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Fiber Bragg Grating sensors for monitoring corrosion of reinforcement in concrete structures

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Abstract : Structural health monitoring involves timely detection of distress in civil engineering structures and implementation of suitable corrective procedures to prevent its failure and extend its service life. Embedded steel bar corrosion is one of the serious damage occurring in a RCC structures subjected to chloride attack during its service. Corrosion of embedded steel bars leads to increase in volume, which in-turn cause bulging and induces thrust to the cover concrete leading to spalling of concrete. This paper reports the experimental studies conducted on the identification of corrosion with the development of a new methodology to identify corrosion using FBG sensors

Keywords : FBG sensor; Reinforcement corrosion monitoring; Strain, Accelerated corrosion test.

INTRODUCTION

Damage occurring in concrete structures due to corrosive environment is a major concern, especially in structures adjacent to the sea. Corrosion and cracking of concrete structures will lead to distress/damage. The detection of corrosion at the initial stage is an important factor in structural health monitoring/condition assessment. There are many traditional methods available in corrosion detection such as half-cell potential method, linear polarization resistance method etc[1]. These techniques of corrosion detection are electro-chemical in mechanism. But these methods have certain disadvantages which limits their application in the field.

The most recent and feasible technology of corrosion detection in concrete structures is by using Fiber Bragg Grating (FBG) sensors. Among the different fiber optic sensors available, FBG sensors have been reported to be most effective in monitoring of reinforced concrete structures. This paper gives the details of the experimental study carried out in the development of a methodology for corrosion detection in reinforced concrete structures using FBG sensors.

FIBER BRAGG GRATING (FBG) SENSOR TECHNOLOGY

In any fiber optic sensor, the principle is that 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 (Figure 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:

$$\lambda_B = 2\eta_{eff}\Lambda \quad (1)$$

where λ_B - Bragg resonant wavelength; η_{eff} - effective refractive index; Λ - 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.

Fiber Bragg Grating sensors find usage in various sensing applications. They are used in the monitoring of various civil structures such as highways, buildings, bridges, dams etc. FBG also finds application in remote sensing, mainly used in pipelines, bridge structures etc. They are also used in smart structures like aircraft wings and ship hulls in sensing changes in various factors such as pressure, strain and temperature.

Fiber Bragg Grating sensor can most favorably used in corrosion sensing applications due to a number of positive aspects. Some of the main factors influencing the selection of the FBG sensor in corrosion monitoring are lightness, micron size transducers and its immunity to corrosion and electromagnetic interference. Also they can be easily embedded or surface mounted and are able to withstand harsh environmental and structural conditions. Another influencing factor is the ability to distribute multiple sensors on a single fiber.

LITERATURE REVIEW

Junqi Gao[2] developed a Fiber Optic Corrosion Sensor (FOCS) for reinforcement corrosion detection. This sensor was devised from one FBG sensor and twin steel rebar elements packaged up with concrete. Five such FOCSs were subjected to constant current accelerated corrosion test. A Fiber Optic Temperature Sensor (FOTS) was also proposed to compensate for the temperature effect. An optical spectrum analyser was used to monitor the outputs of FOCS and FOTS. Here a relationship is obtained between the reflected wavelength change from the grating and the rate of weight loss of the rebar, by gravimetric weight loss method. Thus, the experiment showed that it is feasible to use FOCS in monitoring the degree of corrosion of steel in reinforced concrete structures. Wenbin Hu[3] developed a steel corrosion sensor based on FBG. This sensor was devised by electroplating a Fe-C coating on a metallised FBG. The main principle involved is that the rusting reaction induces a longitudinal change in the sensing film. This in turn results in a Bragg wavelength shift which is detected using a spectrometer. Optical microscopy and SEM imaging are used to evaluate the micro structural changes. To eliminate the effect of temperature, FBG sensor without Fe-C coating was used as the reference sensor and is always installed close to the test sensor to minimize the temperature difference. The testing of sensors was conducted in accelerated corrosion cabinets containing sodium chloride solution.

