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Applications of fiber optic sensors for structural health monitoring

K. Kesavan†, K. Ravisankar, S. Parivallal and P. Sreeshylam

Structural Engineering Research Center, Tharamani, Chennai-600 113, India

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Abstract. Large and complex structures are being built now-a-days and, they are required to be functional even under extreme loading and environmental conditions. In order to meet the safety and maintenance demands, there is a need to build sensors integrated structural system, which can sense and provide necessary information about the structural response to complex loading and environment. Sophisticated tools have been developed for the design and construction of civil engineering structures. However, very little has been accomplished in the area of monitoring and rehabilitation. The employment of appropriate sensor is therefore crucial, and efforts must be directed towards non-destructive testing techniques that remain functional throughout the life of the structure. Fiber optic sensors are emerging as a superior non-destructive tool for evaluating the health of civil engineering structures. Flexibility, small in size and corrosion resistance of optical fibers allow them to be directly embedded in concrete structures. The inherent advantages of fiber optic sensors over conventional sensors include high resolution, ability to work in difficult environment, immunity from electromagnetic interference, large band width of signal, low noise and high sensitivity. This paper brings out the potential and current status of technology of fiber optic sensors for civil engineering applications. The importance of employing fiber optic sensors for health monitoring of civil engineering structures has been highlighted. Details of laboratory studies carried out on fiber optic strain sensors to assess their suitability for civil engineering applications are also covered.

Keywords: EFPI fiber optic sensor; temperature calibration; apparent strain; embedded fiber optic sensor; encapsulation technique; bending; compression; tension; long-term stability; concrete; low cycle fatigue; high cycle fatigue.

1. Introduction

Structures have become complex and are required to be functional even under difficult loading and environmental conditions. Civil engineering structures such as buildings, bridges, dams, tunnels, containment vessels, seaports, highways, etc need an enormous financial investment. If in-built/embedded sensors can improve structural evaluation, the ramification could have enormous value to the multicrore annual construction investment, as ageing and deterioration of many structures are recognized as major problems. Sophisticated tools have been developed for the design and construction of civil engineering structures. However, very little has been accomplished in the area of monitoring and rehabilitation. The problem of maintenance is overwhelming and the lack of appropriate tools to support decisions about

†Scientist, Corresponding Author, E-mail: kesav@sercm.org, kesavankannan@yahoo.com

replacement or selection of repair strategy, leads to inefficient use of resources. The employment of appropriate sensor is therefore crucial, and efforts must be directed towards non-destructive evaluation techniques that will be functional throughout the life of the structure.

Conventional instrumentation techniques for monitoring the performance of existing and new structures are mainly limited to the application of electric and magnetic principles using electrical resistance strain gages, linear variable differential transducers etc. While these can serve well for short-term measurements, they have major limitations in evaluating long-term behaviour of structural members, especially in concrete structural systems. The main problem associated with these conventional sensing techniques stem from their response to electrical noise and potential for degradation with age. Another major problem with conventional sensor system is the cabling. An embedded sensing system for a major civil structure may require large number of sensors which means that many cables will be required to connect them to the measuring instrument. If they are embedded in concrete structure, such bulky cables may affect the integrity of the structure. These cables are prone to electro magnetic interference (EMI), resulting in high noise-to-signal ratio. Recent developments in fiber optic sensor system have the potential to offer advantages that can essentially eliminate conventional sensors deficiency and permit long-term reliable quantitative monitoring. This paper brings out the potential and current status of technology of fiber optic sensors for civil engineering applications. The importance of employing fiber optic sensors for health monitoring of civil engineering structures has been highlighted. Details of laboratory studies carried out on fiber optic strain sensors to assess their suitability for civil engineering applications are also covered.

2. Fiber optic sensor

Fiber optic sensors are fabricated using high strength silica which possesses an inherent immunity to corrosion and electromagnetic interference. The properties of optical fibers allow innovative approaches for the design of optical sensors. Due to this reason, a number of fiber optic sensor types have been developed. Fiber optic sensors can be classified under different categories. Localized, distributed and multiplexed sensors are based on sensing methods. Intensity, Interferometric, polarimetric and spectrometric based sensors are classified according to the transduction mechanism.

A fiber optic sensor system (Udd 1995) basically consists of a light transmitter, a receiver, an optical fiber, a modulator element and a signal processing unit. Light is transmitted to the measurement point (Modulator) using optical fibers and such a scheme is generally termed as extrinsic modulations. If the fiber itself acts as a sensing element, then intrinsic modulation takes place.

Extrinsic Fabry Perot Interferometric (EFPI) sensors are reported to be good for strain sensing in civil engineering applications (Measures 2001). A cavity comprising two mirrors (reflectors) which are parallel to each other and perpendicular to the axis of the optical fiber form the localized sensing region in an EFPI type of sensor. Here the reference and sensing optical fibers are one and the same up to the first mirror(partial mirror), which constitutes the start of the sensing region. Fabry-Perot cavity is formed between the air-glass interface of two fiber end faces aligned in a hollow core fiber (Fig. 1). Changes in the separation between the two fiber end faces, known as air gap length, cause interferometric fringe variations. The interference pattern generated is sinusoidal in shape and is directly related to the intensity of the applied strain field. The period of the wave form constitutes a fringe and by proper calibration the magnitude of the strain can be determined.

