Monitoring of FRP Strengthened Concrete Structures Using FBG Sensors


Structural Health Monitoring Laboratory, Structural Engineering Research Centre, CSIR, India

Abstract

Retrofitting of aged and distressed RC structures is becoming a major concern for structural engineers. The demand for the new materials to strengthen, upgrade and retrofit existing aged and deteriorated concrete structures has increased rapidly. The use of polymer composite materials overcome the problem of structural retrofitting and provides equally satisfactory solutions. Fiber Reinforced Polymer (FRP) composite materials are very attractive for use in civil engineering applications due to their high strength, corrosion resistance and light weight. Monitoring of the deteriorated structures after strengthening is very essential. These strengthened structures can be monitored by bonding sensors at the interface of concrete and FRP. The requirement for any embedded sensor for monitoring FRP strengthened concrete members is that the sensor should not be detrimental to the operational requirement of the strengthened structure. Fiber optic sensor is a good choice for monitoring the strain at the interface of concrete and FRP. This paper deals with the problem of instrumenting the Fiber Bragg Grating (FBG) sensors at the interface of concrete and FRP for monitoring the performance of FRP strengthened concrete structures subjected to bending. The initiation and propagation of debonding of FRP has been identified using the embedded sensors.

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Selection

Keywords: FRP strengthening, Reinforced concrete, Fiber optic sensors, Health monitoring.

* Corresponding author and Presenter

Email: arunsundaram@sercm.org
1. Introduction

The rapid deterioration of infrastructure is becoming a principal challenge for the construction industry. Deficiencies in existing concrete structures caused by insufficient detailing at the time of construction, aggressive chemical attacks and ageing of structural elements augment the need for finding an effective means to improve the performance of these structures without additionally increasing the overall weight, maintenance cost and time. Moreover there is a demand to upgrade the existing concrete structures to satisfy the requirement of the modern codes and to repair, rehabilitate and strengthen the damaged members. The demand for the new materials to strengthen, upgrade and retrofit existing aged and deteriorated concrete structures has increased rapidly. Fiber reinforced polymer composites (FRP) have found widespread usage in civil structures, especially for strengthening and rehabilitation of existing concrete structures. High strength to-weight ratio, resistance to corrosion, and ease of handling are among the primary attributes of FRP composites. Repair of cracked concrete beams involves either wrapping of the beams by FRP fabrics or adhesion of the fabric at the tension face (cracked face) of the beam while still under service load. A common cause of failure in FRP repaired members is abrupt debonding of fabric from the concrete. The fiber optic sensor is broadly accepted as a structural health monitoring device for fiber reinforced polymer materials by either embedding into or bonding onto the structures (Mufti 2003). The requirement for any embedded sensor for monitoring interfacial strain in FRP strengthened concrete structures is that the sensor should not be detrimental to the operational requirement of the strengthened structure. Survey of available literature indicates the cause for abrupt debonding failures, among which, stress concentration at the fabric cutoff point, and existence of transverse cracks along the beam span have been noted as primary causes of failure. The advantage of fiber optic sensors for monitoring of retrofitted and repaired concrete structures using fiber reinforced polymer composites has been discussed by (Lau 2003). In another paper, the authors (Yang Zhao 2002) discussed the use of fiber optic sensors for monitoring the behaviour of FRP strengthened concrete beams subjected to pure bending. This paper describes utilization of Fiber Bragg Grating sensor (FBG) for monitoring of interfacial strains in FRP-repaired concrete elements. The study reported here aims at monitoring the initiation and propagation of debonding failure and also to develop a suitable methodology of measurement for field monitoring of repaired members. Accordingly, the mechanism of debonding is investigated through embedment of an optical fiber sensor at the interface between the cracked concrete and the FRP fabric during repair of reinforced concrete structures. In the previous studies discrete Fiber optic sensors were used for monitoring the strengthened structures. In the present study multiple FBG sensors in a single fiber has been embedded between the concrete and the FRP. Monitoring of the strengthened structures at different locations can be easily done with the help of these multiple FBG sensors. Technique/Methodology developed for instrumentation of the multiple FBG sensors at the interface and to monitor the strain at the interface between FRP and concrete surface up to the debonding of FRP from concrete surface has been discussed in this paper.

