Structural Health Monitoring using Fiber Bragg Grating Sensor : An Overview

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***Abstract*— Civil engineering structures are the most luxurious assets of the country which requires continuous monitoring in order to overcome the distressing effects caused due to environmental conditions, aging and overloading. The Structural Health Monitoring (SHM) plays a major role in determining the health of a structure by number of methods. With the recent development in fiber optic sensor fields, the fiber optic sensors play an important role in monitoring the health of the structures by having several advantages like resistance to electromagnetic interference, corrosion, etc., over the other conventional sensors. Fiber Bragg Grating (FBG) was used for the health monitoring of the civil engineering structures in the western countries from the last decade whereas in India this technology is in budding stage. In this paper it is aimed to determine the usage of Fiber Bragg Grating in monitoring the health of the structure by embedding them within the structure or on the surface. The main aspects studied in this paper are the application of Fiber Bragg Grating sensor in health monitoring of the structure, corrosion monitoring, health monitoring of the repaired structure by measuring interfacial strain between the concrete and the strengthening material. The detailed study on the application of Fiber Bragg Grating in the structural health monitoring is explained in this paper.**

Keywords — Fiber Bragg Grating, Structural Health Monitoring, Corrosion Monitoring, Interfacial Strain Monitoring.

I. INTRODUCTION

Deterioration and functional deficiency of existing civil infrastructure represents one of the most significant challenges facing the engineers. These factors can be overcome by the proper monitoring of the structure by structural health monitoring. The structural health monitoring is done by proper monitoring of the structure using various types of the sensors. The recent advancement in the fiber optic field provide a better fiber optic sensor to monitor the structure with great accuracy. The Fiber Bragg Grating and the Fabry-Perot Interoferometric sensors are the most commonly used fiber optic sensors. Numerous test results can be found in the literature all attempting to investigate the use of fiber optic sensor in the structural health monitoring. The major experiments were carries out to study the application of fiber optic sensor in health monitoring, corrosion, response of the sensor to the induced damages, method of embedding the sensor and interfacial strain during the strengthening of the structure. The subsequent paragraphs describe the various experiments carried out to determine the usage of fiber optic sensor in structural health monitoring.

II. SENSOR

A. Fiber Optic Sensor

Fiber optic sensors are fabricated using high strength silica, which possesses an inherent immunity to corrosion and ElectroMagnetic Interference (EMI). 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 sensors are based on transduction mechanism. Fibre optic sensors are often categorized as being either extrinsic or intrinsic. Extrinsic Fabry–Perot Interferometric (EFPI) sensors and Fiber Bragg Grating (FBG) sensors both are being used for long-term/structural monitoring of concrete structures.

B. Fiber Bragg Grating

Fibre Bragg Gratings are periodic structures that are imprinted directly into the core of glass optical fibre by powerful ultraviolet radiation. Such structure consists of a periodically varying refractive index over typically several millimeters of the fibre core. The specific characteristic of FBG for sensing applications is that their periodicity causes them to act as wavelength sensitive reflectors**.** It is a spectrometric-based fiber optic sensor, where the change in wavelength of the propagating light is considered for measuring various physical parameters. FBG sensors are small in size, very light, flexible, resistant to corrosion, high resolution, highly sensitive, capable of high bandwidth operation, multiplexable, and completely immune to electromagnetic interference. In addition, the characteristics that an FBG reflects a specific wavelength which shifts slightly depending on the strain applied are ideal for mechanical sensing.

Working Principle of Fiber Bragg Grating

The Fiber Bragg Grating is made by the imprinting process. During imprinting process, the intensity of the ultraviolet illumination is made to occur in a periodic fashion along the fiber core. At a sufficiently high power level, local defects are created within the core, which then give rise to a periodic change in the local Refractive Index (RI). This change in RI created is permanent and sensitive to a number of physical parameters, such as pressure, temperature, strain, and vibration. Thus by monitoring the resultant changes in reflected wavelength, FBG can be used for sensing applications to measure various physical quantities.