When the gage is bonded to a substrate, the strain transferred to the gage is converted into air gap

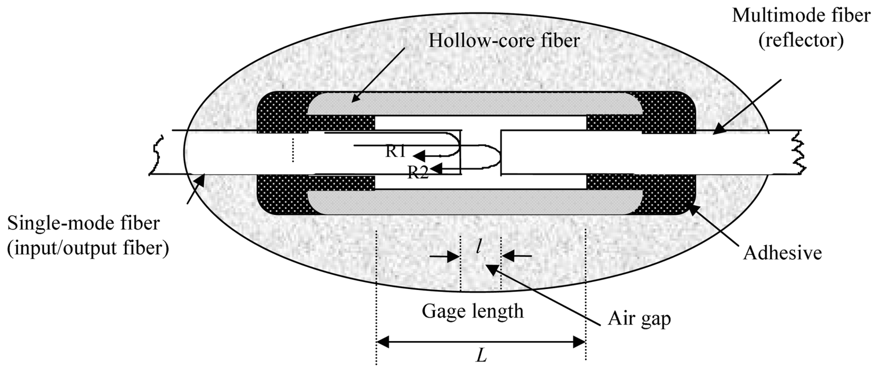


Fig. 1 Fabry-Perot fiber optic sensor configuration

length variation and the strain developed is given by the following equation.

$$\text{Strain, } \varepsilon = \frac{\Delta l(airgap)}{L} \tag{1}$$

Where, Δl(air gap) = change in the air gap.
L = Gage length.

3. Fiber optic sensors for civil engineering applications

The development of optical fiber sensors started in 1977 even though some isolated demonstrations preceded this date. The increased use of advanced composites in aeronautics prompted the development of new damage detection techniques for monitoring the integrity of structural components while in service. Fiber optic sensors have been employed as real time damage detection tool in advanced aircraft and space vehicles. The success of optical fiber sensor technology in condition monitoring of composite materials lead to research and development activities for their use in civil engineering discipline.

Rossi and LeMaou (1989), embedded a series of optical fibers in laboratory concrete beams as well as in concrete caissons of larger structures. Their research involved crack detection in concrete on the basis of light intensity loss in the embedded optical fiber. The principle of this technique is that, an optical fiber embedded in a piece of concrete breaks as soon as a crack propagating in the material reaches the fiber, causing complete disappearance of the luminous signal transmitted through the fiber.

Masri, *et al.* (1994), employed Fabry-Perot interferometric fiber optic sensors in a one-third scale model of a reinforced concrete multistorey frame joint. Conventional strain gages were bonded on the main steel rebars and on selected beam and column stirrups. Two fiber optic sensors were bonded at each conventional gage location to enable comparison of results. The performance of the optical fiber sensors was examined under a variety of static and dynamic tests. The authors concluded that there is good comparison between the two measurement techniques.

In the paper by Maaskant, *et al.* (1997), attention is focused on fiber-optic grating sensor technology, which possesses some unique characteristics and benefits in strain sensing applications. A fiber optic Bragg grating strain sensor array has been installed in the Beddington Trail Bridge in Calgary, Canada, to monitor the response of three types of prestressing tendons. The fiber optic bragg grating sensors were attached to prestressing tendons, which were subsequently embedded in the concrete girders. The main aim of this work is to monitor the long-term characteristics of the tendon-concrete bond and the relaxation behaviour of the tendons, which can help the assessment of the appropriateness of the use of new materials as reinforcing elements. The authors have brought out the potential of using fiber optic bragg grating sensors for long-term monitoring of actual field problems.

The paper by De Vries, *et al.* (1997) reports the design and implementation of an optical fiber sensor based on the Extrinsic Fabry-Perot-Interferometer (EFPI) for the non-destructive quantitative evaluation of advanced civil structures. The performance of the EFPI sensor is demonstrated in two different applications. In the first implementation, optical fiber sensors were used to obtain quantitative strain response from reinforced concrete beam-column joints. In the second implementation, optical fiber sensors were bonded to graphite composite prestressing strands used for reinforcing concrete, to obtain absolute strain information. The paper has concluded with a discussion of practical considerations which need to be taken into account when implementing optical fiber sensors in civil structure applications.

Inaudi, *et al.* (1998) used low coherence fiber optic deformation sensors for monitoring the existing and refurbished concrete bridge (Versoix bridge) near Geneva in Switzerland. This bridge is a concrete bridge consisting of two parallel prestressed concrete beams with a 30 cm concrete deck with two overhangs, and supports two traffic lanes. In order to support a third traffic lane and a new emergency lane, the exterior beams were widened and the overhangs were extended. Because of the added weight and prestressing, as well as the differential shrinkage between new and old concrete, the bridge bends (both horizontally and vertically) and twists during the construction phases. In order to get the information about the interaction between the old and new concrete, the authors have used more than 100 numbers of low coherence fiber optic sensors to measure the displacements of the fresh concrete during the setting phase, as well as to monitor the long-term deformations of the bridge. Only two of the six spans were instrumented and, in each span 4 sections were chosen for instrumentation. In each section, five sensors were embedded in the new concrete and one sensor was installed on the surface of the old concrete. The authors have used deformation sensors of 4m long in this bridge. The authors have brought out the importance of protecting the sensors and, emphasized the need of having sophisticated dedicated software to handle large data collected from the monitoring programme.

The characteristics and the behaviour of different kinds of fiber optic sensors based on the Fabry-Perot interferometers have been presented by Choquet, *et al.* (1999). Sensors used by the authors cover the full range of requirements for dam and structural monitoring. They include strain sensors, pressure sensors, displacement transducers, temperature probes etc. The sensors were subjected to mechanical and thermal strains and a field test was carried out on a bridge and several other field structures. The results of the investigation indicate that these sensors accurately measure strain and they are suitable for static and dynamic measurements.