2. Fiber Bragg Grating Sensors

Fiber Bragg Gratings (FBG) are gratings that are imprinted directly into the core of optical fiber by powerful ultraviolet radiation. Such gratings consist of a periodically varying refractive index over typically several millimeters of the fiber core. The specific characteristic of FBG for sensing applications is that their periodicity causes them to act as wavelength sensitive reflectors. 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, gratings are created with in the core, which then give rise to a periodic change in the local refractive index. This change in refractive index (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 (Udd 1995; Measures 2001). Fiber optic Bragg grating sensor response arises from two sources, namely the induced change in pitch length (N) of the grating and the perturbation of the effective core refractive index (n_{eff}). The wavelength of the reflected spectrum band is defined by the bragg condition as

$$\lambda_B = 2 n_{eff} N$$  \hspace{1cm} (1)

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

$$\varepsilon = \frac{\Delta \lambda_B}{\lambda_B} \left(1 - \frac{1}{p_e}\right)$$  \hspace{1cm} (2)

where, $$\varepsilon$$ = Strain
$$\Delta \lambda_B$$ = change in Bragg wavelength ($\lambda - \lambda_B$)
$$\lambda_B$$ = initial Bragg wave length
$$\lambda$$ = Bragg length after straining/loading
$$p_e$$ = effective photo elastic constant for the fiber (~0.22)

3. Experimental Investigation

3.1. Preliminary Experimental Investigation

Preliminary experimental investigations have been carried out for understanding the issues in instrumenting FBG sensor at the interface of concrete and Carbon Fiber Reinforced Plastic (CFRP) and to measure the interfacial strain. The experimental program consisted of testing small concrete prisms bonded with CFRP and subjected to axial loading. The test specimens consisted of two concrete prisms connected through two CFRP sheets (strips of 200x50mm) externally bonded to the opposite faces of concrete by a wet lay-up process. Two different types of FBG sensors were bonded at the interface. On one side, a dual FBG sensor of size 3mm with a spacing of each sensor 20mm was bonded. On the other side, a single FBG sensor of 25mm long was bonded. The FBG sensors were placed very close to the contact edge of the concrete prisms. The CFRP strips have been bonded to the concrete prisms using epoxy adhesive. There is no contact between the two concrete prisms except through the CFRP sheets. Four conventional strain gages were bonded to the outer surface of the CFRP exactly above the locations of FBG sensors. Instrumented specimens were tested by applying tensile load as shown in Figure 1a. The specimen was loaded gradually till failure and the response from the sensors were recorded continuously. The specimen failed at a load of 12.4 kN by complete debonding of the FRP fabric from concrete. The fiber optic sensor embedded at the interface of concrete and FRP had registered higher level of strain than the strains measured by conventional electrical resistance strain gages bonded on the surface of the FRP. The FBG sensor at the interface has linear response up to 2.8 kN and the change of slope after that load indicates the initiation of debonding at that location. On further loading, the response from the FBG sensor near the edge of the prism increases as there was debonding of the FRP from concrete. When the load was further increased, the strain sensed by the FBG increases at higher rate and there was complete separation of the FRP from the concrete for a load of 12.4kN showing a sudden drop as shown in Figure 1b.
3.2. Experimental Investigations on CFRP Strengthened Concrete Beams