Fiber optic Bragg grating sensor response arises from two sources, namely the induced change in pitch length (Λ) of the grating and the perturbation of the effective core refractive index (n_{eff}). These gratings act as a series of partially reflecting mirrors, which reflect back the optical wavelength that is proportional to their spacing. Whenever a broadband light beam impinges on the grating, it will have a portion of its energy transmitted through, and another reflected back as shown in Fig. 1. The basic principle of FBG is to measure the shift in the Bragg wavelength (λ_B), which is directly proportional to the effective refractive index (η_{eff}) and the periodicity (Λ).

The wavelength of the reflected spectrum band is defined by the Bragg condition

$$\lambda_B = 2n_{eff}\,\Lambda$$

When an FBG is strained, the Bragg wavelength (λ_B) changes and the relation is given by

$$\text{Strain } \varepsilon = \frac{\frac{\Delta\lambda_B}{\lambda_B}}{(1-p_e)} \quad [3]$$

C. Extrinsic Fabry–Perot Interferometric sensor

A Fabry-Perot sensor (FP) measures a gap shift between two facing fiber ends contained in a glass capillary as shown in Fig. 2. The reflected gap between the two faces is represented on a screen. These sensors have high sensitivity for multiple quantities and have simple technique for treatment of the signal (White light interferometry). They have reliable and low cost signal conditioners. They can be repaired if damaged and could have up to a 1000 Hz sampling rate [5].

Working Principle of Fabry–Perot Interferometric sensor

EFPI sensor which is of interferometric type is reported to be good for strain sensing in civil engineering applications. In EFPI type sensor, a cavity comprising of two mirrors (reflection) which are parallel to each other and perpendicular to the axis of the optical fiber form the localized sensing region. Here the reference and sensing optical fiber are one and

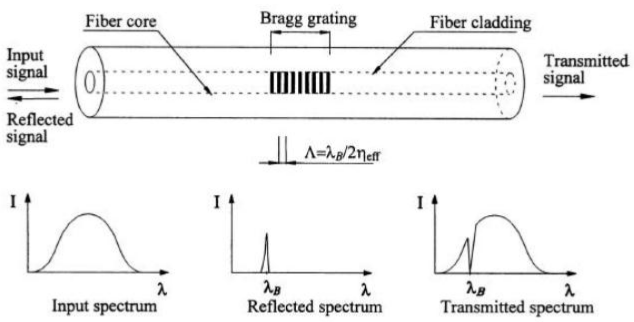

Fig. 1 Typical Refractive Index Profile on FBG [3]

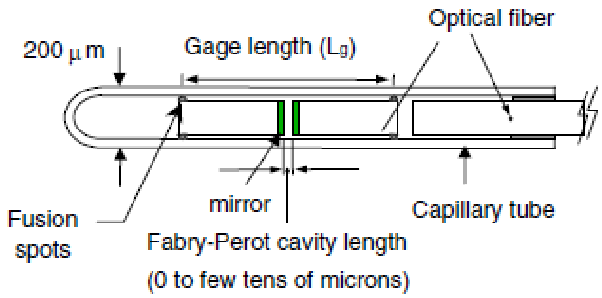

Fig. 2 Fabry-Perot Sensor [5]

the same up to the first mirror, which constitutes the start of the sensing region. Fabry– Perot cavity length (S) is formed between the air–glass interface of two fiber end faces aligned in a hollow core fiber. Variation in separation distance between the two fiber end faces, known as change in cavity length, cause interferometric fringe variations. The interference pattern generated is sinusoidal in shape and directly related to the intensity of the applied strain. The period of the wave form constitutes a fringe and by proper calibration, the magnitude of the strain can be determined.

The phase difference $\Delta\phi$ for light waves reflected from the front and rear surfaces of the Fabry–Perot interferometer can be expressed in the form

$$\Delta\phi = \frac{2\pi n(2S)}{\lambda}$$

where, n is mean index of refraction, S is Fabry–Perot cavity length and λ is wave length.

