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Structural NDE of concrete structures using protected EFPI and FBG sensors

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Abstract

This paper is concerned with the design concepts, modelling and implementation of various fibre optic sensor protection systems for development in concrete structures. The design concepts of fibre optic sensor protection system and on-site requirements for surface-mounted and embedded optical fibre sensor in concrete structures have been addressed. The aspects of finite element (FE) modelling of selected sensor protection systems in terms of strain transfer efficiency from the structure to the sensing region have also been focused in this paper. Finally, the experimental validations of specified sensor protection system in concrete structures have been performed successfully. Protected extrinsic Fabry–Perot interferometric (EFPI) and fibre Bragg grating (FBG) sensors have been used to monitor the structural health status of plain and composite wrapped concrete cylinders. Results obtained indicate that the protection system for the sensors performs adequately in concrete environment and there is very good correlation between results obtained by the protected fibre optic sensors and conventional electrical resistance strain gauges.

Keywords: Fibre optic sensor (FOS); Sensor protection system (SPS); Concrete structures; Extrinsic Fabry–Perot interferometric sensor (EFPI); Fibre Bragg grating (FBG); Non-destructive evaluation (NDE); Smart structures

1. Introduction

The structural non-destructive evaluation (NDE) in-service is very important and definitely demanded for safely working of engineering structure such as concrete structures. It is very difficult to carry out by using conventional methods. New reinforced concrete construction 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 the 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 structure is a new concept that will allow engineers to add a neural system to their designs, enabling 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 can be quite large. The most probable candidates will be smart civil structures such as smart skyscrapers, smart bridges, dams, decks, etc. Fibre optic sensors can offer many potential advantages for application in civil structural systems. In fact, a lot of fibre optic sensors have been developed for use in smart civil structures, for example, polarisation FOS, extrinsic Fabry–Perot interferometric (EFPI), fibre Bragg gratings (FBGs), multimode FOS, etc. [1–8]. However, the vulnerability of fibre optic sensor makes it is very difficult to protect the fibre from concrete aggregate in the pour duration. Therefore, the FOS could be very easy to be damaged and corroded during

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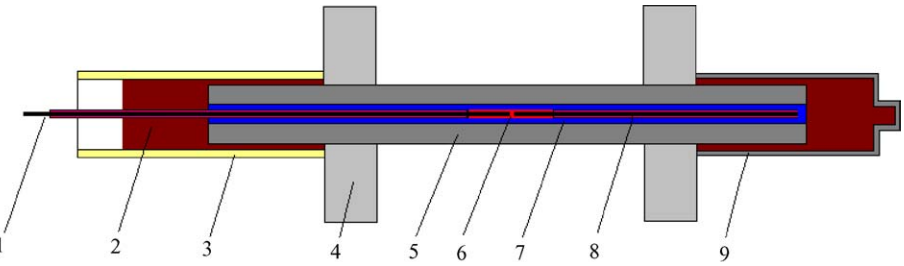


Fig. 1. Schematic illustration of the steel tube-based ESPS: (1) Optical fibre, (2) silicone rubber, (3) thick PTFE tube, (4) steel flange, (5) steel tube, (6) sensor element, (7) epoxy adhesive, (8) thin PTFE tube and (9) fixed steel tube.

the practical application of long term. This reason really limits the application of fibre optic sensor in concrete structures.

There are few types of protected fibre optic sensors are used in concrete structures by previously researchers [9–12]. Normally, the FOSs are covered by steel sheet, steel tube and silicone rubber. Previously researchers also performed mechanical measurement of concrete structures with embedded protected FOS [10–17].

In this paper, two kinds of protection system of fibre optic sensors that are surface-mounted and embedded protection system have been developed. Furthermore, experiments of structural health monitoring based on plain and composite wrapped concrete cylinders also have been performed by using protected FOS. The results indicate that the FOSs had been protected very well. Furthermore, the results gave very good accordance comparing with the results of related reference electrical resistance strain (ERS) gauges.

2. Concept of sensor protection system (SPS) of fibre optic sensor

The primary requirements for the sensor protection system are protection of the silica fibres from the alkaline environment and protection of the sensor system: (a) during the concrete pouring operation and (b) against mechanical or abrasion damage caused by the aggregates and against any aggressive chemical environments. The sensor system also must ensure good transduction for the measurement of interest; in this paper, embedded sensor protection system (ESPS) and surface-mountable sensor protection system (SSPS) have been developed.

