Fibre Optic Protection System for Concrete Structures

J.S.Leng[1)†], *A.Hameed*[2)], *D.Winter*[2)], *R.A.Barnes*[2)], *G.C.Mays*[2)] *and G.F.Fernando*[2)]
1) Centre for Composite Materials, Harbin Institute of Technology, Harbin 150001, China
2) Engineering System Department, Defence Academy of the United Kingdom, Cranfield University, Shrivenham, Wiltshire, SN6 8LA, UK
[Manuscript received July 29, 2005]

The design concepts, modelling and implementation of various fibre optic sensor protection systems for development in concrete structures were investigated. Design concepts and on-site requirements for surface-mounted and embedded optical fibre sensor in concrete were addressed. Finite element (FE) modelling of selected sensor protection systems in strain-transfer efficiency from the structure to the sensing region was also studied. And experimental validation of specified sensor protection system was reported. 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.

KEY WORDS: Fibre optic sensor (FOS); Sensor protection system (SPS); Concrete structures; Extrinsic Fabry-Perot interferometer (EFPI) sensor; Smart Structures; Strain transfer

1. Introduction

The structural health monitoring (SHM) in-service is very important and definitely demanded for safely working of engineering structure such as concrete structures. It is very difficult to be carried 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 structures are an enabling technology that will allow engineer to add a nervous 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 building and skyscrapers, smart bridge, dams, bridge decks *etc.* FOS can offer many potential advantages for application to civil structural systems. In fact, a lot of FOS have been developed for use in smart civil structure such as polarisation FOS, extrinsic Fabry-Perot interferometer (EFPI), and fibre Bragg gratings (FBGs), multimode FOS, *etc.*[1~8]. However, the vulnerability of FOS is difficult to protect the fibre from concrete aggregate in the pour duration. That is the FOS could be very easy to damaged and corroded during the practical application of long term. This reason really limits the application of FOS in concrete structures.

There are a few types of protected FOS used in concrete structures by previously researchers[9~11]. In these designs, the FOS were covered by steel sheet, steel tube and silicone rubber. Previous researchers also performed mechanical measurement of concrete structures with embedded protected FOS[9~14].

In this paper, a new kind of protection systems of FOS that is surface-mounted and embedded protection system was developed. Furthermore, the experimental validation of concrete cylinders with embedded and surface-mountable protection system with EFPI sensors were performed. The results indicate that the EFPI sensors had been protected very well and given very good accordance compared with the results of related reference electrical resistance strain (ERS) gauges on the concrete.

2. Concept of Sensor Protection System (SPS) of FOS

The primary requirements for the sensor protection system are protection of the silica fibres from the alkaline environment and protection of the sensor system (1) during the concrete pouring operation, (2) 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 measurand of interest. In this paper, a number of embedded sensor protection system (ESPS) and surface-mountable sensor protection system (SSPS) have been developed.

2.1 ESPS

For the ESPS, the strain transfer is very important except the protection of sensors. To get the best strain transfer between the sensor and protection system, three types of ESPS are designed in this paper which are ESPS based on metal, ESPS based on carbon fibre reinforced composite (CFRP) and ESPS based on concrete materials, respectively. In fact, these ESPSs have different application fields.

2.1.1 Metal-based ESPS   Figure 1 shows the sche-

† Prof., Ph.D., to whom correspondence should be addressed, E-mail: lengjs@hit.edu.cn.

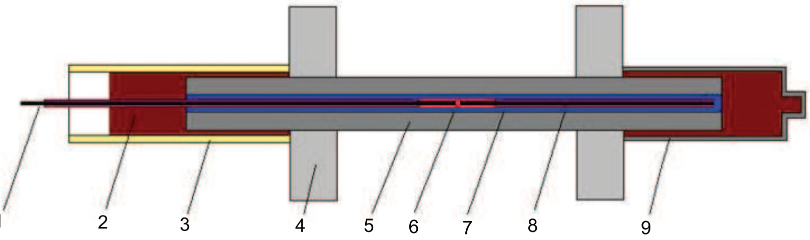

Fig.1 Schematic illustration of the steel tube-based ESPS: 1-Optical fibre, 2-Silicone rubber, 3-Thick PTFE tube, 4-Steel flange, 5-Steel tube, 6-FP (Fabry-Perot) sensor, 7-Epoxy adhesive, 8-Thin PTFE tube, 9-Fixed steel tube