Tennyson, *et al.* (2001) describes the development and application of fiber optic sensors for monitoring bridge structures in Canada. Fiber Bragg Grating (FBG) sensors have been used to measure static and dynamic response on bridge decks and columns during load testing and also during rehabilitation time and during load testing time. The main objective of this work is to check the fiber optic system reliability over several years in a hostile environment. A total of 16 bridges have been instrumented across Canada with various combinations of fiber optic sensors, strain gages and temperature gages. The examples described in this study were chosen to show the advantages in using advanced composite materials as reinforcements and fiber optic sensors for sensing in bridge structure.

Moerman, *et al.* (2001) describes the application of Fiber Bragg Grating (FBG) sensor on a newly built bridge, consisting of three spans with central span of 67 m long and two side spans of 40 m long.

The bridge consists of two parallel concrete box girders. A monitoring system consisting of 18 FBG sensors was used in the first box girder to monitor the prestressing operation, and subsequent deformations of this box girder. Three different sections of the first girder were instrumented with six FBG sensors. In order to verify the FBG sensor measurements, additional measurements were performed inside the box girder by means of mechanical gages (DEMEC). Each FBG sensor was attached to a reinforcing bar which was then attached to reinforcement cage. At each position of a Fiber Bragg Grating sensor, five DEMEC measurements were made. The authors concluded that, there is a good agreement between the measurements of the FBG sensors and the mechanical gages. The authors have brought out the advantage of using FBG sensors.

Li (2004) presents the application of fiber optic sensor for health monitoring of critical civil structures like buildings, piles, bridges, pipelines, tunnels, and dams. In this, the author briefly describes the three commonly used fiber optic sensors namely, Fabry-Perot fiber optic sensor, Long-gage fiber optic sensor and Bragg grating sensor. In this paper it has been emphasized that one of the exciting fields wherein fiber optic sensors and health monitoring are expected to play significant role is smart structures and intelligent systems.

4. Laboratory studies on performance assessment of EFPI fiber optic sensors

4.1. Studies on surface mounting type sensors

Experiments were conducted to assess the behaviour of EFPI fiber optic sensors, when bonded to concrete and steel surfaces. In order to assess the behaviour of fiber optic sensor under tensile loading, experiments were conducted using standard uniaxial steel specimens. A fiber optic strain sensor of 10 mm size was bonded to the steel specimen and a conventional electrical resistance strain gage also bonded near the fiber optic sensor to compare the strain response during uniaxial tensile testing. The specimen was subjected to axial tension. Three cycles of loading and unloading was carried out and strain responses from fiber optic sensor and conventional strain gage were recorded. Strain responses between fiber optic sensor and conventional sensor were compared and found to be within 2% variation.

A fiber optic strain sensor of 50 mm size was bonded to the outer surface of a standard concrete cylinder to assess the behaviour of fiber optic sensor under compressive loading. One conventional electrical resistance strain gage of 50 mm size was also mounted very close to the fiber optic strain sensor for comparison. The cylinder was subjected to a compressive load and the output from fiber optic sensor and conventional strain gage were recorded during loading. Strain responses between fiber optic sensor and conventional sensor were compared. The strains from both sensors were found to be within 6% variation.

In order to assess the behaviour of fiber optic sensors under flexural loading, a four-point bending test was conducted. One mild steel I-beam was prepared and was instrumented with one surface mounted EFPI fiber optic strain sensor (kept at top flange). Two conventional electrical resistance strain gages were also used, one each kept at top and bottom flanges, adjacent to fiber optic sensor. The test set-up was designed to create a constant bending zone at the instrumented locations of the I-beam. The beam was subjected to four-point bending load and the load was applied in steps. Strain responses from fiber optic sensor and conventional strain gages were recorded for all loading steps. The I-beam specimen was then kept upside down and bending load was again applied to the beam. The above technique helped to collect tensile as well as compressive strain responses from same fiber optic strain sensor.

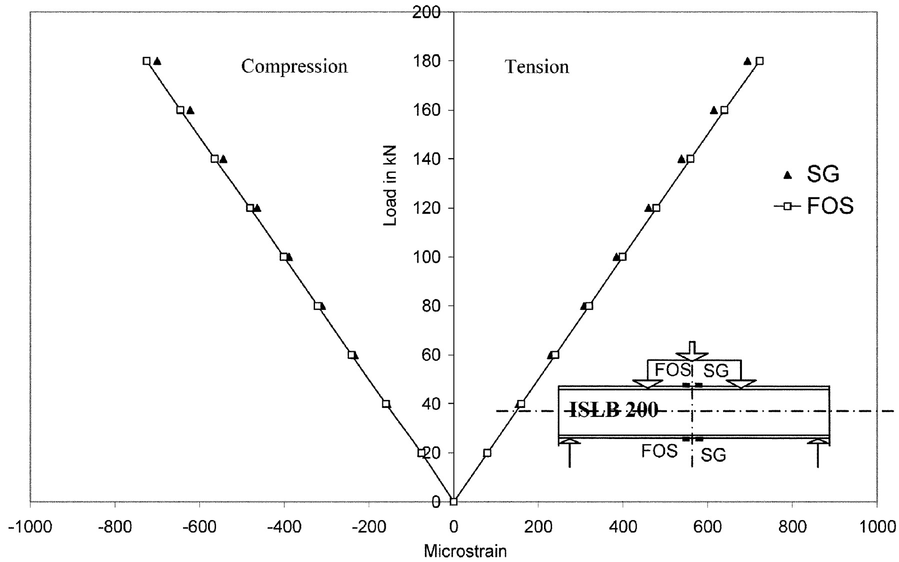


Fig. 2 Load vs strain obtained from flexure test on steel I Beam

Close comparison between the fiber optic sensor values and conventional strain gage values was observed and the sensitivity was found to be nearly identical in both tension and compression (Fig. 2).