2.1. Embedded sensor protection systems

For the embedded sensor protection system, the strain transfer is a most important issue aside from the protection of sensors. To get best strain transfer between the sensor and protection system, three types of ESPS are designed in this paper, respectively, which is ESPS based on metal, ESPS based on CFRP composite and ESPS based on concrete materials. In fact, these ESPSs have different application fields.

2.1.1. Metal-based ESPS

Fig. 1 shows the schematic illustration of the steel tube-based embedded sensor protection system. Photograph of steel tube-based ESPS is shown in Fig. 2.

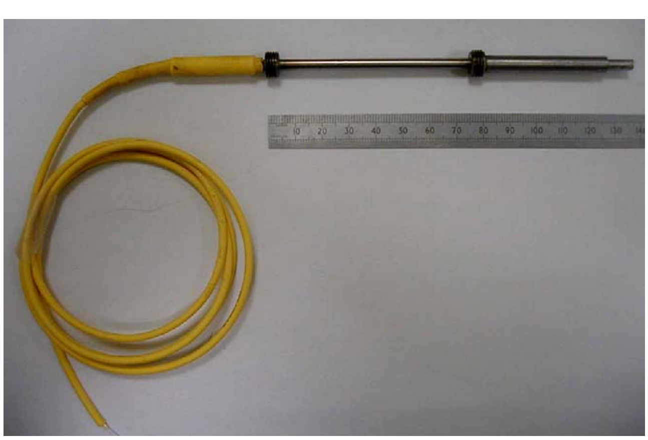


Fig. 2. Photograph of the steel tube-based ESPS.

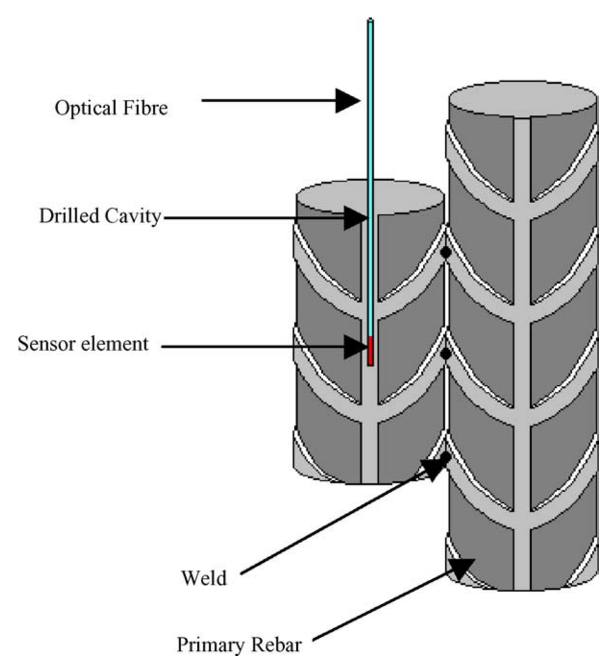
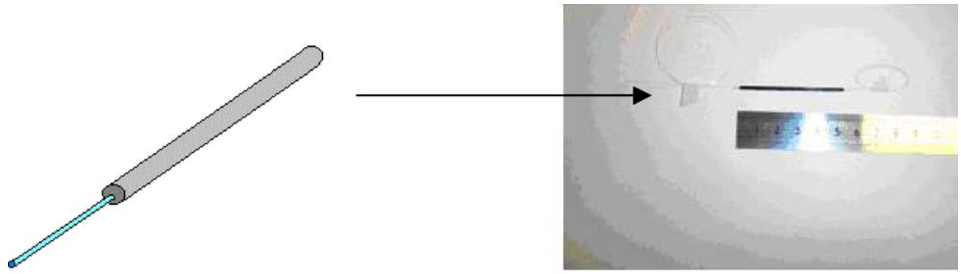
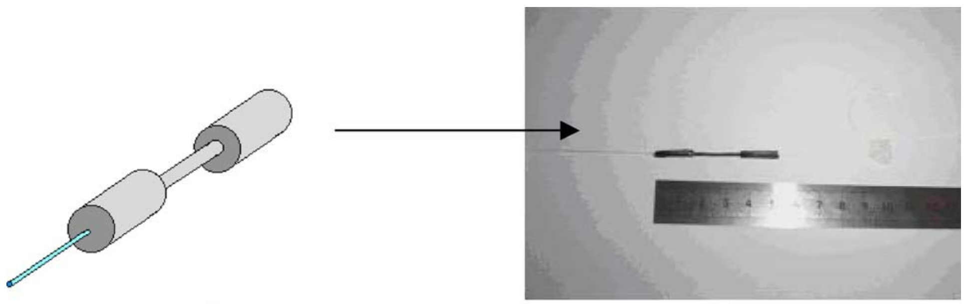


Fig. 3. Schematic illustration of the rebar-based ESPS.