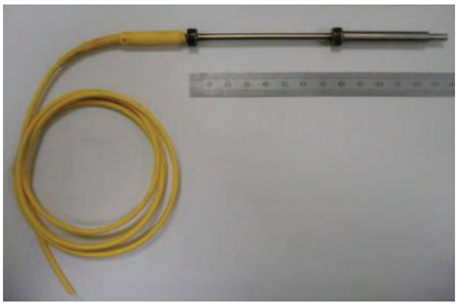

Fig.2 Photograph of the steel tube-based ESPS

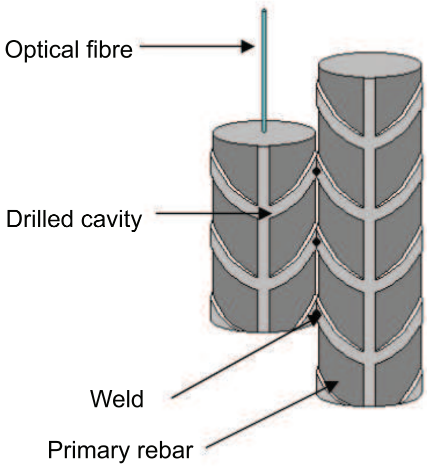

Fig.3 Schematic illustration of the rebar-based ESPS

matic illustration of the steel tube-based ESPS. Photograph of steel tube-based ESPS is shown in Fig.2.

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 problem if the stainless steel materials were not used in the ESPS. Hence, the option of using CFRP was considered predominantly for 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. Figure 4 shows the unidirectional rolled-up CFRP-based ESPS. To increasing the strain transfer, the dumb-bell CFRP-based ESPS have 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.

2.1.3 Concrete or resin-based ESPS In this study, the feasibility of using concrete as the matrix to prefabricate the SPS was investigated. In this instance, a thin layer of a cement-compatible thermosetting resin was applied to the fibre optic sensor. The coated sensor was then encapsulated with concrete within the confines of a cylindrical mould. The rationale was to minimize the mismatch in the mechanical and thermal properties of the ESPS in comparison with the concrete structure. ESPS of this design can mimic more closely the chemical environment of the concrete structure. The concrete SPS offers some interesting options here as it can be pre-fabricated and then secured onto the structure using cement-based grout or a compatible resin as the bonding medium. A schematic illustration of this design is illustrated in Fig.7.

2.2 SSPS

To apply the fibre optic sensor on the ageing engineering structures, SSPS has been developed. The methods of surface mounted SPS can use the existing techniques and procedures that have been developed for surface mounting electrical resistance strain gauges. Figure 8 presents the schematic diagram of composite surface-mountable SSPS (CFRP-based SSPS) for FOS. Figures 9 and 10 show the flat GRP 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.11.

3. Design of Embedded SPS Finite Element (FE) Modeling

For the ESPS, a kind of SPS with different shape and size of flanges has been presented. Figure 12 shows the photographs of different type of steel flanges for the ESPS. To evaluate the effectivity of steel flanges for strain transfer between the sensor and concrete materials, the nonlinear FE analysis of concrete cylinder with embedded SPS were performed in this paper[15]. A compressive load of 12.73 MPa was appl-

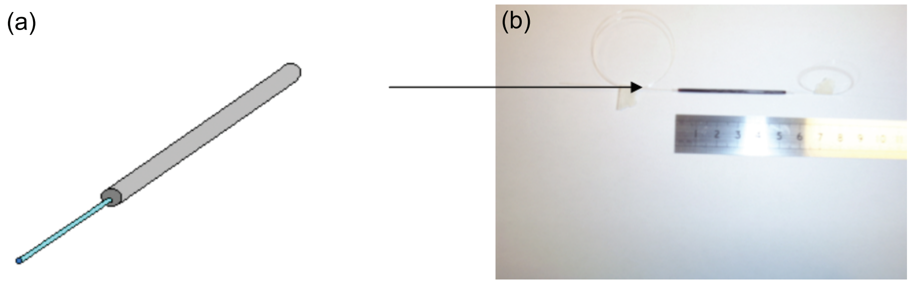

Fig.4 Unidirectional rolled-up CFRP-based ESPS: (a) schematic illustration, (b) photograph