4.2. Studies on fiber optic sensors embedded in concrete

Embedded sensors have been generally used in concrete and composites. Embedding bare fiber optic strain sensors in concrete structures is not advisable because of their fragility. The process of placing concrete and compacting through vibration exerts severe stress on the bare optical fiber causing damage to the sensor. Hence they must be properly protected. Another important aspect of sensor embedding is the ingress/egress of the sensor lead to/from the host structure. The optical lead wires which are very fragile also need to be protected from damage at ingress/egress location.

Between the optical fiber sensor and the host structure there must be a protective layer called encapsulation. The properties of this encapsulation can have a major influence on the life and functionality of the sensor. Providing suitable encapsulation to bare fiber optic sensor is important and this encapsulation should be compatible to the surrounding concrete material to ensure complete strain transfer.

Experimental studies were carried out to assess the level of strain transfer through the encapsulation (Kesavan, *et al.* 2004). For this study, a standard concrete cylinder was prepared and, the encapsulated fiber optic sensor was embedded inside the concrete cylinder during casting. After completion of curing of concrete cylinder, four electrical resistance strain gages were bonded to the outer surface of the cylinder (Fig. 3). The instrumented concrete cylinder was subjected to compressive load using an UTM. The load was applied in steps and for each step, the output from embedded fiber optic strain sensor and the surface mounted electrical resistance strain gages were recorded. The strain response obtained from embedded fiber optic sensor was compared with the average of electrical resistance strain gage response and the comparison is found to be good (Fig. 4). To check the reliability of the method the experiment was repeated on a second specimen and response was found to be good.

To study the performance of fiber optic strain sensor bonded to the reinforcement of a RCC beam, a

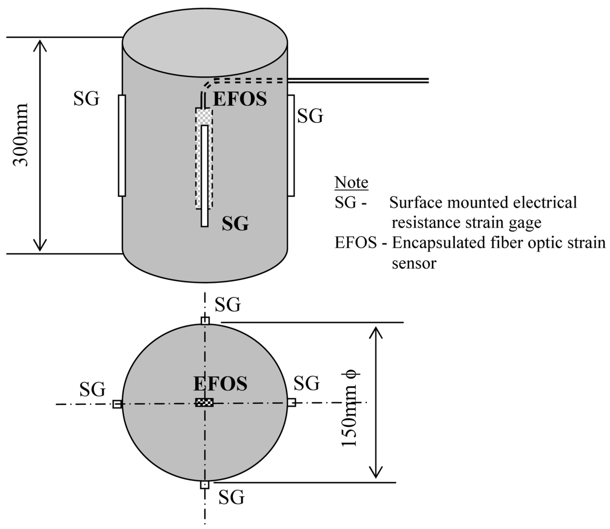


Fig. 3 Instrumentation details of concrete cylinder with encapsulated fiber optic sensor

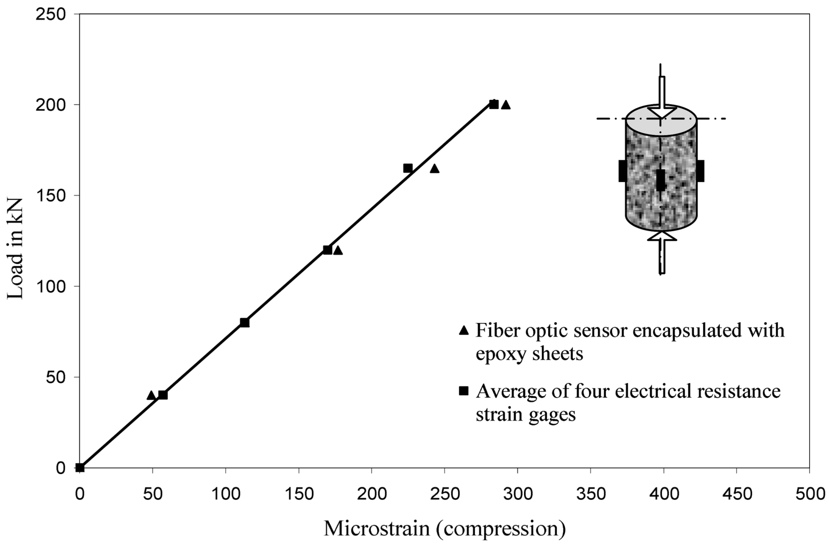


Fig. 4 Comparison of strain response between encapsulated fiber optic strain sensor and electrical resistance strain gages

reinforced concrete beam of size 100×200×1500 mm was cast. A fiber optic strain sensor (10 mm size) was bonded to the bottom reinforcement of the beam and an electrical resistance strain gage was also bonded very close to it, to compare fiber optic strain sensor (Fig. 5). When strain gages are installed on reinforcing steel, the major cause of failure is due to damage during compacting and placing the concrete that surrounds the rebar. To prevent these damages, the sensors need to be protected. Suitable techniques were evolved to protect the sensors bonded to the reinforcing bars.