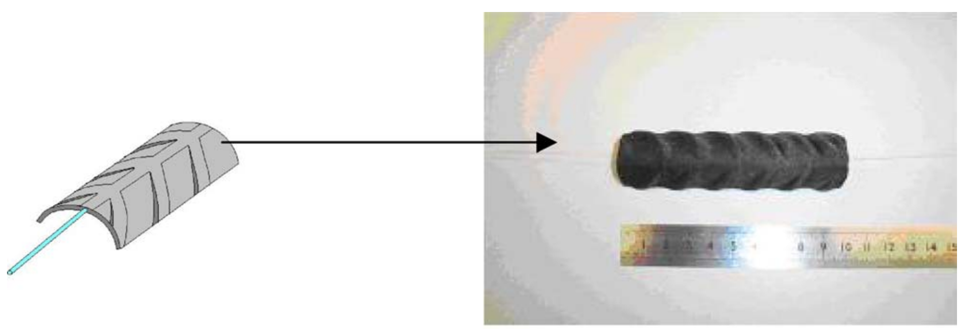
(a) (b)

Fig. 4. Unidirectional rolled-up CFRP-based ESPS: (a) schematic illustration and (b) photograph.



(a) (b)

Fig. 5. Dumb-bell CFRP-based ESPS: (a) schematic illustration and (b) photograph.



(a) (b)

Fig. 6. Rebar-shape CFRP-based ESPS: (a) schematic illustration and (b) photograph.

For the metal-based ESPS, we also develop the rebar-based ESPS that is used to mount the fibre optic sensor on the rebar in concrete structures. The schematic illustration is given in Fig. 3. The fibre optic sensor can be potted into the drilled cavity in the rebar using suitable adhesive. Then the short rebar with embedded sensor can be welded with the primary rebar.

2.1.2. CFRP-based ESPS

Whilst the metal-based ESPS is robust, it is time-consuming to manufacture. By the way, there also have some corrosion problems if stainless steel material has not been used in the ESPS. Hence, the option of using carbon fibre reinforced composites (CFRP) was considered predominantly due to its ease of manufacture and corrosion resistance via the composite prepreg. A schematic illustration of the various sensor designs that were considered is presented in this paper. Fig. 4 shows the unidirectional rolled-up CFRP-based ESPS. In order to increase the strain transfer, the dumb-bell CFRP-based ESPS has been developed and shown in Fig. 5.The prepreg manufacturing route also enables it to be moulded and cured over complex shapes such as rebar. The rebar-shape CFRP-based ESPS is presented in Fig. 6.

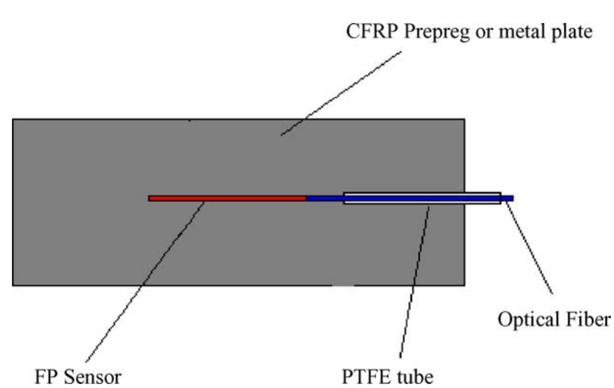


Fig. 7. Schematic diagram of CFRP-based SSPS for FOS.