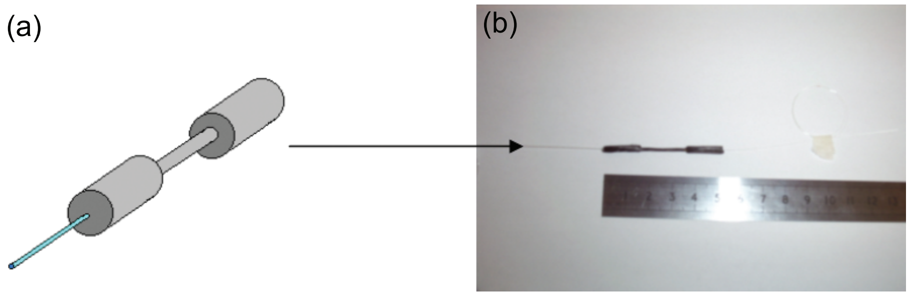

Fig.5 Dumb-bell CFRP-based ESPS: (a) schematic illustration, (b) photograph

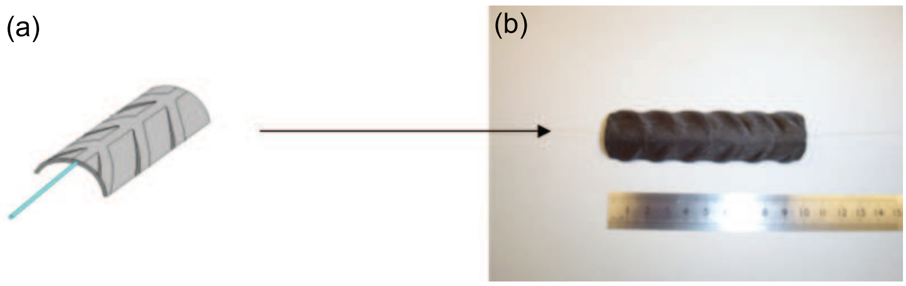

Fig.6 Rebar-shape CFRP-based ESPS: (a) schematic illustration, (b) photograph

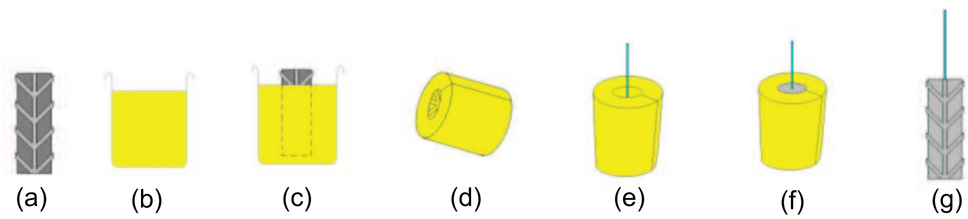

Fig.7 Schematic illustration of the concrete or resin-based ESPS: (a) rebar, (b) silicone rubber, (c) silicone rubber in rebar, (d) female silicone rubber mould, (e) fibre optic sensor in silicone rubber mould, (f) potting the cement or resin, (g) removing the mould