If λ_1 and λ_2 are the wave lengths of two consecutive fringe maxima produced by scanning the source wavelength (λ); the cavity length (S) can be expressed in terms of these two wave lengths

$$S = \frac{\lambda_1\lambda_2}{2(\lambda_2-\lambda_1)}$$

When the sensor is bonded to a substrate, the strain transferred to the sensor is converted into cavity length variation and the strain is given by the following equation

$$\text{Strain, } \varepsilon = \frac{\Delta S}{L}$$

Where, ΔS is change in cavity length and L is gage length. [7]

III. EXPERIMENTAL METHODS

A. Embeddment of Sensor

The embedment of sensor plays a major role in the results obtained from them at the end of the experiment. The fiber sensors are very small and fragile so without proper method of embedment the sensor will break and become useless. The lead wires from the sensor are also fragile and it also needs protection. This can be done by proper protective layer called encapsulation. The properties of this encapsulation can have a major influence on the life and functionality of the sensor. Hence selecting a suitable material as encapsulation is very important.

Kesavan et al., have carried out experiments to find the suitable procedures for embedding fiber optic sensors in concrete structures. Four different methods of encapsulation, namely, (i) using a pair of flat acrylic sheets, (ii) using liquid epoxy, (iii) using a pair of cast epoxy sheets and (iv) using a rod assembly, were attempted. The flat acrylic sheets as encapsulation gave results of lower strain response when compared with the conventional strain gage response. Experiments carried out using liquid epoxy have shown that this approach of encapsulation may not be satisfactory. The approaches of encapsulation using a pair of cast epoxy sheets and rod assembly were found to be satisfactory. In epoxy sheet a groove is cut in one sheet and sensor is placed inside and another sheet is placed above them. In rod assembly, sensor is bonded to the steel with welded end flanges. The steel rod is covered in such a way that the strain transfer takes place only through the end flanges. To test the efficiency of epoxy sheet and rod assembly, experiments were carried out on the cylinder along with four strain gages. The strain response obtained from embedded fiber optic sensors was compared with the average of the four conventional electrical resistance strain gage responses. The strains from both sensors were found to be within 2% variation. Experiments were also carried out under four point flexural loading on the beams along with the embedded sensor assembly at 30 mm from top and with strain gages. The strain responses from fiber optic sensor and electrical resistancestrain gages were found to be 7% variation[7].

B. Interfacial Strain

The strain which is induced between the concrete and the strengthening material is known as interfacial strain.

Arun Sundaram et al., have carried out an experimental investigation to understand the issues in placing the FBG sensor at the interface of concrete and Fiber Reinforced Polymer (FRP) to measure the interfacial strain. The experiment was carried out on two concrete prism specimens with 20 mm mild steel rod protruding from both the specimens and two Carbon Reinforced Polymer (CFRP) sheets. Two FBG sensors single and dual types were used. Single grating sensor will only sense strain at a point while the dual grating sensor will measure the debonding strain. Both the sensors were fixed on the specimen on either side in alternate manner. The CFRP sheets are fixed over the FBG sensors on both sides of the specimen using bonding agents. The electrical strain gages are fixed on the surface over the FBG sensors. The load is applied using universal testing machine and the sensor readings were measured by FBG interrogator. The test results showed that the FBG sensors provide good results regarding the debonding of the CFRP sheet when comparing to the electrical strain gages. With the multiple FBG sensor the initiation and propogation of debonding can be very well monitored in the FRP strengthened concrete structures.[1]