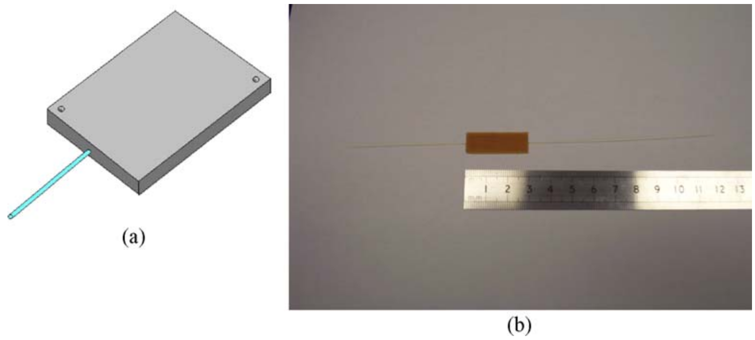


Fig. 8. Flat CFRP composite SSPS: (a) schematic illustration and (b) photograph.

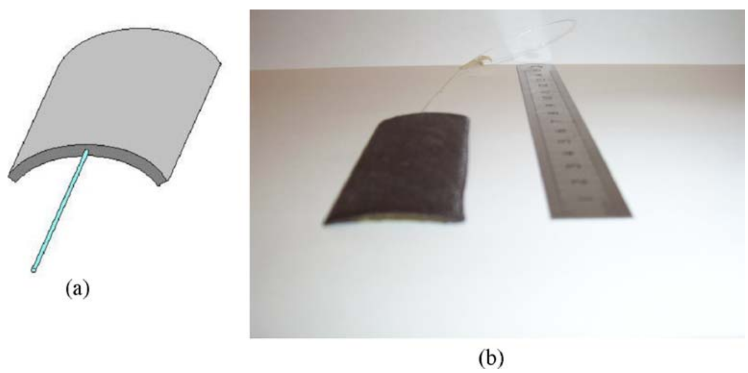


Fig. 9. Curved CFRP composite SSPS: (a) schematic illustration and (b) photograph.

2.2. *Surface-mountable SPS*

In order to apply the fibre optic sensor on the ageing engineering structures, the surface-mountable sensor protection system has been developed. The surface-mounted SPS can be made by using the existing techniques and procedures that have been developed for surface mounting electrical resistance strain gauges. Fig. 7 presents the schematic diagram of composite surface-mountable SPS (CFRP-based SSPS) for FOS. Figs. 8 and 9 show the flat and curved CFRP composite SSPS. These devices can be mechanically fastened or bonded to the concrete structure. The steel tube-based SPS discussed previously can be adapted for retrofitting onto existing ageing structures. Photograph of concrete cylinder with retrofitting SPS is shown in Fig. 10.

3. Design of embedded sensor protection system by FE modelling

For the embedded sensor protection system, a series of SPSs with different shape and size of flanges have been presented. Fig. 11 shows the photographs of different type of steel flanges for the ESPS. In order to evaluation the efficiency of steel flanges for strain transfer between the sensor and concrete materials, the non-liner finite element (FE) analysis of concrete cylinder with embedded SPS has been performed in this paper [18]. A compressive load of 12.73 MPa was applied on the concrete cylinder with ESPS.

The strain results along the SPS–concrete interface of a disc-shape flange having various bond types are shown in Fig. 12. It can be seen that the strain results are in good agreement with the experimental and theoretical values irrespective of the type of bonding between the flanges. The results present that the strain can be transmit across the SPS system. Comparison with the experimental results, it shows that the maximum difference in strain magnitude is less than 3.5%. For the disc-shape flange

Fig. 10. Photographs of concrete cylinder with retrofitting steel tube SPS.

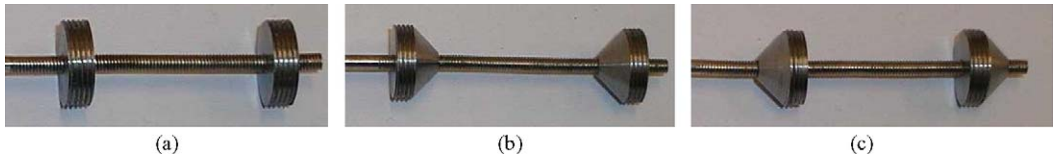


Fig. 11. Photographs of different type of steel flanges for ESPS: (a) disc, (b) cone and (c) inverted cone.