A test set-up was designed to create a constant bending zone at the instrumented locations of the beam. The beam was subjected to four-point bending load and the load was applied in steps. Strain

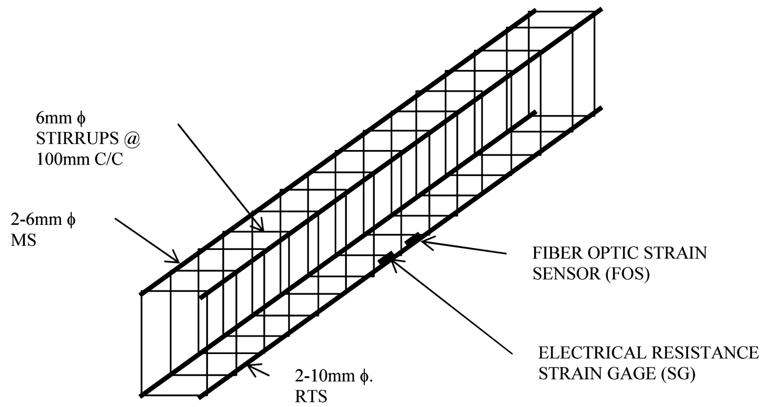


Fig. 5 Instrumentation details on rebar of RCC beam

responses from fiber optic sensor and conventional electrical resistance strain gages were recorded for all the loading steps. Load vs strain plots were prepared to evaluate the behaviour of fiber optic strain sensor and compare it with conventional electrical resistance strain gage. Strain responses between fiber optic sensor and conventional electrical resistance strain gage were compared and found to be within 2% variation.

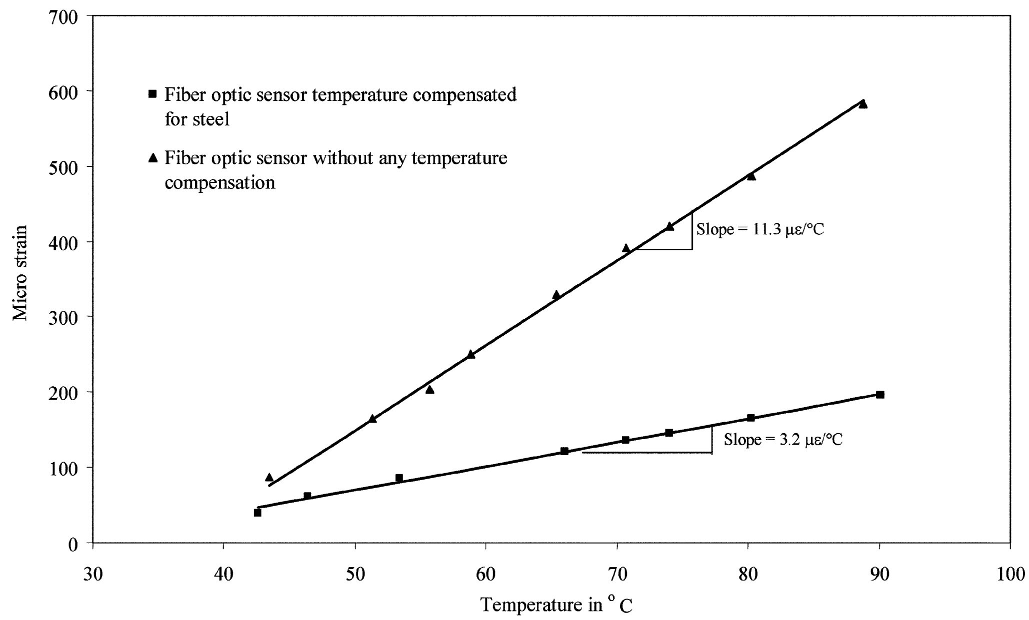
4.2.1. Temperature calibration for EFPI fiber optic strain sensor

During health monitoring of civil engineering structures like bridges, the output from the fiber optic strain sensors may have a significant component of apparent strain due to temperature effect, which is to be properly accounted for. The variation in temperature of structures between extreme seasons can be as much as 30 to 40^{o}C, and this variation may cause an apparent strain of large magnitude. When making strain measurements in a variable temperature environment, the indicated strain is equal to the sum of stress-induced strain in the test specimen and the temperature induced apparent strain of the gage bonded to the test specimen. With the thermal output expressed in strain units, correction for this effect can be made by simply subtracting (algebraically) the apparent strain from the measured strain. To correct the measured strain, the apparent strain must be established separately.

EFPI fiber optic strain sensors are the only known fiber optic strain sensor that can be self temperature compensated. Self-temperature compensation of EFPI fiber optic strain sensor is theoretically possible, primarily because the EFPI strain sensor itself contributes very little to thermal strain. Self-temperature compensation of the EFPI is achieved by replacing the standard optical fiber reflector with a metal reflector.

In order to correct the temperature effects, temperature calibration was carried out from laboratory experiments on two structural materials namely steel and concrete using EFPI fiber optic strain sensors. In this investigation, EFPI strain sensors which are temperature compensated for steel materials as well as sensors without any temperature compensation were used. Temperature calibration studies were also carried out for embedment type EFPI fiber optic strain sensors.

