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## Monitoring of Corrosion in RC Structures Using FBG Sensor

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**ABSTRACT:** Monitoring embedded steel bar corrosion is one of the important factors affecting the long term durability and can cause serious damage to RC structure when subjected to high chloride environment. Monitoring concrete structures is important for structural health monitoring (SHM). FBG sensors are reported a viable option for SHM of structure and advantage of multiplexing, strain sensing, temperature sensing and corrosion monitoring. This paper reports the experimental studies conducted to identify corrosion at initial stage possible and prevent corrosion and prolong service life of structure. This paper also presents the viability and effectiveness of FBG sensor for corrosion monitoring under accelerated corrosion.

**KEYWORDS:** FBG sensor; corrosion monitoring; accelerated corrosion test.

### 1. INTRODUCTION

Corrosion of reinforcing steel due to chloride contamination can result in considerable reduction in service life of concrete structures. In general, corrosion is of most concern because of the associated reduction in steel cross-sectional area, cracking, spalling of cover concrete and loss of bond, which over time will lead to reductions of strength and serviceability of structures.<sup>[1]</sup> Cracks play an important role in promoting and accelerating corrosion process. Cracks can causes aggressive agents to come in direct contact with the reinforcing bars in high amount over a small area which is the factor in promoting intense pitting corrosion of rebar. Today SHM is mostly done through visual or periodic inspection. But the environment is changing rapidly and can cause corrosion at any time than anticipated and corrosion in RC structures can only be identified visually when cracks are formed on surface which is very difficult to repair. But finding the corrosion at initiation can help in prevention of corrosion further. So continuous monitoring of corrosion in concrete structures is very essential. In this paper the performance of FBG sensor embedded with rebar in concrete has been studied before and after coating of epoxy paint is studied and proper instrumentation of rebar with FBG has been discussed.

### II. FIBER BRAGG GRATING (FBG) SENSOR TECHNOLOGY

In fiber optic sensor, when light is sent through the optical fiber the properties of light such as wavelength, intensity etc. are changed in response to a physical phenomenon. Fiber Bragg Grating sensor is basically a wavelength dependent spectral filter that reflects particular wavelengths of light near Bragg resonance wavelength while the rest of the optical spectrum is transmitted (Fig.1). The signal that gets reflected will be narrow and will be within the range of Bragg wavelength. The fiber gratings are formed by introducing a periodic change in the refractive index of the fiber core in the direction of propagation of the optical light by subjecting it to ultraviolet radiations. The center wavelength of the reflected optical spectrum is defined by the Bragg condition as:

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$$\lambda_B = 2\Lambda_B n_{\text{eff}} \quad (1)$$

where,

$\lambda_B$  - Bragg resonant wavelength ,

$n_{\text{eff}}$ - effective refractive index ,

$\Lambda_B$  - grating period

When any change occurs in the strain, it induces a change in the grating pitch of the fiber which in turn causes a shift in the Bragg wavelength. This property of the FBG is used in sensing applications.

$$\varepsilon = \frac{\Delta\lambda_B/\lambda_0}{(1-Pe)} \quad (2)$$

Where  $\varepsilon$  – Strain,  $\Delta\lambda_B$ - change in Bragg wavelength;  $\lambda_0$ - initial wavelength;  $Pe$ -photo elastic coefficient of the fiber.

$$\varepsilon = \frac{\Delta\lambda_B/\lambda_0}{(1-Pe)} = \frac{\Delta D}{D} \times 10^6(\mu\varepsilon) \quad (3)$$