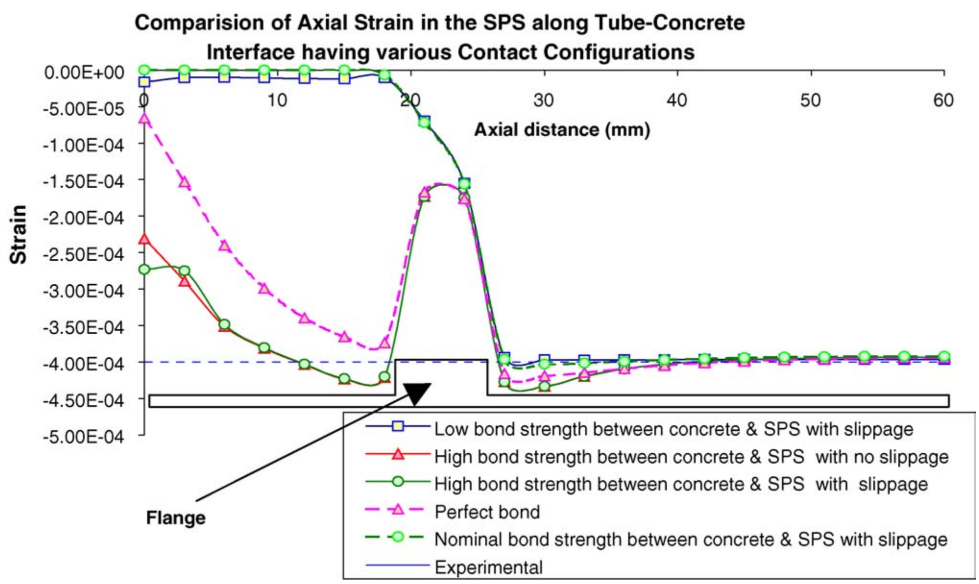


Fig. 12. Axial strain in an embedded steel tube with flange for different contact configuration.

with different diameters, the shear stress and strain along the concrete–SPS interface are shown in Figs. 13 and 14, respectively. It can be found that the flange root (base) is under high shear and slippage is clearly occurring in the area before the flange. However, shear stress between the flanges is well within the limits. It is clear that the shear stress for the disc type flange having a 5 mm diameter gives best results, the overall slippage is least and a good anchorage is maintained. The strain and stress profile present that there is not much difference with different diameter sand the strain transfer across the interface is good approximately 35 mm away from the flanges.

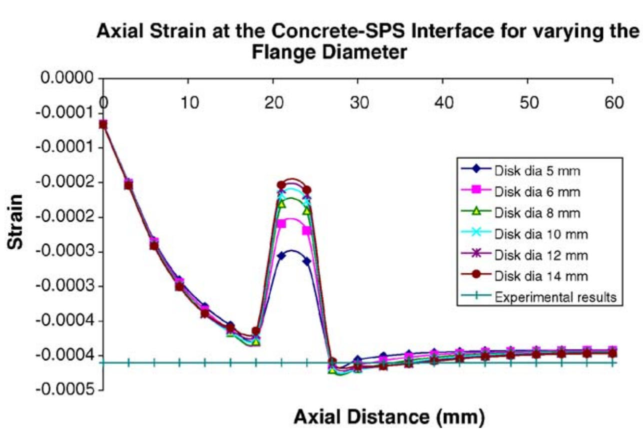


Fig. 13. Axial strain at the concrete–tube interface along the tube length of steel tube with disc flanges.

4. Experimental validation of protected FOS in concrete cylinders

4.1. Plain concrete cylinders with fibre optic sensors

The schematic illustration of experimental set-up of compression test of concrete cylinder with steel tube-based ESPS with EFPI sensor is shown in Fig. 15a. The size of concrete cylinder is 200 mm (length) × 100 mm (diameter). The concrete has a water/cement ratio of 0.52, an aggregate/cement ratio of 6. Fig. 15b shows the FOS during concrete pour. In fact, the FOS is still working properly after pour and shake duration of concrete. The strain gauges which have 60 mm length are bonded on the surface of concrete cylinder by using adhesive AE-10 from Measurement Group after surface treatment. The embedded protection system already has been calibrated before embedding it in the concrete cylinder.

The compression test has been carried out in the INSTRON 1195. The experimental results of compression test of concrete cylinder with embedded protection systems compared with results of electrical resistance strain gauges are shown in Fig. 16. Compared the results of FEM with ERS gauges it can be find that they have very good agreement. The experimental results also show that the strain from embedded EFPI sensor is a little bit smaller than FEM and ERS results because there are not 100% strain transfer from concrete materials to protection system.