Kesavan et al., have carried out experimental studies to identify the initiation and propagation of CFRP debonding from concrete surface using FBG array sensors. They also studied issues and methods in application of FBG sensors for interfacial strain measurement of reinforced concrete beams strengthened with carbon fiber-reinforced polymer (CFRP) as shown in Fig.3. FBG array of five gratings at equal intervals bonded at the interface between Fiber Reinforced Polymer and concrete to monitor the initiation and propagation of the debonding. Two beams were cast and CFRP was bonded to the tension side of the beam and electrical resistance strain gage were bonded on the CFRP and subjected to static load. When load was applied through Universal Testing Machine the debonding of CFRP sheet happened from edge. The same test was repeated with the CFRP plate, it showed failure by peeling of the cover concrete. The CFRP sheet and CFRP plate was tested for the cyclic loading. The test results show that in CFRP sheet the failure was due to insufficient strength of adhesive between the sheet and concrete. The strain increased from edge grating towards the centre. The strain distribution occurs once a strain of 2700 $\mu\varepsilon$ was obtained. The debonding will occur from middle. In CFRP plate the failure occur due to separation of concrete cover. Since the plate act as a beam the strain in the middle is more from initial stage itself. The failure pattern is shown in Fig. 4. The numerical model was created using ABAQUS which showed the same results. The test results obtained from FBG is more accurate than the ERS when compared with the numerical results [9, 10].

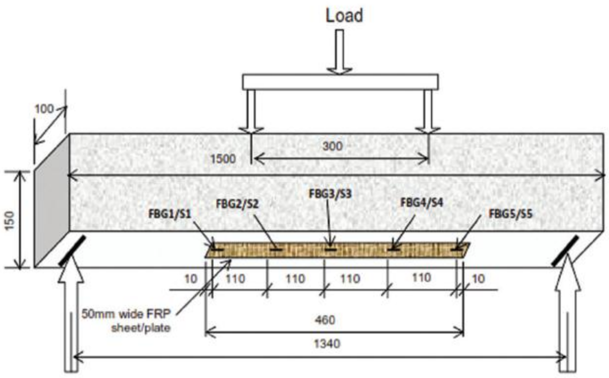

Fig. 3 Typical Instrumentation for Strengthened Beam [9]

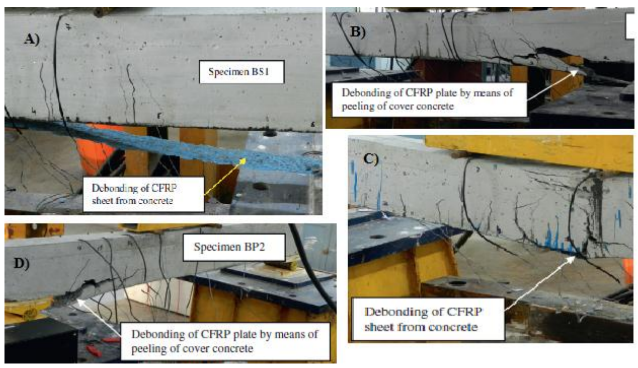

Fig. 4 Debonding Failure in beam with
A) CFRP Sheet subjected to Static Loading
B) CFRP Plate subjected to Static Loading
C) CFRP Sheet subjected to Cyclic Loading
D) CFRP Plate subjected to Cyclic Loading [10]

C. Apparent Strain

The apparent strain is induced in the structure due to the effect of temperature without any external load. The apparent strain due to thermal expansion has to be eliminated to obtain the exact mechanical strain in the structure.

Kesavan et al., have carried out experimental work using bonded and unbonded FBG sensors to determine the temperature curve since the FBG sensor was not temperature compensated so the strain obtained is combination of strain due to load and temperature. The experimental work was carried out to determine the apparent strain using materials like mild steel, concrete and CFRP. Incase of concrete and mild steel two FBG sensors were used. One bonded to specimen and other free along with a strain gage based temperature sensor. While for CFRP four FBG sensors are used along with strain gage based temperature sensor. Two FBG sensors are bonded in longitudinal and transverse direction respectively and remaining two unbonded. For mild steel and CFRP the total setup was placed in an oven and temperature was increased in steps. For concrete the specimen was placed in a water bath to avoid strain due to drying shrinkage and temperature was increased in steps. The readings were taken after the specimen was stabilised in that temperature. The apparent strain was obtained by subtracting the strain in unbonded FBG from the bonded FBG. The obtained apparent strain was compared with the electrical resistance strain gage. In FBG array one of the FBG should be left free to measure temperature effects. The temperature calibration curve for the concrete is shown in the Fig. 5[8].