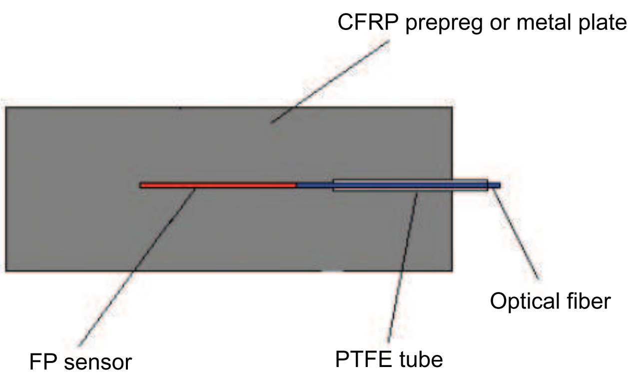

Fig.8 Schematic diagram of CFRP-based SSPS for FOS

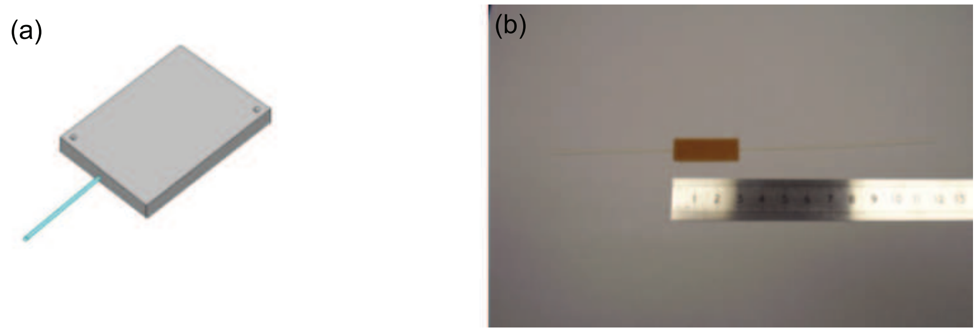

Fig.9 Flat GRP composite SSPS: (a) schematic illustration, (b) photograph

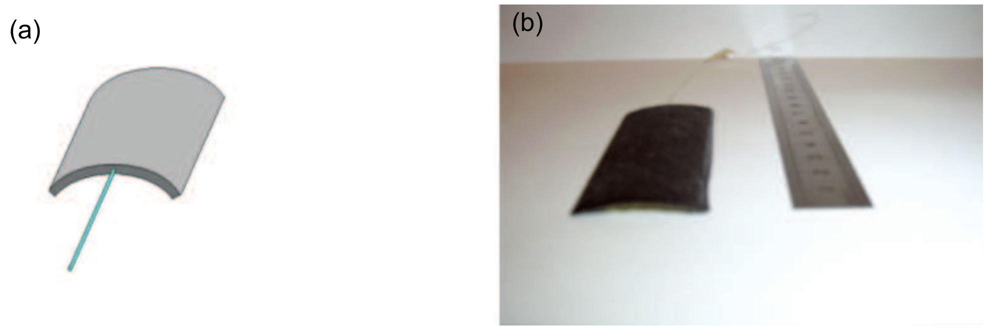

Fig.10 Curved CFRP composite SSPS: (a) schematic illustration, (b) photograph

Fig.11 Photographs of concrete cylinder with retrofitting steel tube SPS

ied 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.13. 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 indicate that the strain can be transmitted across the SPS system. Comparison with the experimental results, it is shown that the maximum difference in strain magnitude is less than 3.5%. For the disc shape flange with different diameters, the shear stress and strain along the concrete-SPS interface are shown in Figs.14 and 15, respectively. It can be seen that the flange base is under high shear and slippage clearly occurs in the area before the flange. However the shear stress between the flanges is well within the limits. The shear stress for the disc type flange with 5 mm in diameter gives best results. The overall slippage is least and a good anchorage is maintained. The strain and stress profile presents that there is not much difference with different diameter and strain transfer across the interface is good approximately 35 mm away from the flanges.

4. Experimental Validation of SPS in Concrete Cylinders

The schematic illustration of experimental setup of compression test of concrete cylinder with steel tube-based ESPS with EFPI sensor is shown in Fig.16(a). The size of concrete cylinder is 200 mm (length)×100 mm (diameter). The concrete had a water/cement ratio of 0.52, an aggregate/cement ratio of 6. Figure 16(b) shows the FOS during concrete pour. In fact, the FOS is still working properly after pour and shake duration of concrete. The strain

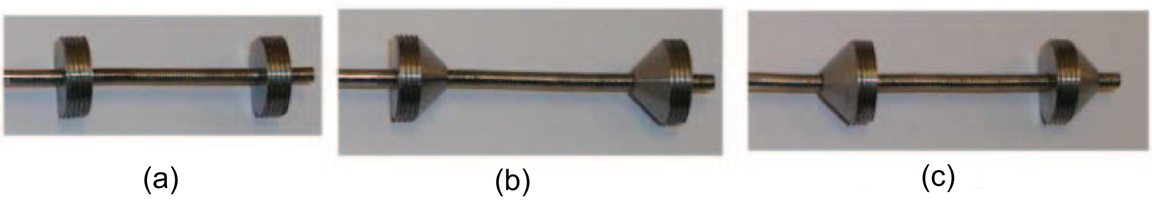

Fig.12 Photographs of different type of steel flanges for ESPS: (a) disc, (b) cone, (c) inverted cone