From the experiments conducted in the laboratory to identify the problems related to temperature effects on fiber optic strain sensors for strain measurements, it was found that the fiber optic sensors which are claimed to be fully temperature compensated for steel, still shows a little apparent strain for steel specimen and non-temperature compensated fiber optic strain sensor shows the apparent strain per



Note: Initial strain reading set to zero at room temperature

Fig. 6 Temperature calibration curves for apparent strain correction-steel specimen

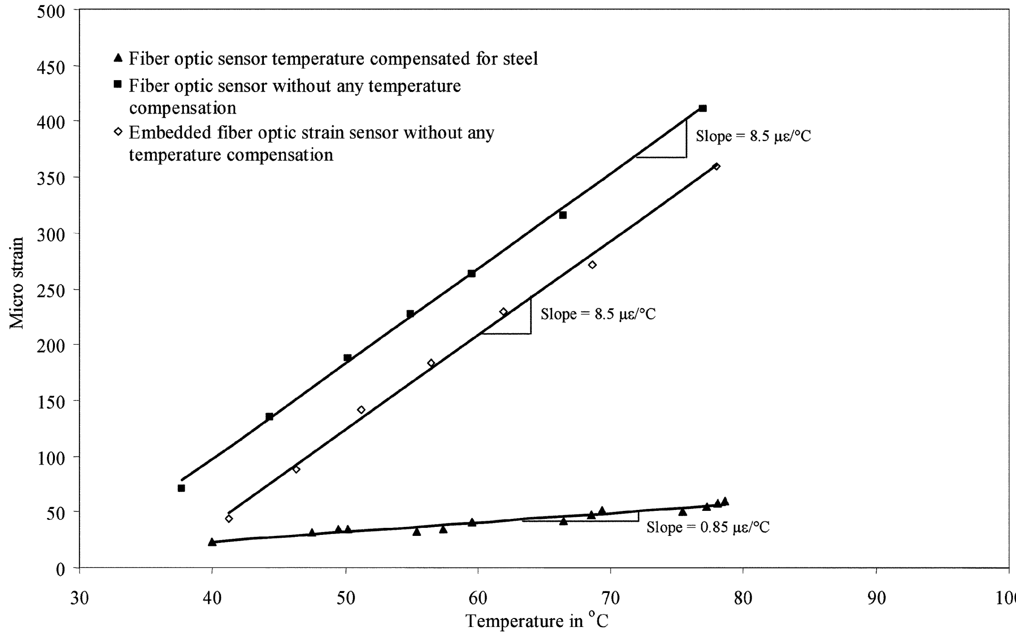
degree Celsius, very close to the thermal expansion coefficient of the steel material used in the experiments (Fig. 6). Hence using a non-compensated EFPI fiber optic strain sensor in a test specimen, one can directly measure the thermal expansion coefficient of any material. From the experiments conducted on the concrete specimen, it was found that the fiber optic strain sensor which is temperature compensated for steel specimen, gives nearly zero apparent strain and the fiber optic strain sensor with out any temperature compensation gives apparent strain very close to the thermal expansion coefficient of this particular concrete mix (Fig. 7).

4.2.2. Studies on long-term stability assessment of EFPI fiber optic strain sensors

Reliable measurement of strains over longer periods is an essential requirement for health monitoring of structures. To get reliable measurements, the sensor should be stable over the time. Long –term stability assessment of EFPI fiber optic strain sensors, subjected to sustained loading was carried out. For this study, a 7 mm dia. high strength prestressing wire was instrumented with two fiber optic sensors and a temperature sensor. A special self straining frame was fabricated and the instrumented prestressing wire was tensioned by means of a hydraulic jack. After locking the prestressing force on the instrumented wire suitably, the strains from the two fiber optic sensors were measured. Two test specimens were prepared for this study (Fig. 8). The measured strain data for a duration of 400 days was corrected for temperature effect and strain vs. time was plotted (Fig. 9). The strain output is almost constant during this period, indicating that EFPI fiber optic strain sensors are stable and suitable for long-term monitoring of structures.

4.2.3. Performance assessment of EFPI fiber optic strain sensors under fatigue loading

Bridges and other critical civil engineering structures operate in a dynamic environment subjected to



Note: Initial strain reading set to zero at room temperature

Fig. 7 Temperature calibration curves for apparent strain correction-concrete specimen

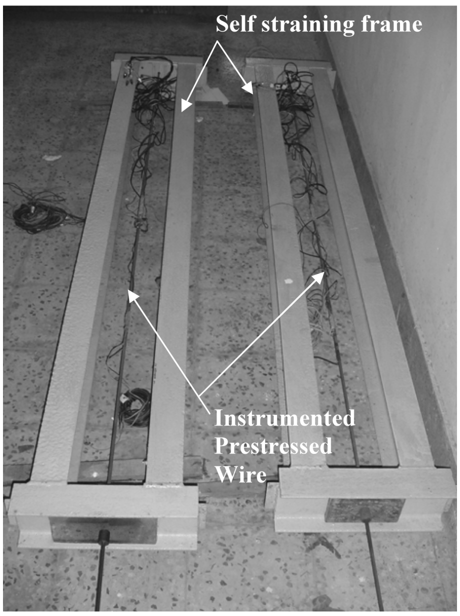


Fig. 8 Experimental set-up for long-term stability assessment of fiber optic sensor

repeated cyclic loading. The integrity of structures under such load conditions cannot be predicted from their responses under a static load. Predicting fatigue life of structures subjected to repeated load cycles