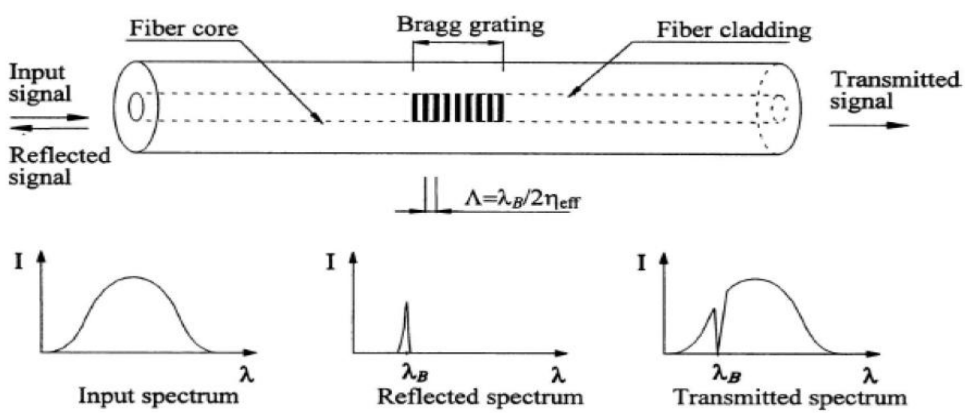

Figure 1 : Light spectra of a Fiber Bragg Grating sensor

Changes occurring in the spectra and structure of sensor are analyzed. Multiple peaks are observed in the spectra when the sensing film cracks, it indicates severe corrosion. When the corrosion occurs, the dense structure of the coating film turns into a porous structure loosely packed on the FBG. As the corrosion proceeds, the coating cracks and peels off from the FBG. Thus by this study, it is shown that this sensor is sensitive to corrosion of the metallic coating film. Grattan[4,5] made use of fiber optic sensors in monitoring the production of corrosion by products. This paper provides an evaluation on the suitability of using fiber optic sensors in corrosion monitoring and it compares the output results of the strain FOS and a standard Electrical Resistance Strain (ERS) gauge, attached to a steel reinforcement bar embedded in concrete. The aim of this experimental work was to determine the possibility of measuring or monitoring any localized strain induced due to the corrosion process. Leung et al.[6] developed a low cost sensor for monitoring corrosion based on a very simple physical principle. In this technique, the flat end of a cut optical fibre is coated with a thin iron film. The fibre is then embedded in concrete. The signal that gets reflected when light is sent through the fibre is monitored. Initially most of the light signal gets reflected. But later on as corrosion of the iron layer occurs, the reflected signal will get reduced. Hence, this principle can be effectively utilized in corrosion monitoring of steel.

FIBER BRAGG GRATING SENSOR METHODOLOGY FOR CORROSION MONITORING

Zheng[7] developed a corrosion monitoring technique for reinforced concrete structures using FBG sensors. This methodology is based on the fact that the diameter and hence the volume of the rebar increases due to corrosion, 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 values obtained from the sensor are detected and analyzed using an interrogator. An interrogator records the variations in wavelength of the light passing through the sensor. This measured value of wavelength can be used to relate the strain using the following relationship:

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

where ε–strain; $\Delta\lambda_B$–change in Bragg wavelength; λ_0–initial wavelength; p_e–photo elastic coefficient of the fiber

The relation between the geometry of the bar and the strain in FBG sensor is given by the following equation:

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

Hence,

$$\Delta D = \frac{D \times \Delta\lambda_B / \lambda_0}{(1-p_e)} \times 10^{-6} \tag{4}$$

where D – diameter of the reinforcement; ΔD – increase in diameter of the reinforcement

$$\rho = \frac{\Delta V}{V} = \frac{(D+\Delta D)^2 - D^2}{D^2} \tag{5}$$

$$= \left(1 + \frac{\Delta D}{D}\right)^2 - 1 \quad = (1+\varepsilon)^2 - 1$$

$$= \left(1 + \frac{\Delta\lambda_B / \lambda_0}{(1-p_e)}\right)^2 - 1 \tag{6}$$

where ρ - percentage increase in steel volume

The corrosion intensity can be obtained from Eqn. 6.

LABORATORY STUDIES

Laboratory studies were carried out to evaluate the developed methodology for corrosion monitoring. The reinforcement bar chosen in this study is mild 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. 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 epoxy coating to prevent any undesirable damage that might occur during pouring of concrete. The cross sectional view of the instrumented reinforcement bar is as shown in Figure 2. The sensor chosen here is of gage length 10mm and wavelength 1540nm. Figure 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 does not get damaged as shown in Figure 4. Two cylindrical specimens were cast for the study.