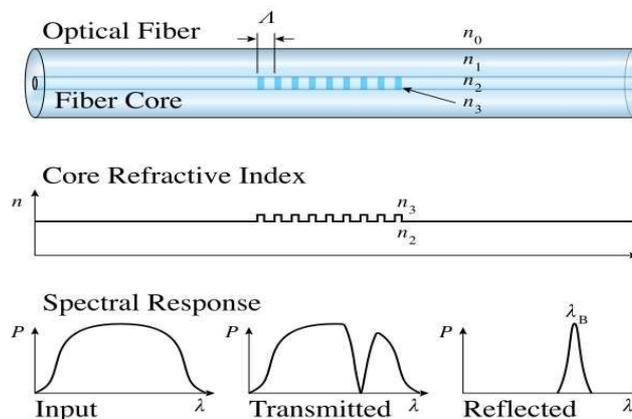


Fig1: Light spectra of a Fiber Bragg Grating sensor

### III. FIBER BRAGG GRATING SENSOR METHODOLOGY FOR CORROSION MONITORING

This methodology is based on the fact that the diameter of rebar will increase due to corrosion and hence the volume of the rebar increases, which in turn induces strain in a FBG sensor firmly wound on the reinforcement along its circumference. This induced strain is sensed by the shift in wavelength of the FBG sensor. Based on this a corrosion sensing methodology is designed using FBG sensors to detect the process of corrosion such as initiation and propagation of corrosion in reinforcements embedded in concrete structures. The wavelength from sensor can be converted to strain using equation 3. The percentage increase in steel volume can be calculated by using equation 5. From equation 4 we can relate the percentage increase in rebar with respect to volumetric change of the rebar.

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Hence,

$$\Delta D = \frac{D \times \frac{\Delta \lambda b}{\lambda_0}}{(1 - P_e)} \times 10^{-6}$$

$$\rho = \frac{\Delta V}{V} = \frac{(D + \Delta D)^2 - D^2}{D^2} = \left[ 1 + \frac{\Delta D}{D} \right]^2 - 1 \tag{4}$$

$$= (1 + \epsilon)^2 - 1$$

$$\rho = \left( 1 + \frac{\Delta \lambda b / \lambda_0}{(1 - P_e)} \right)^2 - 1 \tag{5}$$

Where,  $\rho$ - percentage increase in steel volume. The corrosion intensity can be obtained from equation.

## IV. LABORATORY STUDIES

Laboratory studies were carried out to evaluate the developed methodology for corrosion monitoring. The reinforcement bar chosen in this study is HYSD steel rods of 20mm diameter and 200mm length. One half of the reinforcement is cleaned and prepared for bonding the sensor. The FBG sensor was fixed on the steel rod along the circumferential direction at a distance of 50 mm from bottom. FBG sensor is bonded to the Rebar with available bonding agent. It is to be ensured that the sensor is bonded firmly to the surface of the reinforcement. The sensor is then protected with a layer of silicon rubber coating to prevent any undesirable damage that might occur during pouring and vibration of concrete. The cross sectional view of the instrumented reinforcement bar is as shown in Fig. 2. The sensor chosen here is of gauge length 10mm and wavelength 1540nm. Fig. 3 shows the instrumented rod. After bonding the sensor, the rod was vertically embedded in the middle of the concrete cylinder specimen. During casting, pouring of concrete was done carefully to ensure that the FBG sensor or FC/APC connectors does not get damaged as shown in Fig.4. Three cylindrical specimens of height 200mm and diameter 100mm were cast for the study.

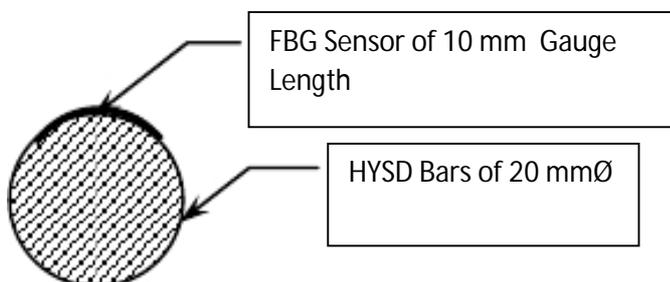


Fig. 2 Cross Sectional View of the Instrumented Rebar

Fig. 3 FBG instrumented rebar

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Fig.4 Embedding of FBG instrumented rebar

M40 grade concrete with the mix ratio of 1:2.25:2.35 (cement: fine aggregate: coarse aggregate) was used to cast the cylinders. The cement used is Ordinary Portland Cement (OPC) of grade 53. The fine aggregate used is medium sand and the coarse aggregate is of 10mm size. The water/cement ratio adopted is 0.5 to obtain high workable concrete and reduce vibration of concrete. After curing, the instrumented cylindrical specimens were subjected to Accelerated Corrosion Test. This test was done by first placing the specimens in a water basin containing salt saturated water, i.e. 3.5% NaCl solution (Fig.5).