3.2.1. Beams strengthened with CFRP strip

The experimental program consisted of testing concrete beams of size 100x200x1500mm of M40 grade concrete subjected to two point bending. Some of commonly noted failures in FRP strengthened concrete beams are FRP rupture, crushing of concrete, concrete shear failure, concrete cover separation, plate end interfacial debonding and intermediate crack induced debonding. Generally, FRP rupture and concrete crush can be regarded as flexural failures where the full composite action between concrete and FRP is achieved. Failure modes such as concrete cover separation, plate-end debonding and intermediate crack-induced debonding are regarded as local failures where the composite action between concrete and FRP is lost and prevents the strengthened beam from reaching its ultimate flexural capacity due to debonding. The CFRP strip (woven carbon fiber sheet and epoxy matrix) of size 460 mm by 50 mm was bonded to tension side of the specimen at the centre of the beam using suitable adhesive. The beams were instrumented with multiple FBG sensors (five sensors in a single fiber optic cable) at the interface between FRP and concrete. Electrical resistance strain gages were bonded over the fabric and on the concrete surface at locations of interest as shown in Figure 2. The beams were loaded by displacement controlled actuator (Figure 3). Instrumented fiber optic sensors were connected to the interrogator and the strain gages were connected to the strain gage data logger. Debonding of FRP strip from concrete occurred at a load of 43.5 kN. Load vs strain measured from strain gages and FBG sensors are plotted in Figure 4. Because of the occurrence of a discontinuity between FRP and the concrete beam at a load of about 15kN (at location S3), there was no strain transfer from the concrete to the FRP which is clearly indicated by the strain measured from strain gage on the FRP strip. As the load was further increased, the strain from the FBG and strain gage on concrete surface increases and during debonding of the FRP, the strain from FBG reaches a peak and drops down indicating complete debonding of the FRP strip. The strain on the concrete surface goes on increasing until there is failure of the concrete beam. Hence with the embedded FBG sensor the initiation and propagation of debonding can be identified.
Figure 2: Instrumentation details of the Beam

Figure 3: Test Setup for beam strengthened with CFRP strip
3.2.2. Beams Strengthened with CFRP Plate

Two numbers of reinforced concrete beams of size 100x150x1500mm were cast and on the tension side, CFRP plate (pultruded strip of compressed resin bound carbon fibers) was bonded. FBG arrays consisting of five FBG sensors of 10mm long with a spacing of 100mm was placed over the adhesive and pressed in such a way that the sensor was placed at the middle of the adhesive. Then the plate was placed in position and rolled for proper bonding to the concrete. The testing of these beams was done similarly and the strains were measured from all the FBG sensors and the strain gages. The mode of failure in the beams strengthened with CFRP strip and plate is shown in Figure 5. The load vs strain plot for the beam strengthened with CFRP plate is shown in Figure 6.

In the case of beams strengthened with CFRP plate, the mode of failure observed was crushing of concrete with out debonding of FRP since the stiffness of CFRP plate seems to be high. For any load, the strain measured from strain gage on the CFRP plate was higher compared with the sensors at interface and on concrete surface. This is because the CFRP plate was the farthest fiber in the beam subjected to flexure and hence it was subjected to higher strains.
Figure 5: Mode of Failure in Beams strengthened with (a) CFRP strip and (b) CFRP plate

Figure 6: Load vs Strain measured from FBG and Strain Gage during testing of beam strengthened with CFRP plate
4. Conclusions

The initiation and propagation of debonding in the beams strengthened with CFRP strip/plate was monitored by the FBG sensors present at the interface. From the experimental studies carried out on beam specimens strengthened with CFRP strip, the mode of failure observed was debonding of the CFRP strip from concrete surface. The FBG sensors embedded at the interface very well indicate the initiation and propagation of debonding of the CFRP strip. In the case of beams strengthened with CFRP plate, the mode of failure observed was concrete crushing before debonding of the CFRP plate. The CFRP plate was subjected to higher strain since it was the farthest point in the beam subjected to flexure and hence the strain measured from the strain gage on CFRP plate was higher compared to the strain measured at other sections.

Acknowledgement

The authors thank the technical staff of Structural Health Monitoring Laboratory, Advanced Material Testing Laboratory and Structural Testing Laboratory of SERC, Chennai for their help in carrying out the experimental work. This paper is being published with the kind permission of the Director, CSIR-Structural Engineering Research Centre, Chennai, India.

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