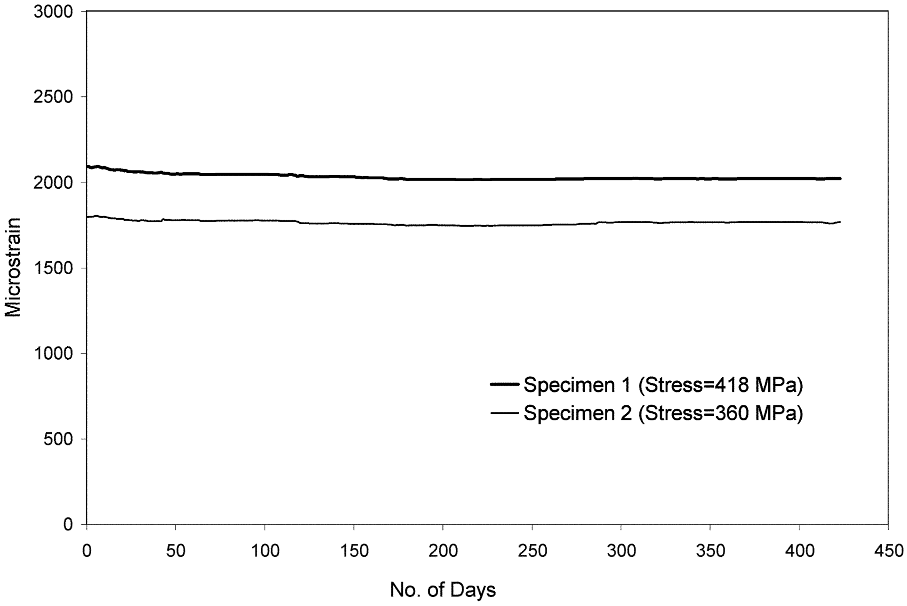


Fig. 9 Plot of strain vs time(days)-long-term monitoring of prestressing wire

during their service is an important issue. Reliable performance of fiber optic sensors under cyclic/ fatigue load is to be ascertained before using the sensors for health monitoring of critical civil engineering structures. Experimental investigations were carried out in the laboratory to evaluate the performance of EFPI fiber optic strain sensors under high cycle low stress fatigue and low cycle high

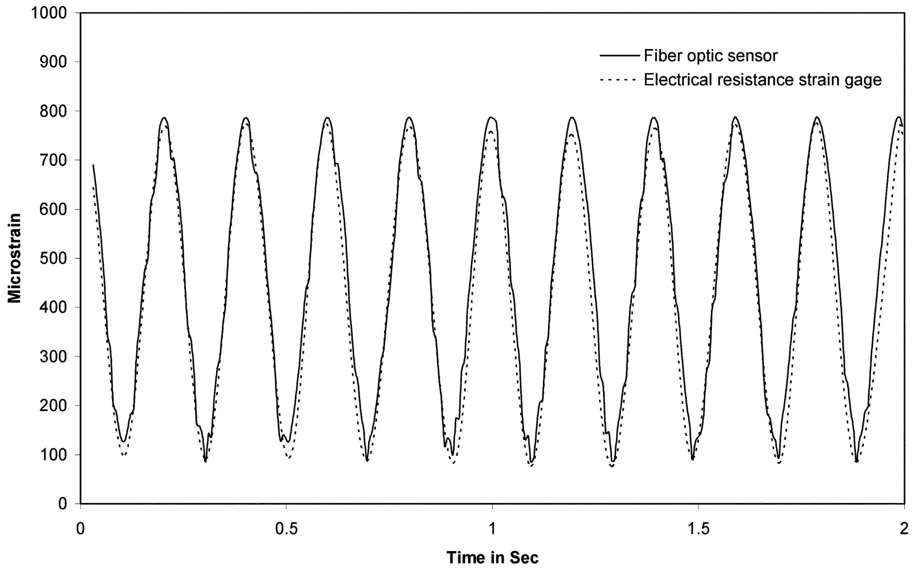


Fig. 10 Comparison of strain response from fiber optic sensor and electrical resistance strain gage during fatigue test

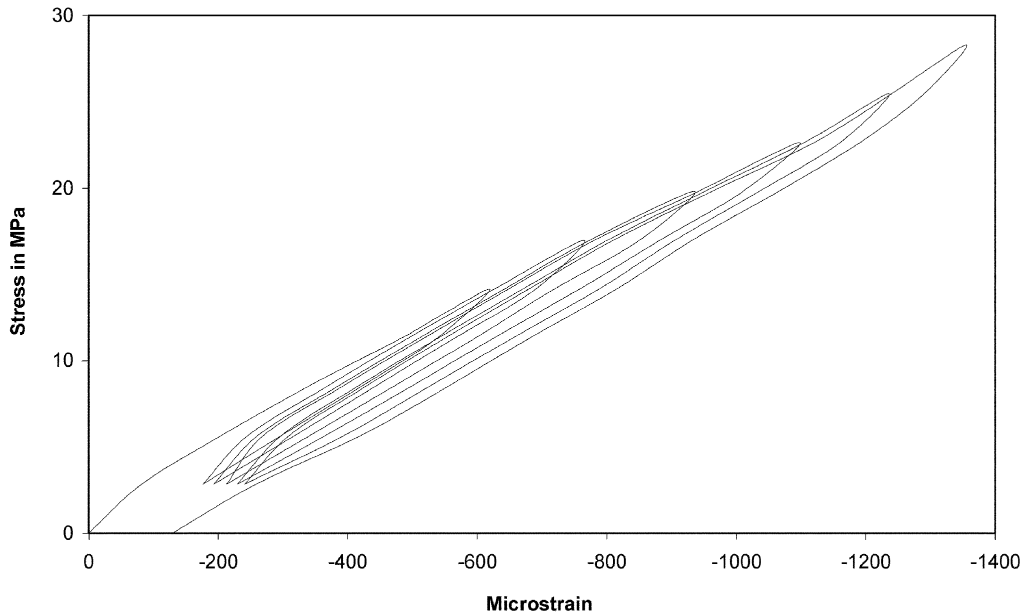


Fig. 11 Stress vs strain of encapsulated EFPI sensor during high stress low cycle loading

stress cyclic loading.