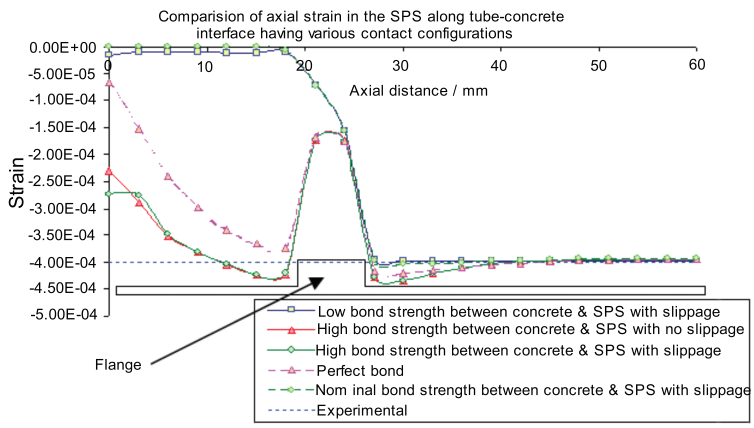

Fig.13 Axial strain in an embedded steel tube with flange for different contact configuration

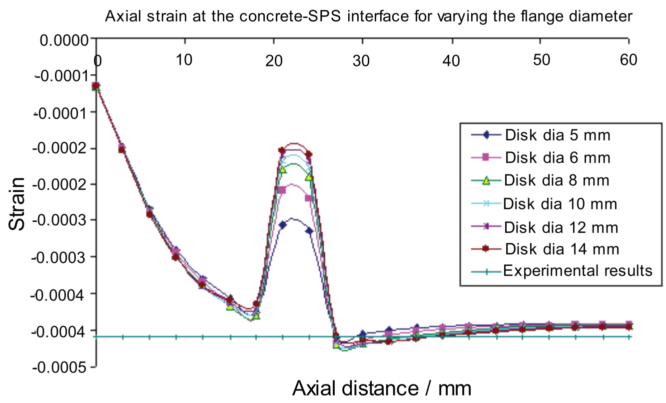

Fig.14 Axial strain at the concrete-tube interface along the tube length of steel tube with disc flanges

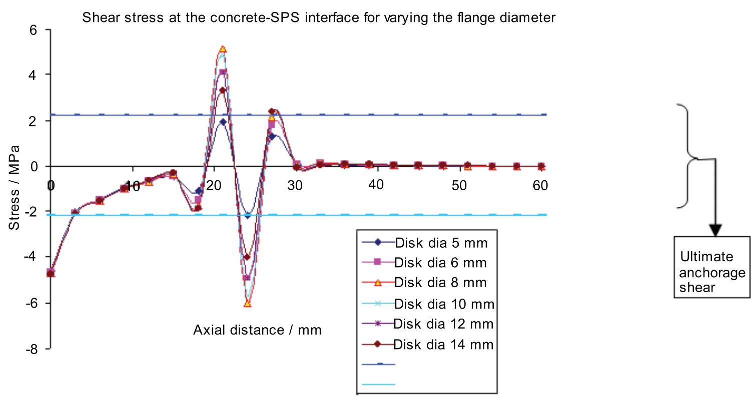

Fig.15 Shear stress at the concrete-tube interface along the tube length of steel tube with disc flanges

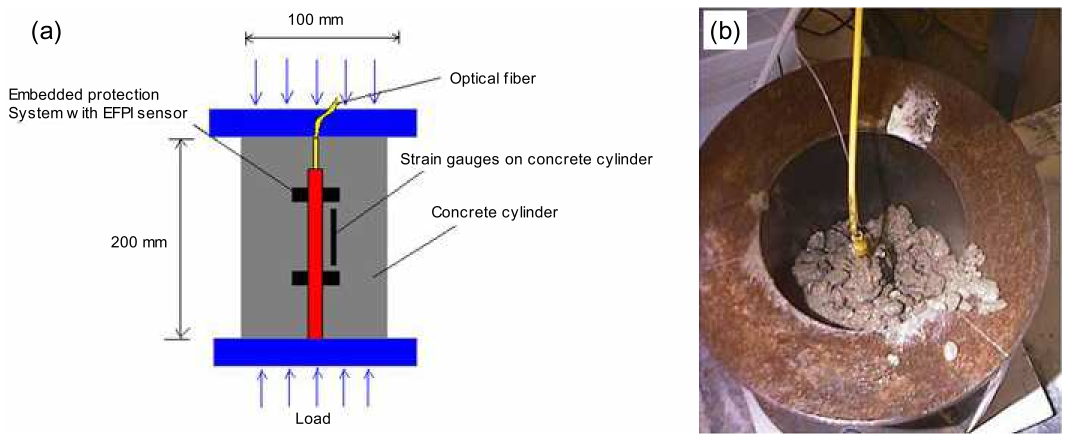

Fig.16 Compression test of concrete cylinder with ESPS: (a) schematic illustration, (b) photograph during the pour