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. After curing, the instrumented cylindrical specimens were subjected to polarization test under constant voltage[8]. This test was done by first placing the specimens in a water basin containing salt saturated

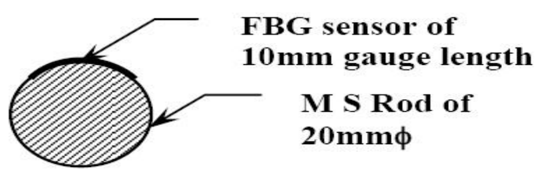

Figure 2 : Cross sectional view of the instrumented rebar

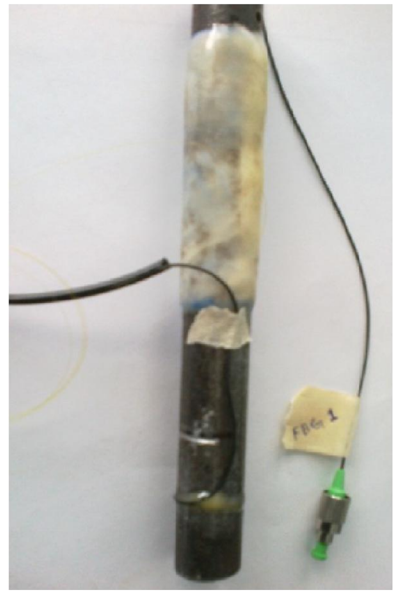

Figure 3 : FBG instrumented rebar

Figure 4 : Embedding of FBG instrumented rebar

Figure 5 : Accelerated corrosion test set up

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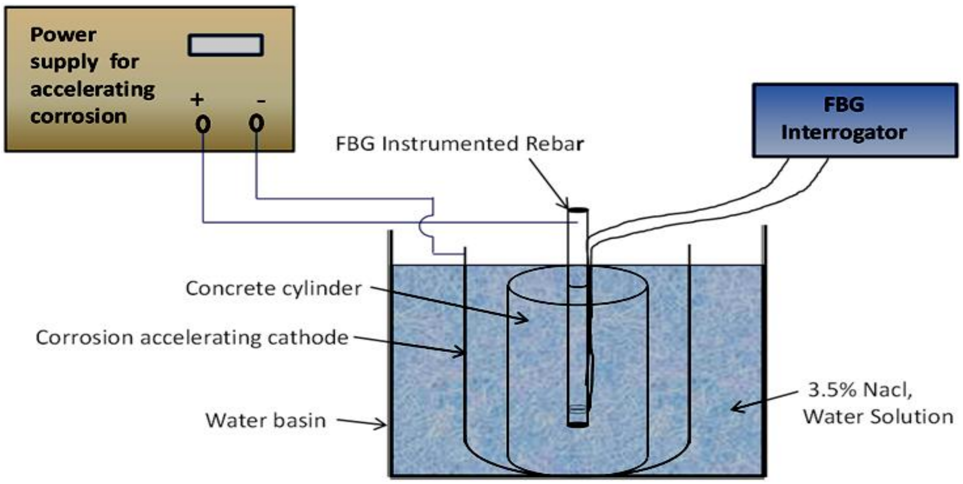

Figure 6 : Schematic illustration of accelerated corrosion test set up

water, i.e. 3.5% NaCl solution (Figure 5).

The specimens are left in this state for another 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 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 Figure 6.

The wavelength values measured from the FBG sensors in each cylinder at regular intervals using an FBG interrogator. 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.

Figure 7 : Concrete specimen after cracking

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 Figure 7. The strain developed in the each concrete specimen, measured from the FBG sensor can be used to identify the corrosion process.

RESULTS AND DISCUSSIONS

The wavelength values obtained from the interrogator were converted in to strain by using Eq. 2 and the variation in strain vs time was plotted for both the specimens as shown in Figure 8. It was seen that there was no considerable variation in the strain in the sensor till the 50th hour for both the specimens. After the 50th hour, the stain value showed a constant increase up to 170th hour for both the specimens. After 170th hour there is a steep increase in strain value till 213th hour for specimen 1 and 198th hour for specimen 2 when the interrogator stopped recording strain values, i.e. the FBG sensor has become inactive. At this stage, the cylinders have completely cracked. It is seen that, the point of initiation of corrosion for both the specimens were identical. The initiation of cracking was also seen to be identical.