Fig. 17 is the experimental illustration of compression test of concrete cylinder with CFRP-based SSPS. The CFRP plates

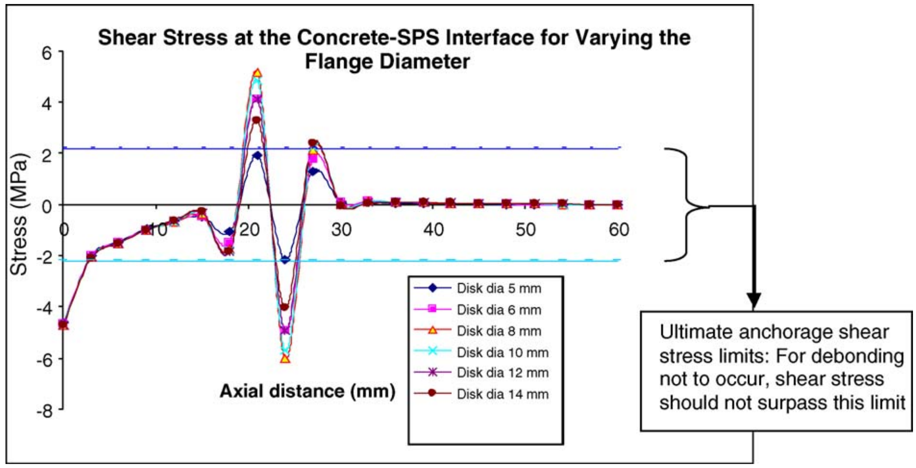


Fig. 14. Shear stress at the concrete–tube interface along the tube length of steel tube with disc flanges.

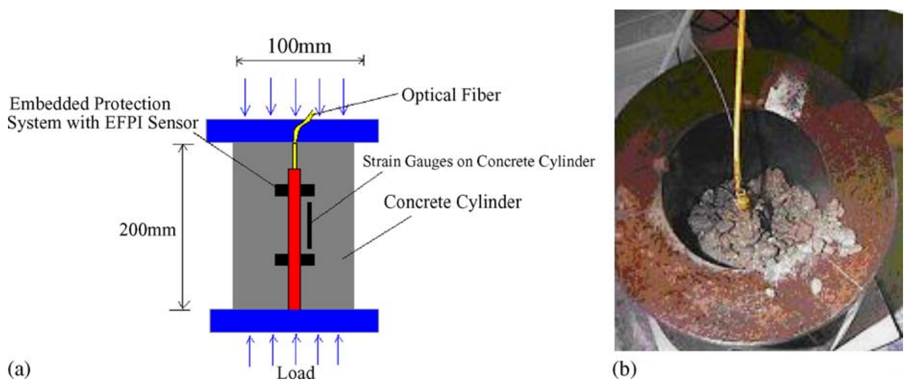


Fig. 15. Compression test of concrete cylinder with ESPS: (a) schematic illustration and (b) photograph during the pour.

$((0^0)_8)$ were made in the autoclave by using CFRP prepregs. The EFPI sensors that have 50 mm long capillary and 145 μm cavity gap were embedded within the fourth ply and fifth ply. The size of CFRP plate is 145 mm × 20 mm × 1 mm. Then the CFRP protection plates were bond to the concrete cylinder by two-component epoxy resin (SIKA 30) which widely used to bond CFRP plates to concrete for strengthening purposes. The ERS gauges were axially bonded on the surface of CFRP plate as well as concrete surface as the reference source for applied strains.