Fig. 5 Accelerated corrosion test set up

The specimens are kept in this state for 7 days till the specimen becomes fully saturated in the NaCl solution. After the specimens are fully saturated, the rod exposed in each cylinder was connected to an electrical circuit which acting as the anode and a steel metal plate acting as the cathode. A constant DC supply of 10V was applied. This set up was used to accelerate the corrosion process. The schematic diagram of accelerated corrosion test set up is shown in Fig.6

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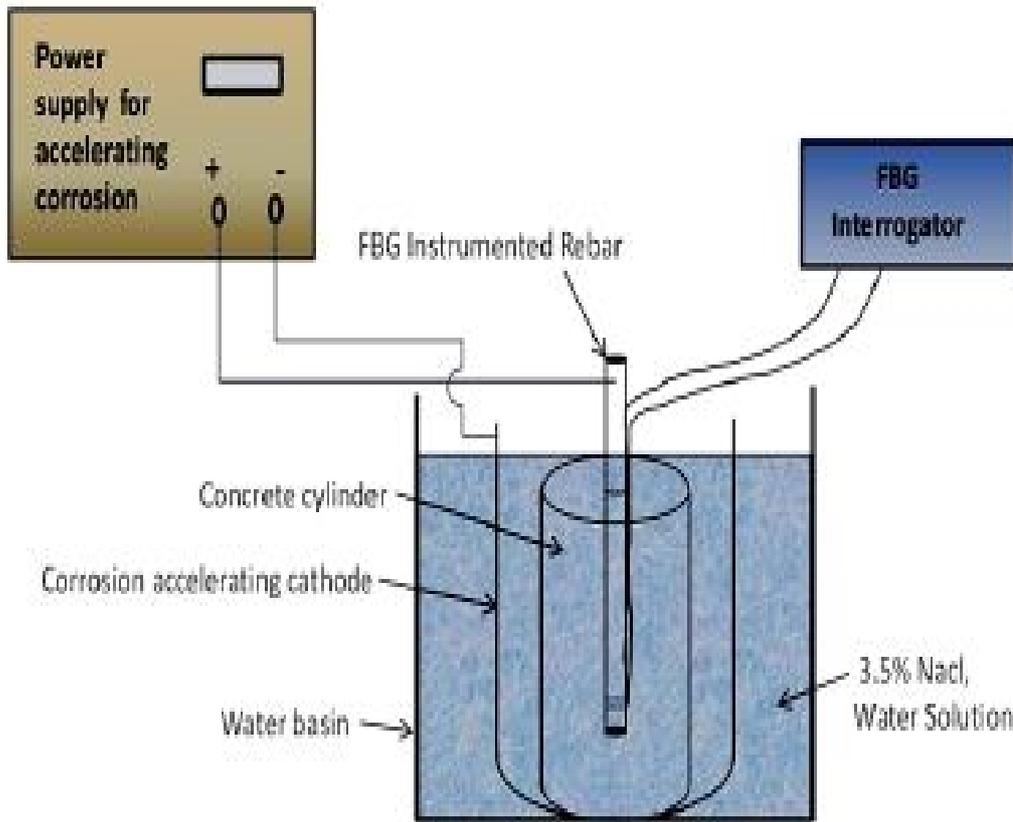


