sizes can be mounted on the surface of the structure. As an example, a concrete cylinder with surface-mounted CFRP-based SSPS illustrated in figure 14(a) is subjected to a compression test, where a load is applied to the specimen along the direction shown in figure 14(b). The CFRP plate ($(0^0)_8$) is made in an autoclave using CFRP prepregs. An EFPI sensor that has a 50 mm long capillary and 145 μm cavity gap is embedded within the fourth and fifth plies. The dimension of the CFRP plate is 145 mm × 20 mm × 1 mm. Then the CFRP protection plate is bonded to the concrete cylinder using a two-component epoxy resin (SIKA30) that is widely used to bond CFRP plates to concrete for strengthening purposes. The ERS gauges 1, 2 and 3 are axially bonded to the



(a)

(b)

Figure 11. Compression testing of a concrete cylinder with an ESPS. (a) Schematic illustration. (b) Photograph during the pouring stage.

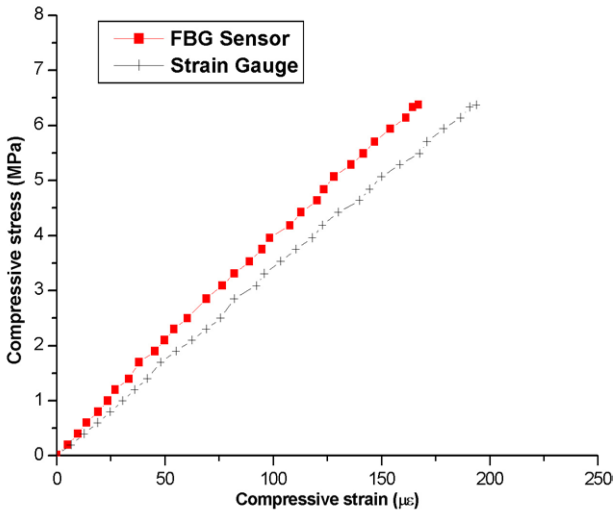


Figure 13. Experimental results of compression testing of a concrete cylinder using an ESPS with a FBG sensor compared with an ERS gauge.

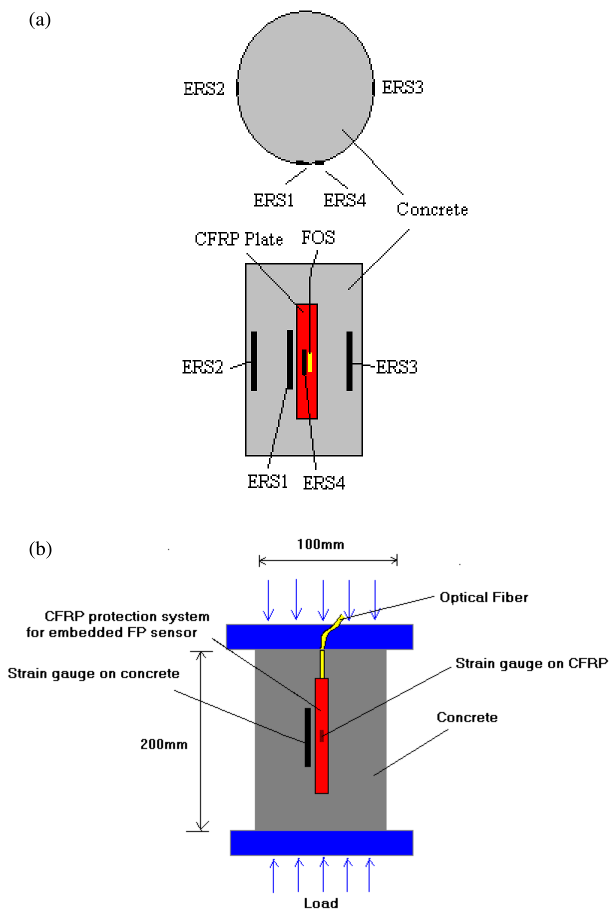


Figure 14. Schematic illustration of a concrete cylinder with SSPS: (a) position of the sensors; (b) compression test.

surface of the concrete as the reference source for the applied strain. ERS gauge 4 is surface-mounted on the CFRP plate.

A photograph of a concrete cylinder with CFRP-based SSPS is shown in figure 15. The stress–strain curves for

Figure 15. Photograph of a concrete cylinder with a CFRP-based SSPS.

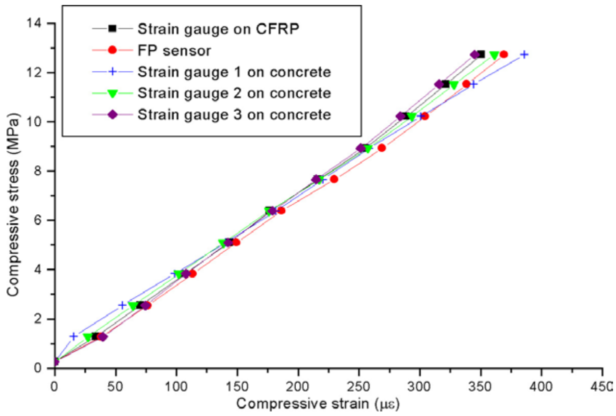


Figure 16. Stress–strain curves of a concrete cylinder with a surface-mounted CFRP protection system compared with ERS gauges.

the surface-mountable CFRP plate compared with that of the ERS on the concrete surface are presented in figure 16. It is apparently found that the compressive strains measured in the experiment give a consistent reading between the EFPI sensor and ERS gauges when the applied compressive stress is 9 MPa. The readings diverge slightly when the applied load continuously increases. However, there is still perfect accordance (within 5%) and a linear relationship. This very effectively indicates strain transfer between the CFRP prepregs, the protected CFRP plate and the concrete surface.

4. Conclusions

SPSs including ESPSs and SSPSs have been developed in this paper. ESPSs with EFPI and FBG have been embedded in concrete cylinders to monitor the cure development over 10 days. Furthermore, validation experiments for concrete cylinders with ESPS and SSPS have been carried out. Some important conclusions can be outlined:

(a) FOS can be protected effectively in concrete structures by both ESPS and SSPS.
(b) The cure strain of concrete materials can be monitored from an early cure stage by using EFPI and FBG sensors. Better sensitivity is found using ESPS for comparison with commercial special strain gauges.

(c) The results of compression tests of a concrete cylinder with ESPS and SSPS show that protected FOS exhibit very good linear sensor properties and excellent agreement with ERS gauges.

Therefore, the above mentioned SPS can be used in the future in smart civil structures such as smart bridges, smart highway and smart buildings for different types of the FOS such as fibre Bragg grating, fluorescence-based temperature sensors, etc.

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