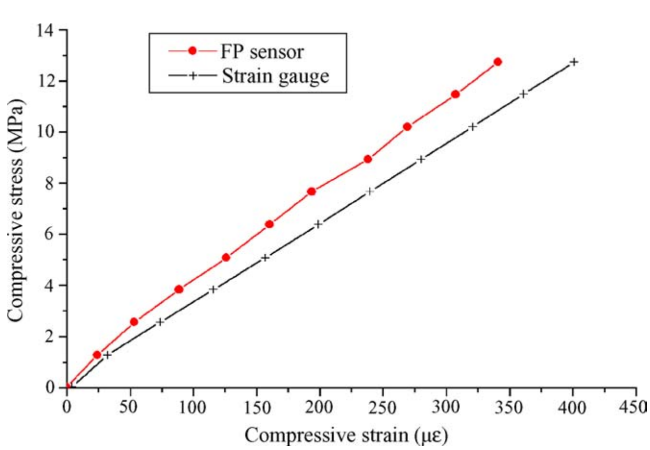
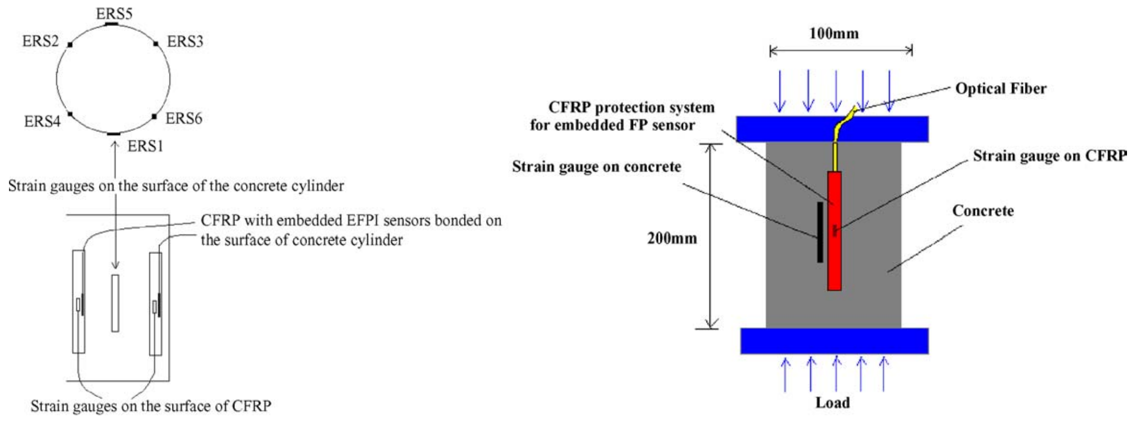


Fig. 16. Experimental results of compression test of concrete cylinder embedded steel protection systems with EFPI sensor compared with ERS gauge.

Photograph of concrete cylinder with CFRP-based SSPS is shown in Fig. 18. The stress–strain curves for one of surface-mountable CFRP plate compared with that of ERS on the concrete surface are presented in Fig. 19. It is apparent that there was very good accordance (within 5%) and linear relationship between protected EFPI sensor, ERS on the CFRP surface and ERS on the concrete surface. Similar results were obtained for the other bonded plates. That also indicates that there is very effectively strain transfer among CFRP prepregs, protected CFRP plate and concrete surface.

4.2. *CFRP wrapped concrete cylinder with fibre optic sensors*

The schematic illustration of CFRP wrapped concrete cylinder with FOSs and strain gauges was shown in Fig. 20. A FBG sensor was surface mounted on the surface of concrete cylinder in longitudinal direction. An EFPI sensor was embedded in the CFRP composite prepregs in same direction to evaluate the strain transfer before laid up it directly on the concrete surface. For the strain measurement in hoop direction, a FBG sensor was also embedded in the CFRP composite prepregs. A biaxial electrical resistance strain gauge was externally bonded on



(a) (b)

Fig. 17. Schematic illustration of concrete cylinder with SSPS: (a) position of sensors and (b) compression test.

Fig. 18. Photograph of concrete cylinder with CFRP-based SSPS.

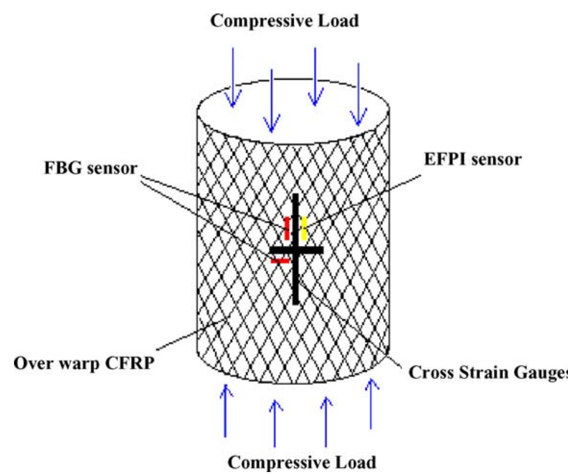


Fig. 20. Schematic illustration of CFRP wrapped concrete cylinder with FOSs and strain gauges.

the outside composite surface of wrapped concrete cylinder at the same location that sensors were embedded as the reference measurement.