Fig. 6 Schematic Illustration of Accelerated Corrosion Test Set up

The wavelength values are measured from the FBG sensors in each cylinder at regular intervals using an FBG interrogator. Here SM130 optical Sensing interrogator and Micron Optics ENLIGHT software is used for monitoring. Any deviation in the wavelength from the Bragg wavelength range is detected as the initiation of corrosion in the reinforcement bar. When the sensor stops giving any reading, it is considered that the FBG sensor has broken due to the excessive tensile stresses. At this level cracks will appear on the surface of the concrete specimen due to the increase in diameter of the reinforcement as shown in Fig. 7. The strain developed in the each concrete specimen, measured from the FBG sensor can be used to identify the corrosion process and the control specimen is left in accelerated corrosion set up until failure of FBG sensor but specimen 1 and 2 are taken out of accelerated corrosion after initiation of corrosion and the concrete is applied with Epoxy coating to stop further ingress of chloride ion into concrete as shown in Fig 8. For treatment of concrete first a primer coat is applied to concrete and after curing of primer a layer of epoxy coating is coated to concrete and after setting of epoxy on primer coat the specimens are again kept in accelerated corrosion to verify whether ingress of chlorides have been stopped or it still cause corrosion as shown in Fig 9.



Fig. 7 Control Specimen after Cracking



Fig: 8 Specimens Treated with Epoxy Coating and Control Specimen



Fig 9: Accelerated corrosion of specimen 1 & 2 after Epoxy Coating

## V. RESULTS AND DISCUSSIONS

The wavelength values obtained from the FBG sensor were converted in to strain by using Eq. 2 and the variation in strain vs time was plotted for all the specimens as shown in Figure 10. It was seen that there was no considerable variation in the strain in the sensor till the 50<sup>th</sup> hour for all the specimens. After the 50<sup>th</sup> hour, the strain value showed a constant increase for all the specimens which clearly indicates the occurrence of corrosion in all the specimens. After 50<sup>th</sup> hour the control specimens is left in Accelerated corrosion and Specimen 1&2 are taken out of Accelerated corrosion. It was seen that there is a constant increase in strain in the control specimen upto 180<sup>th</sup> hour and after 180<sup>th</sup> hour there was rapid increase in strain values at this stage cracks are visually identified on the surface after 280<sup>th</sup> hour

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there was drop in strain values which indicates the collapse of concrete and release of tensile stress developed after 325<sup>th</sup> hour the sensor of control specimen stopped reading. At this stage, the cylinders have completely cracked. Though specimen 1 and 2 are taken out of accelerated corrosion there is some increase in strain values upto 75<sup>th</sup> hour due to the presence of chlorides in pore structure of concrete and presence of moisture, oxygen and carbon di oxide makes way for carbonation and thus cause corrosion. Between 50<sup>th</sup> and 95<sup>th</sup> hour the specimens are coated with epoxy. At 95<sup>th</sup> hour the specimen 1 &2 are kept again in Accelerated corrosion. It was seen that after 100<sup>th</sup> hour the steep increase of wavelength in specimens has marginably decreased and almost became constant in specimen 1 &2 which indicates the control of corrosion process in rebar. It is seen that, the point of initiation of corrosion for all the specimens were identical. It is also seen that the value of strain is different in the specimens and it is due to the fact that the maximum thrust may occur anywhere in the rebar depending upon the formation of corrosion cell and since the location of sensor is predetermined i.e. 50 mm from bottom of rebar it is not necessary maximum corrosion occur at the location of sensor.