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 dia mild steel rod,

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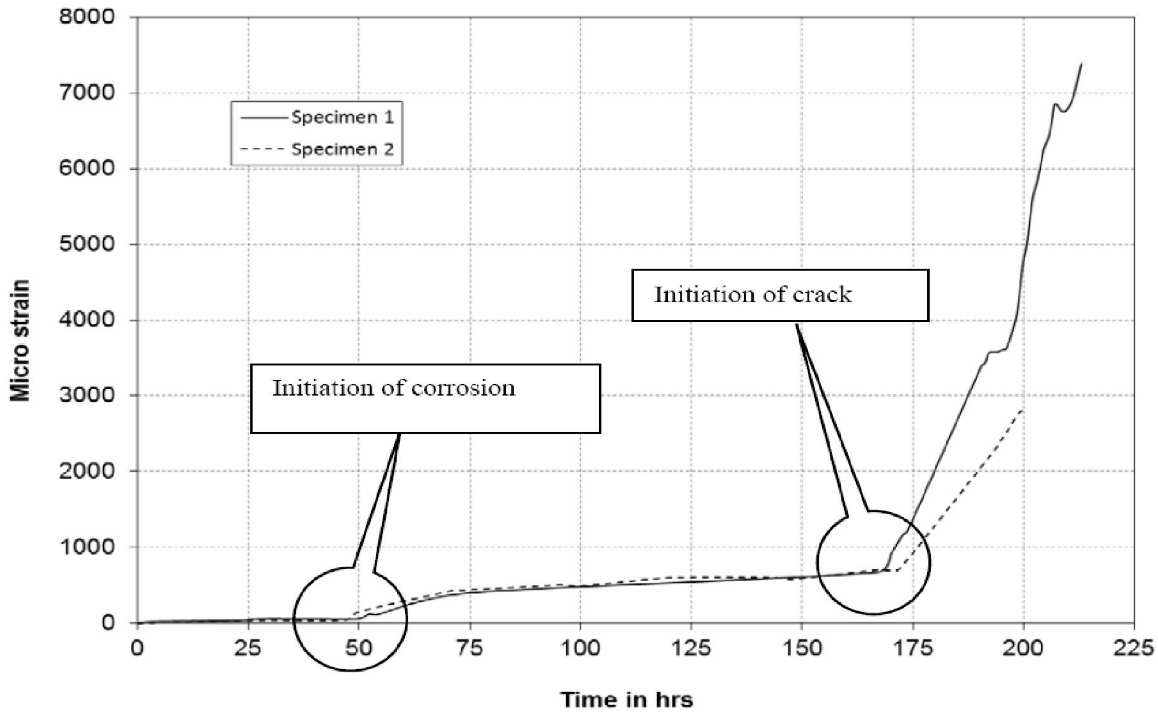

Figure 8 : Strain v/s time graph for specimens 1 and 2

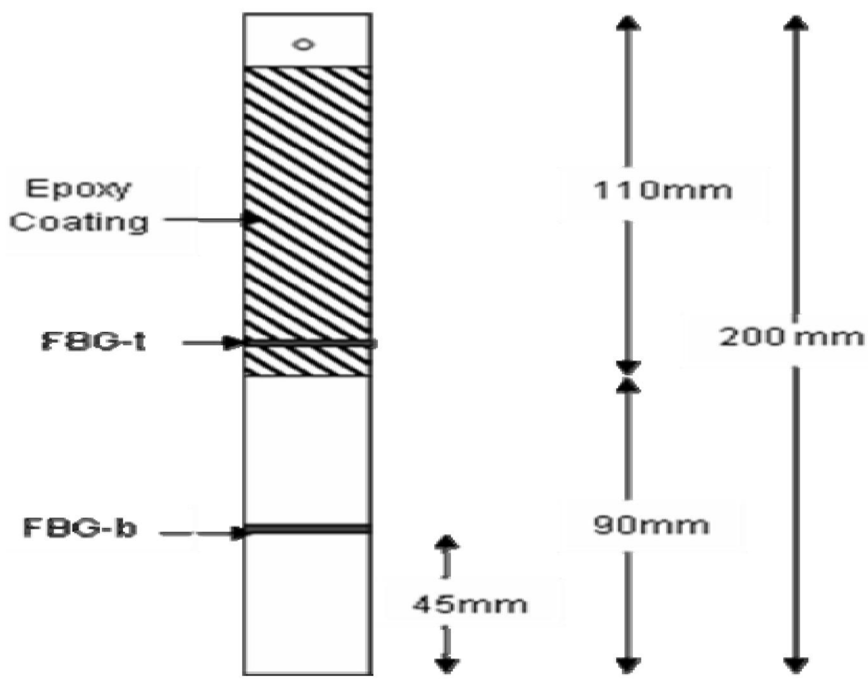

Figure 9 : Instrumentation details of MS rod for verification of methodology

one of the sensors (FBG-t) was bonded on the rod and covered with a layer of epoxy coating to prevent the occurrence of corrosion in that portion of the rebar and the other FBG sensor (FBG-b) was bonded at the location of occurrence of corrosion (Figure 9). Three specimens were cast by instrumenting mild steel rod embedded in concrete cylinder. The instrumented cylinders were 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 (Figure 10). It was seen that the sensor coated with epoxy (FBG –