The experimental results of CFRP wrapped concrete cylinder with embedded EFPI and FBG sensors were shown in Fig. 21. Obviously, it can be seen that the measured strain using EFPI and FBG sensors in both longitudinal and hoop directions have excellent agreement compared with results obtained from electrical resistance strain gauges. It is noted that the measured strain in longitudinal direction is compressive strain, whereas the strain is tensile strain in hoop direction. It is emerged that the ultimate failure strain in longitudinal direction is about 4600 $\mu\varepsilon$, which is much higher than that in hoop direction when the compres-

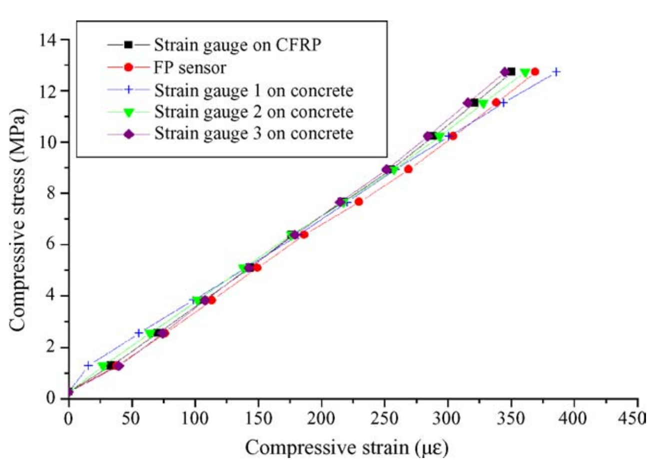


Fig. 19. Stress–strain curves of concrete cylinder with surface-mounted CFRP protection systems compared with ERS gauges.

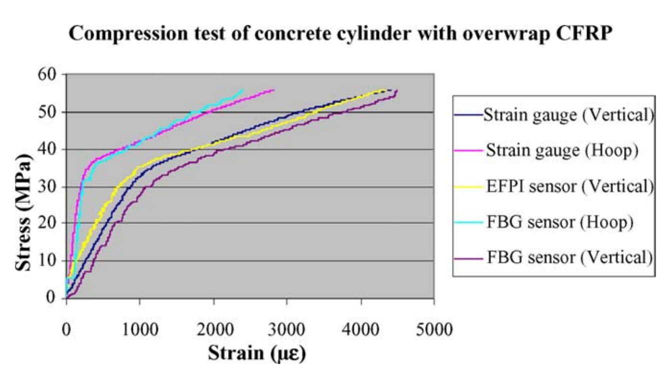


Fig. 21. Ultimate compression curves of concrete cylinder with wrapped CFRP prepregs using FBG and EFPI sensors.

sive stress applied to 56 MPa. For the hoop tensile strain, the strain measured by FBG sensor and ERS gauge provide a linear stress strain relationship below 43 MPa. After that point, the measured strain in hoop direction was slightly diverged. It is noted that the strain rate inside of CFRP prepregs in the longitudinal direction is between that on the surface of concrete cylinder and surface of CFRP materials after 42 MPa. It is speculated the different strain transfer effectivity from insider concrete to outer composite materials. Apparently, it is also found that the longitudinal strain obtained by FBG sensor is always higher than that measured by EFPI sensor inside of CFRP materials and strain gauge on the surface of composite materials. Therefore, the strain condition and failure of the concrete materials can be monitored and detected by using FBG earlier than the conventional ERS gauge, which is mounted on the surface of the outer reinforcement materials. Both embedded EFPI and FBG sensors were working properly during the failure test until the concrete cylinder collapsed.

5. Conclusions

A series of designs have been proposed for the sensor protection system including embedded sensor protection systems and surface-mountable sensor protection systems in this paper. The ESPSs based on steel tubes have been designed by FE modelling. Furthermore, the evaluation validation experiments of concrete cylinders with protected fibre optic sensors have been achieved. Some important conclusions can be obtained:

a. The fibre optic sensors can be protected very well by both of ESPS and SSPS in concrete structures. Each SPS has different application. For example, embedded sensor protection system is for new concrete structures, surface mountable sensor protection system is for aging concrete structures, rebar-shape CFRP-based ESPS is for special measurement of embedded rebar in the concrete structures, etc.
b. Based on axial strain and shear stress results, it is recommended that the 5 mm disc type flange will provide optimum anchorage and good strain transfer at the interface.
c. The results of compression tests of concrete cylinder with FOSs present that protected FOSs exhibit very good linear sensor properties and excellent agreement compared with electrical resistance strain gauges.

Therefore, the protected FOSs would be used in the smart civil structures such as smart bridge, smart highway, smart building in future.

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Biography

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