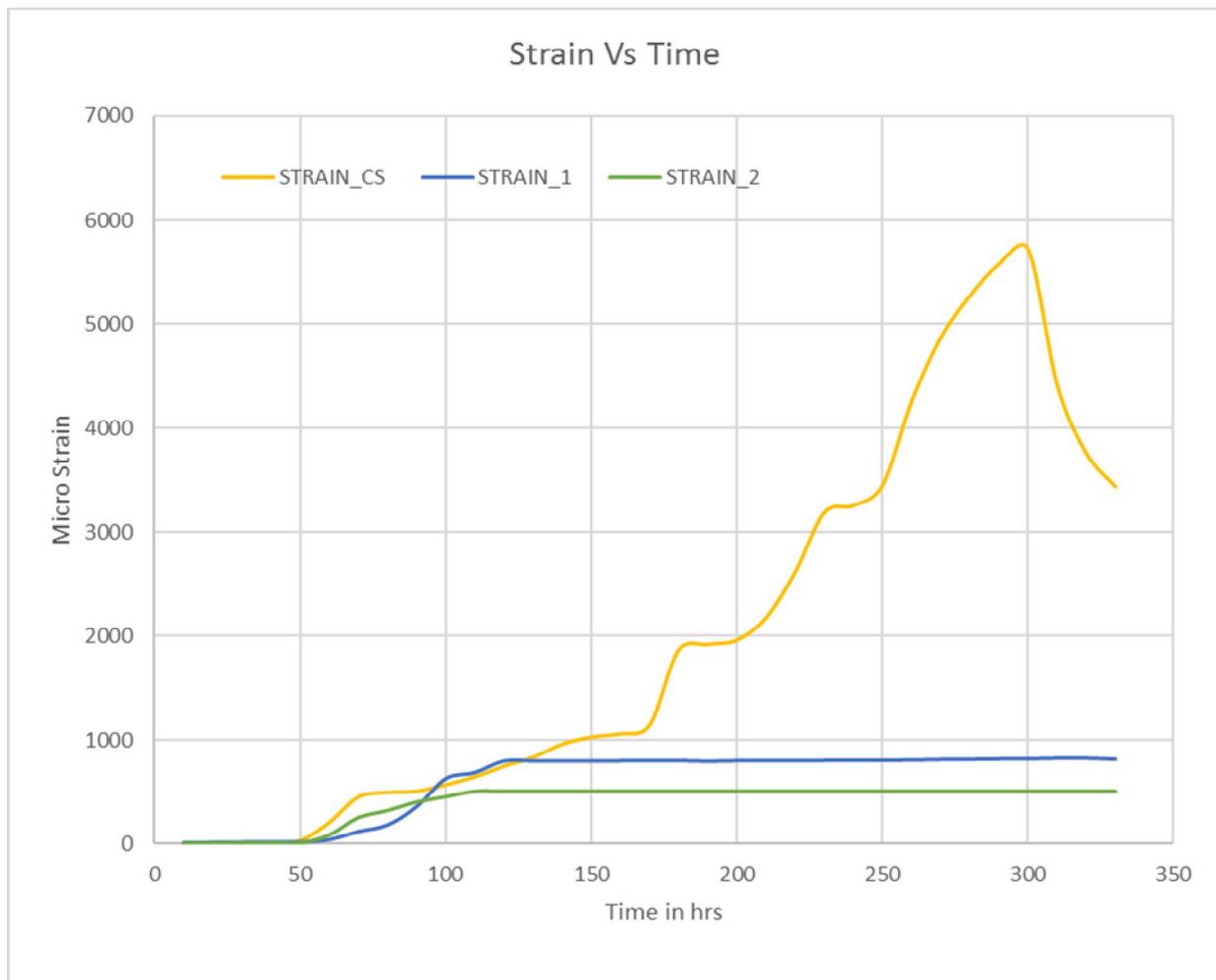


Fig 10: Strain v/s time graph for Specimens 1,2 and control

### 5.1 Verification of methodology

In order to verify that the strain sensed by the FBG sensor is only due to the occurrence of corrosion in the rebar, an experimental study was carried out. Two FBG sensors were instrumented on 20mm diameter HYSD steel rod, one of the sensors (FBG-t) was bonded on the rod and covered with a layer of epoxy coating to prevent the occurrence of

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corrosion in that portion of the rebar and the other FBG sensor (FBG-b) was bonded at the location of occurrence of corrosion (Fig.11). One specimen is casted by instrumenting HYSD steel rod embedded in concrete cylinder. The instrumented cylinder is subjected to accelerated corrosion by using 3.5% NaCl solution and supplying constant voltage. The wavelength values obtained from both the FBG sensors (FBG-t and FBG-b) were recorded at regular intervals. The variation in strain response with respect to time for both the sensors was obtained (Fig.12). It was seen that the sensor coated with epoxy (FBG -t) develops much lower response (almost negligible) which shows that no corrosion has occurred whereas the sensor FBG-b shows continuous variation in the strain value. The variation in strain values in FBG-b shows that corrosion can be sensed by the FBG sensor at that region of the rebar. Hence FBG sensor is a viable technique for monitoring corrosion in reinforced concrete structures.