D. Corrosion

Kesavan et al., have done an experiment on concrete cylinder specimens to determine the corrosion of reinforcement in concrete structures. 20 mm rebar of 200 mm length have been taken for the test and 10 mm length FBG was fixed in circumferential direction on the rebar. Two cylindrical specimens with M_{40} mix were cast by keeping the rebar at the center and after curing the specimens were kept in a water bath containing 3.5% Nacl solution to induce the accelerated environment. This was done to carry out the polarization test. After 50^{th} hour the strain have shown a constant increase in strain upto 170^{th} which indicates the initiation of corrosion and steep increase in strain between 170^{th} and 198^{th} hour indicates propagation of corrosion. After 198^{th} hour the sensor stops and visual cracks appear on the surface. The test have been verified by attaching 2 FBG sensors to a 20 mm rebar, one FBG is coated with epoxy and other FBG is uncoated. The three cylindrical specimens were cast with the instrumented rebar and kept in accelerated environment and the results shows that the uncoated FBG shows a variation in strain with time while the coated FBG shows constant strain [11].

Bharath kumar et al., carried out an experiment on three concrete cylinder specimens to study the effectiveness of fiber bragg grating in the study of corrosion. The specimens were kept in accelerated environment. After initiation of corrosion two specimens (Specimen 1 and Specimen 2) were removed and coated with epoxy coating to prevent further corrosion. Again the two specimens are placed in the tub and the reading from the sensor show that there is no change in strain which indicates the effectiveness of the sensor. The variation in strain due to corrosion and the strain due to protective method is shown in the Fig. 6 [2].

E. FBG Sensor on Live Structures

Chan et al., have conducted an study to investigate the feasibility of using the developed FBG sensors for structural health monitoring, via monitoring the strain of different parts of the TMB under both the railway and highway loads as well as comparing the FBG sensors performance with the conventional structural health monitoring system — Wind and Structural Health Monitoring System (WASHMS) that has been operating at TMB since the bridge’s commissioning in May 1997. The test was carried out at three locations in the bridge namely hanger cable, rocker bearing and truss girder. The Tsing Ma bridge consist of three lane road traffic on top deck and two lane railway line in the bottom deck. The sensor is properly protected by nitinol, Teflon sheets and ABC enclosures. The reading on the FBG sensor mounted on hanger cable clearly provides the train passing time and direction also. The FBG sensor and strain gauges on the rocker bearing provides the similar results and the train passing time was clearly detected. The total results are obtained in the form of strain which provides the effective functioning of the bridge. Since the sensor would not undergo deformation they can be used for long term monitoring of the structure [4].

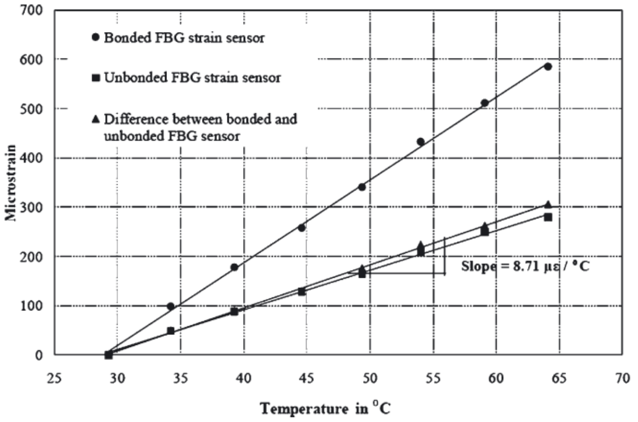

Fig. 5Temperature Calibration Curve for Concrete [8]