Experimental studies were carried out on steel beams instrumented with surface mounting type EFPI fiber optic strain sensors to evaluate the performance of the sensor under high cycle low stress fatigue loading. A sinusoidal loading corresponding to a minimum of 20 MPa to a maximum of 160 MPa stress at a frequency of 5 HZ was applied to the instrumented steel beam. The beam was tested up to 2 million cycles and it was found that the fiber optic strain measurement was consistent with the load amplitudes during the two million cycle fatigue test. The strain responses obtained from fiber optic sensors was also compared well with the conventional strain gages (Fig. 10). The performance of fiber optic sensor was found to be consistent with the load amplitudes indicating that the sensor as well as the bonding technique can withstand the required stress ranges during the 2 million cycles of loading.

Experiments were also carried out to assess the performance of embedded fiber optic sensors under high-stress low-cycle loading. A concrete cylinder of 150mm dia. and 300 mm long was cast. One encapsulated EFPI fiber optic sensor was embedded at the middle of the cylinder prior to casting. Six cycles of loading-unloading were applied to the instrumented cylinder. In each cycle, the minimum stress was kept constant at 2.83 MPa and the maximum stress was varied from 14.14 MPa to 28.3 MPa, in steps of 2.83 MPa. These stresses are corresponding to minimum of 8% and maximum of 34% to 69% of its strength. Stress vs strain for the instrumented cylinder under cycle load was plotted (Fig. 11). From the results, it is seen that a maximum of around 1300 $\mu\varepsilon$ was measured during the test. The encapsulated fiber optic sensor continued to perform well, even beyond this high strain range.

5. Conclusions

In this paper, the potential and current status of technology of fiber optic sensors for civil engineering applications have been brought out. From the various experimental studies conducted, it is seen that fiber optic strain sensor's response compare well with that of conventional strain gages. The sensitivity of fiber optic sensor is found to be nearly identical in both compression and tension. Embedded type fiber optic sensors are generally recommended for health monitoring of reinforced concrete/prestressed concrete structures and details of laboratory studies carried out on embedded sensors are presented.

From the experiments carried out for temperature calibration of EFPI fiber optic sensor, it is found that the temperature induced apparent strain is significant and should be properly accounted to have an accurate strain analysis. Since the so called temperature compensated fiber optic strain sensors are not fully compensated for temperature effect, it is advisable to use non-temperature compensated fiber optic strain sensors. In such cases, the apparent strain correction can be carried out theoretically also by knowing the thermal expansion coefficient of the structural material and the temperature at the location of measurement.

Stability of the EFPI fiber optic sensor over longer periods under sustained load has been assessed. Performance of EFPI fiber optic sensors under high cycle fatigue was ascertained from the laboratory tests. The performance of the sensor is found to be reliable and consistent during 2 million cycles. The encapsulated fiber optic sensor also performed well during the high stress low cycle test. From the tests carried out in the laboratory, fiber optic sensors are found to be performing satisfactorily under cyclic loading.

Fiber optic sensors have several important advantages over conventional sensors, which make fiber optic sensors very attractive for structural health monitoring. The availability of high band width transmission and immunity to EMI make the task of employing multi-sensor systems that can serve for the long-term health monitoring of new and rehabilitated structures.

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References

Choquet, P., Juneau, F. and Dadoun, F. (1999), "New generation of fiber optic sensors for dam monitoring", *Proceedings of the 99 International Conference on Dam Safety and Monitoring*, China.

De Vries, M., Arya, V., Meller, S., Masri, S. F., Claus, R. O. (1997), 'Implementation of EFPI-based optical fiber sensor instrumentation for the NDE of concrete structures", *Cement Concr. Comp.*, 19(1).

Inaudi, D., Vurpillot, S., Glisic, B., Kronenberg, P. and Sandra, L. Loret (1998), "Long-term monitoring of a concrete bridge with 100+ fiber optic long-gage sensors", *Newport Beach Conference on Nondestructive Evaluation Techniques for Aging Infrastructure & Manufacturing.*

Kesavan, K., Ravi Sankar, K., Parivallal, S., Sreeshylam, P. and Narayanan, T. (2004), "A technique for embedding EFPI fiber optic strain sensors in concrete", *Experimental Techniques*, **28**(4), 31-33.

Li, H.-N., Li, D.-S. and Song G.-B. (2004), "Recent applications of fiber optic sensors to health monitoring in civil engineering", *Eng. Struct.*, **26**, 1647-1657.

Maaskant, R., Alavie, T., Measures, R. M., Tadros, G., Rizkalla, S. H. and Guha Thakurta, A. (1997), "Fiber optic bragg grating sensors for bridge monitoring", *Cement Concr. Comp.*, **19**(1).

Masri, S. F., Agbabian, M. S., Abdel Ghaffar, A. M., Higazy, M., Claus, R. O. and De Vries, M. J. (1994), "Experimental study of embedded fiber optic strain gages in concrete structures", *ASCE-EMD*, 120.

Measures, R. M. (2001), *Structural Monitoring with Fiber Optic Technology*, Academic Press, California.

Moerman, W., Waele, W. De., Coppens, C., Taerwe, L., Degrieck, J., Baets, R. and Callens, M. (2001), "Monitoring of a prestressed concrete girder bridge with fiber optical bragg grating sensors", *J. Strain,* **37**(4), 151-153.

Rossi, P. and LeMaou, F. (1989), "New method for detecting cracks in concrete using fiber optics", *RILEM Mater. Struct.*, **22**.

Tennyson, R. C., Mufti, A. A., Rizkalla, S., Tadros, G. and Benmokrane, B. (2001), 'Structural health monitoring of innovative bridges in Canada with fiber optic sensors", *Smart Mater. Struct.*, **10**, 560-573.

Udd, E. (1995), *Fiber Optic Smart Structures*, John Wiley & Sons, Inc., New York.

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