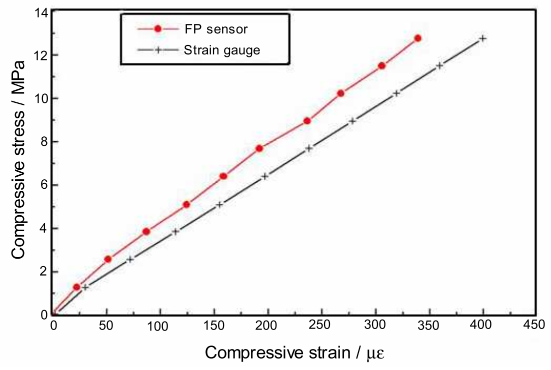

Fig.17 Experimental results of compression test of concrete cylinder embedded steel protection systems with EFPI sensor compared with ERS gauge

gauges with 60 mm in 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 it is embedded in the concrete cylinder.

The compression test was 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 (ERS) gauges are shown in Fig.17. The experimental results also show that the strains from embedded EFPI sensor are slightly smaller than ERS results because there are not 100% strain transfer from concrete materials to protection system.

Figure 18 is the experimental illustration of compression test of concrete cylinder with CFRP-based SSPS. The CFRP plates $(0^0)_8$ 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 4 ply and 5 ply. The size of CFRP plate is 145 mm×20 mm×1 mm. Then the CFRP protection plates were bonded to the concrete cylinder by two component epoxy resin (SIKA 30) which was 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.

Photograph of concrete cylinder with CFRP-based SSPS is shown in Fig.19. The stress-strain curves for one of surface-mountable CFRP plate compared with that of ERS on the concrete surface are presented in Fig.20. 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 performed for the other bonded plates. That also indicates very effectively strain transfer between CFRP prepregs, protected CFRP plate and concrete surface.

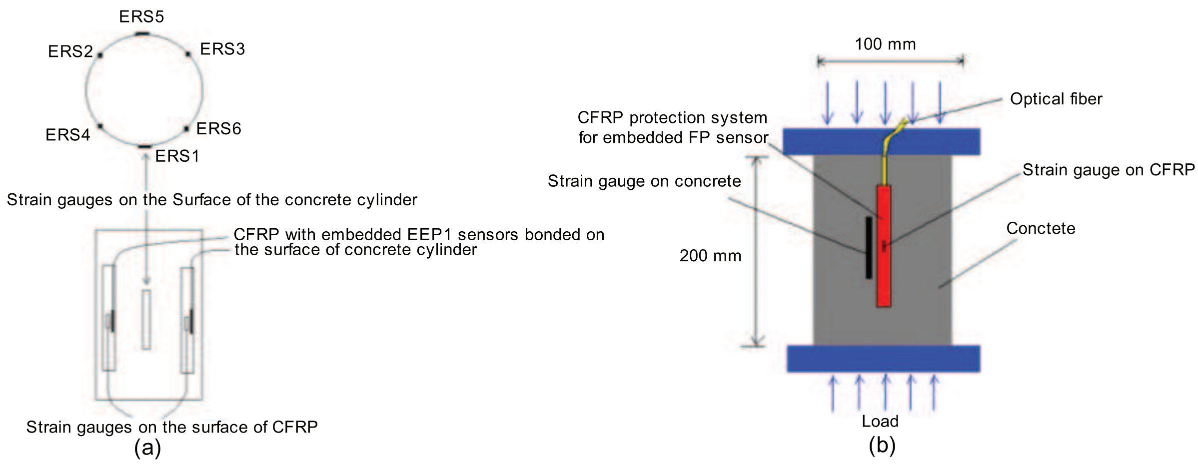

Fig.18 Schematic illustration of concrete cylinder with SSPS: (a) position of sensors, (b) compression test