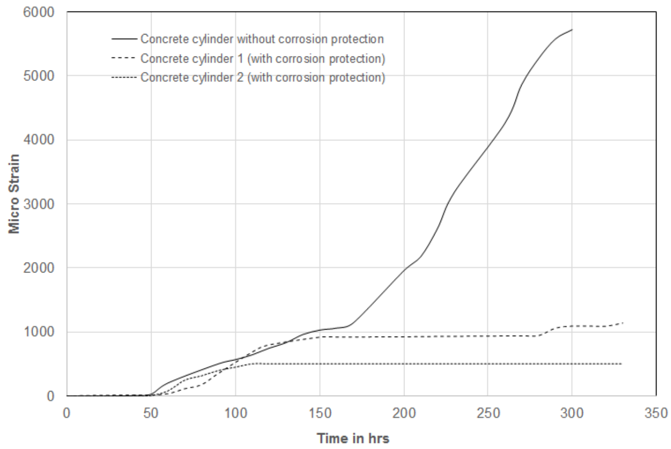

Fig. 6 Strain vs Time graph [2]

Mufti et al., have conducted an experiment to monitor the health of the confederation bridge in Canada. The fiber optic bragg grating sensors were bonded to the instrumented rebar of 2 m length and the instrumented rebars were connected to the structural rebars. The three sensors were connected to the girder and two more sensors were connected between the girders (near the junction). The temperature compensation is done by either a thermocouple or a strain decoupled fiber optic sensor. The data acquisition system was employed at the site while the monitoring is done at remote location by using radio signals or fiber optic cables. The bridge was continuously monitored for static and dynamic loads. The test was conducted to found that whether the bridge can satisfy its expected life time by continuous using FBG sensor [12].

Idriss et al., have conducted an experiment on the full scale model of the bridge structure by using a multiplexed bragg grating sensor and the results were compared with the results of strain gages and bragg grating. The test bridge is a 40 ft span non-composite steel girder concrete deck bridge. The girder layout is shown in the Fig. 7. The network of sensors is used to measure the strain throughout the bridge, with sensors bonded to the tension steel in the slab and attached to the bottom flange of the girders. Resistive strain gages and Bragg grating sensors are placed side by side to compare results. The strain data are obtained for the pristine structure and then damage is introduced at midspan for an exterior girder. Several levels of damage in the form of cuts in one of the girders are imposed with the final cut resulting in a half depth fracture of the girder. At each level of cuts the response of the sensor near the cut changes drastically. At final cut (half depth fracture) the sensor showed very drastic change, since the concrete slab was placed on top of steel girder a composite action would takes place. Hence sensors were embedded inside the slab also and the sensor in the slab at the cut shows very high strain rates. The test results showed the system to be a powerful bridge diagnostic tool. When damage was introduced in the bridge, the monitoring system recorded a definite change in the structure's response. It indicated damage had occurred, along with the time and the location of the damage. The time of occurrence corresponds to the time the change in condition was recorded. The crack location could be determined from the actual response of the structure. When observing the change in the response of the bridge the slab indicated damage in the bridge at the vicinity of cross section C. The girder response indicated damage in the east girder where the loss in load occurred. The change in response was most accentuated at the vicinity of the crack. The larger the damage, the greater would be the response from the system [6].

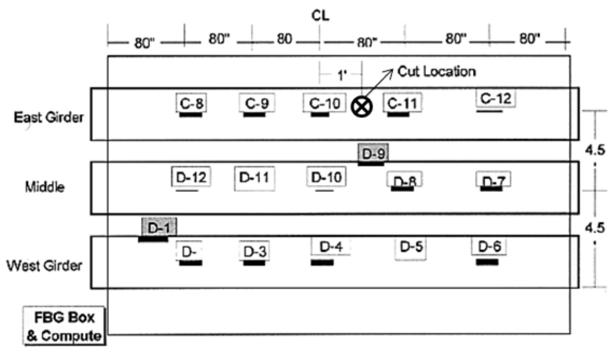

Fig. 7 Girder Layout [6]

- The sensors have to be embedded properly by compatible packaging.
- By studying the interfacial strains between concrete and strengthening material (CFRP sheet and Plate) we can clearly understand the debonding mechanism.
- The method to determine the apparent strain using FBG sensor is clearly explained which is useful to carry out the correction in actual measurement.
- The method to determine the corrosion of reinforcement using FBG sensor is explained and the effect of corrosion protection using FBG measurement also explained.
- The effect of FBG sensor on the live structure (concrete and steel girders) is clearly explained.

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