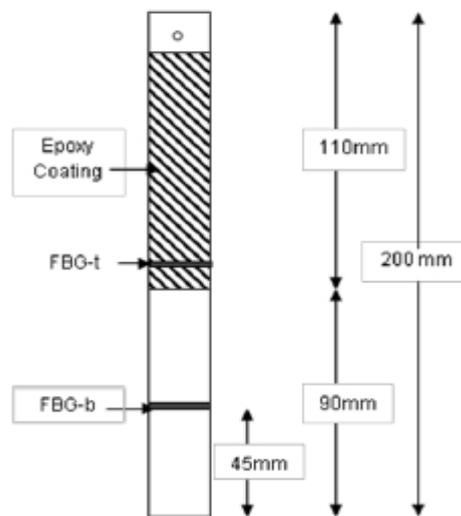


Fig. 11 Instrumentation Details of HYSD Rod for Verification of Methodology

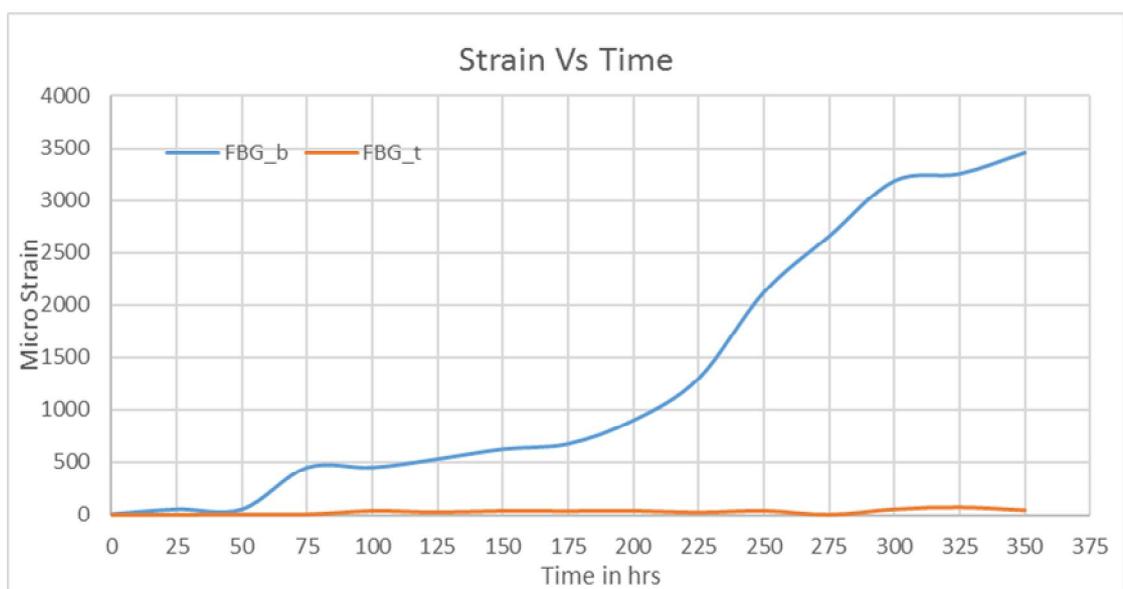


Fig.12 Typical sFig 12: strain vs time graph from verification test

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## VI. CONCLUSION

- 1) Continuous Corrosion monitoring has successfully been conducted on the concrete specimens instrumented with HYSD rod using FBG sensor and the feasibility of the methodology was verified.
- 2) This corrosion sensing methodology can be applied in field measurements for structural health monitoring as it gives useful data for health assessment of RCC structures.
- 3) This technique of corrosion monitoring, was found to be easy to identify the point of initiation of corrosion in reinforced concrete structure and this will be useful to prevent corrosion by applying suitable epoxy coating on concrete surface and further the corrosion was monitored using the FBG sensor.
- 4) The performance of FBG sensor under Accelerated corrosion was good and can be used for corrosion monitoring under high chloride environment.
- 5) To get more accurate results Multi array FBG sensors are recommended for corrosion monitoring of RC structures.

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