Fig.19 Photograph of concrete cylinder with CFRP-based SSPS

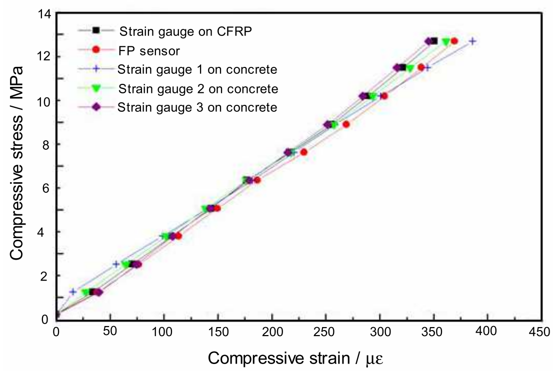

Fig.20 Stress-strain curves of concrete cylinder with surface-mounted CFRP protection systems compared with ERS gauges

5. Conclusions

A series of designs were proposed for the sensor protection system (SPS) including embedded sensor protection system (ESPS) and surface-mountable sensor protection system (SSPS). The ESPS based on steel tubes has been designed by FE modelling. Furthermore, the evaluation validation experiments of concrete cylinders with ESPS and SSPS have been achieved. Some important conclusions can be obtained:

(1) The fibre optic sensors (FOS) can be protected very well by both of ESPS and SSPS in concrete structures.

(2) Based on FE modelling results, it is recommended that the 5 mm disc type flange will provide optimum anchorage and good strain transfer at the interface.

(3) The results of compression tests of concrete cylinder with ESPS and SSPS present that protected EFPI sensors exhibit very good linear sensor properties and excellent agreement with electrical resistance strain (ERS) gauges.

Therefore, the above mentioned SPS would be used in the smart civil structures such as smart bridge, smart highway, smart building in future for different type of the FOS such as fibre Bragg grating, fluorescence-based temperature sensors, *etc*.

REFERENCES

[1] C.I.Merzbacher, A.D.Kersey and E.J.Friebele: *Smart Mater. Struct.*, 1996, **5**, 196.

[2] M.V.Gandhi and B.S.Thompson: *Smart Materials and Structures*, Chapman Hall, London, 1992.

[3] K.T.V.Grattan and B.T.Meggitt: *Optical Fiber Sensor Technology: Devices and Technology*, Chapman & Hall, London, 1998.

[4] B.Culshaw and J.Dakin: *Optical Fiber Sensors: Applications, Analysis, and Future*, Artech House Inc., Boston, 1997.

[5] E.Udd: *Fiber Optic Smart Structures Technology, Fiber Optic Smart Structures*, John Wiley Sons, New York, 1995.

[6] R.M.Measures: *Fibre Optic Strain Sensing, Fibre Optic Smart Structures*, ed. E.Udd, John Wiley & Sons, New York, 1995.

[7] Shanyi DU and Jinsong LENG: *Smart Material Systems and Structures*, Science Press, Beijing, 2001. (in Chinese)

[8] J.S.Leng and A.Asundi: SPIE-The Int. Symp. on *Photonics and Applications (ISPA'99)*, SPIE 3897, Singapore 29 Nov.-3 Dec, 1999, 505.

[9] W.R.Habel, D.Hofmann and B.Hillemeier: *Cement Concrete Comp.*, 1997, **19,** 81-102.

[10] W.Lee, J.Lee, C.Henderson, H.F.Taylor, R.James, C.E.Lee, V.Swenson, R.A.Atkins and W.G.Gemeiner: *Appl. Optics*, 1999, **38**(7), 1110.

[11] Marco Quirion and Gerard Ballivy: *J. Mater. Civil Eng.*, 2000, **12**(3), 254.

[12] M.De Vries, M.Nasta, V.Bhatia, T.Tran, J.Greenet and R.O.Claus: *Smart Mater. Struct.*, 1995, **4,** 107.

[13] M.De Vries, V.Arya, S.Meller, S.F.Masri and R.O.Claus: *Cement Concrete Comp.*, 1997, **19,** 59.

[14] R.O.Claus, M.F.Gunther, A.B.Wang, K.A.Murphy and D.Sun: *Applications of Fibre Optic Sensors in Engineering Mechanics*, ed. F.Ansari, ASCE, New York, 1993, 60-70.

[15] A.Hameed, G.F.Fernando, J.G.Hetherington, R.A.Brown, J.S.Leng and R.A.Barnes: *Mater. Struct.*, 2002, **35,** 557.