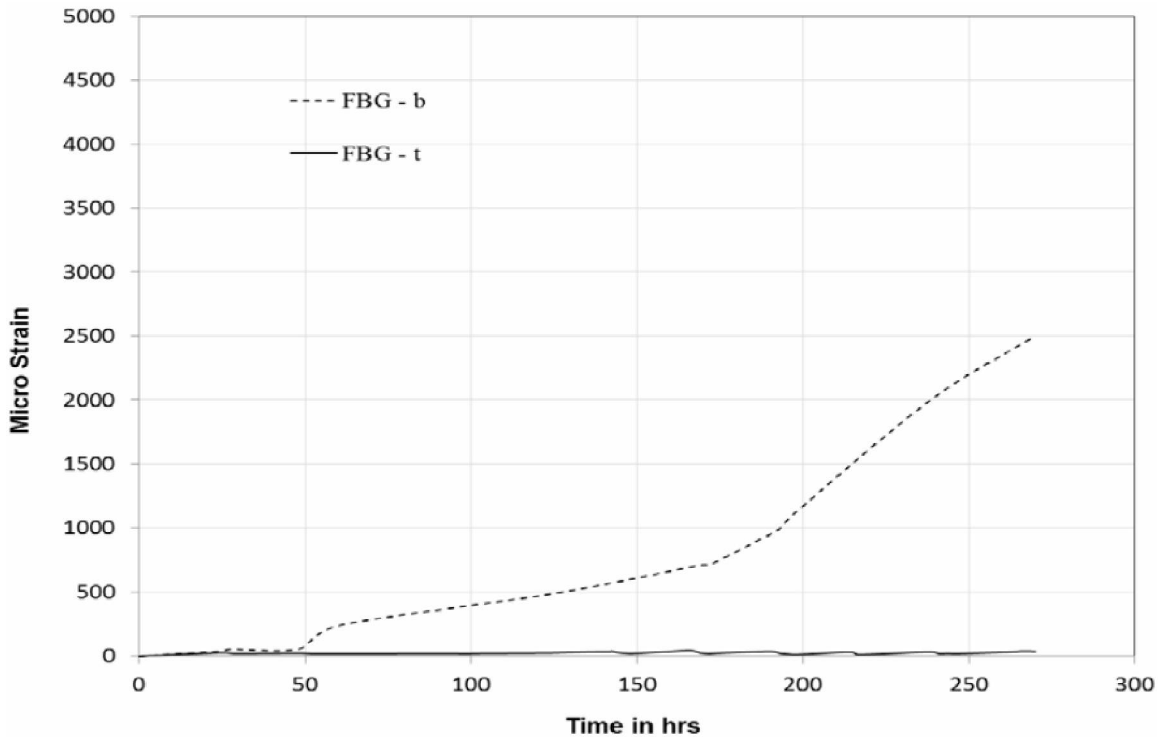

Figure 10 : Typical strain vs time graph from verification test

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.

CONCLUSION

The following salient conclusions are drawn from the limited studies carried out:

- A novel methodology was developed for monitoring of corrosion of reinforced concrete by using FBG sensors.
- Experimental studies shows that the suitability of FBG sensors to identify corrosion activity in reinforcement in RCC structures.
- Corrosion monitoring has successfully been conducted on the concrete specimens instrumented with rod using FBG sensor and the feasibility of the methodology was verified.
- 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.
- This technique of corrosion monitoring, was found to be easy to identify the point of initiation and propagation of corrosion in a reinforced concrete structure and this will be useful in minimize further damage to the structure.
- This corrosion monitoring method also verified by conducting experiments and it is concluded that, the continuous variation in strain values in FBG sensor shows that corrosion has occurred at that region of the rebar and is being sensed due the volumetric change of the rebar only
- It is also noted that the point of initiation of corrosion and the point of starting of corrosion propagation in both the specimens are almost coinciding.
- Monitoring of corrosion is an essential part of structural health monitoring and necessitates the proper instrumented facilities for identifying the corrosion at the earliest in RCC structures

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