First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Laboratory Evaluation of FBG Sensors in Full-Scale Concrete Beams

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ABSTRACT: A laboratory investigation to evaluate FBG sensors is being conducted at the University of Sherbrooke. In this study, FBG sensors inserted into a FRP bar were used as internal instrumentation for full-scale reinforced concrete beam specimens. The beam specimens were also instrumented with conventional electrical resistance strain gauges in order to compare the results of the FBG sensors to the conventional readings. Two beams specimens have been tested up to failure by monotonic loading. The results show that the strains obtained by the FBG sensors have a similar trend compared to the strains recorded by the strain gauges. However, the readings of the FBG sensors were slightly higher in the cracked stage of the tested beams.

1 INTRODUCTION

The structural performance of reinforced concrete members is usually monitored in the field or during testing in the laboratory to determine their responses under different loadings conditions. Strains in the reinforcing bars are of great interest to be measured so that the stresses at desired locations can be calculated. The strains can be captured using conventional electrical resistance strain gauges attached to the surface of the reinforcing bars at desired locations. However, closely spaced strain gauges are not recommended solution for strain measurement because the protection of these gauges against the surrounding environment affects the bond of the reinforcing bars. Besides, the long-term behavior of conventional electrical resistance gauges is very questionable.

The Integrated Fiber Bragg Grating (FBG) sensors provide an innovative solution to capture the strain (Tremblay et al. 2009) in the Fiber-Reinforced Polymer (FRP) reinforcing bars without affecting the surface. The FBG sensors are inserted in the FRP bars and can be installed at any desired locations without affecting the original surface configuration of the bar. Moreover, closely spaced sensors can be installed without affecting the reinforcing bars. The optical cable is also inserted inside the bar, thus, this fabrication method provided a very high protection of the optic cable and sensors again potential damages that could occur during the installation of the bar in the field applications. Furthermore, the long-term performance of fiber optic sensors are well established (Schmidt-Hattenberger et al., 2003).

This paper presents the strain readings for FBG sensors that were attached to reinforcing bars in beam specimens tested up to failure by the research personnel of the NSERC industrial research Chair in Innovative FRP Composite Reinforcement for Concrete Infrastructure at the Department of Civil Engineering of the Université de Sherbrooke in September 2009. The readings of the FBG sensors are also compared with the electrical resistance strain gauge readings that were attached to the reinforcing bars at the same location of the FBG sensors.

2 RESEARCH SIGNIFICANCE

For more than a decade, there has been a high interest for structures reinforced with FRP rebar. The demand and the number of structures reinforced with FRP are increasing very fast everywhere the corrosion of the steel rebar is a concern (Benmokrane et al., 2007 and 2008). In order to eliminate incertitude, validate theoretical models and ensure safety of the users, the monitoring of those structures is a key factor. The validation of this new type of sensor could lead to a very large number of field applications where the durability of the monitoring is a concern; bridges and parking garages for example.

3 OBJECTIVE

The main objective of this research program is to evaluate the strain measurements of the new technology of Integrated Fiber Bragg Grating (FBG) sensors compared to common electrical resistance strain gauges.

4 FIBER BRAGG GRATING STRAIN AND TEMPERATURE SENSOR BASICS

It is first important to understand the basic constituent of a fiber optic cable. Effectively, the fiber optic itself needs to be protected against the environment. The most common optical cable is presented in Figure 1. The visible part of the cable is called the jacket, this one can have different configurations depending of the application (regular or armored). Inside the jacket there are Kevlar™ fibers to reinforce the longitudinal strength of the cable. The fiber optic has itself three constituents which typically are: tight buffer (900 μm), protective coating (250 μm) and finally the optical fiber made of ultra pure fused silica (125 μm, the cladding) and doped region where the light is travelling (≈ 8 μm, the core). When we refer to the Fiber Optic Sensor, it is important to observe that it is the change in physical properties of the fused silica that are monitored. We emphasize this point to the reader to understand that the importance of any optical sensor reside in the packaging. The packaging must be able to transfer the physical properties to be monitored most efficiently to the optical fiber.

The Fiber Bragg Grating (FBG) is manufactured by a controlled process to alter the physical properties of the core of the fiber. The FBG consists of a periodic modulation of the index of refraction. This alteration can be seen as a partial reflector for a specific wavelength. By using the appropriate instrumentation (interrogator), it is possible to monitor the wavelength reflected by the FBG and obtain the following optical response:

$$\frac{\Delta\lambda}{\lambda} = \left(1 - \frac{n_{eff}^2}{2}\left(P_{12} - \nu_f\left(P_{11} + P_{12}\right)\right)\right)\varepsilon_z + \left(\alpha_f + \xi\right)\Delta T \tag{1}$$

Where λ is the wavelength reflected by the FBG; $\Delta\lambda$ is the variation of the wavelength observed upon physical property; ε_z is the longitudinal strain applied to the optical fiber; ΔT is the variation of temperature; n_{eff} is the effective index of refraction of the fiber; P_{12}, P_{11} and ν_f are the opto-mechanical constants of the optical fiber and α_f and ξ are the thermo-optical constants of the optical fiber. For a specific wavelength the typical response for strain and temperature for the bare fiber is 1.2 pm/μstrain and 10.6 pm/°C respectively.

Since only one wavelength is affected by the FBG, all the light injected in the optical fiber will be guided through the FBG except for the wavelength reflected by the FBG. It is then possible to write another FBG that will reflected another wavelength on the same fiber; that is, having two sensors on the same optical fiber. In fact, it is possible to monitor as many as 100 FBG on the same optical fiber depending on the application.

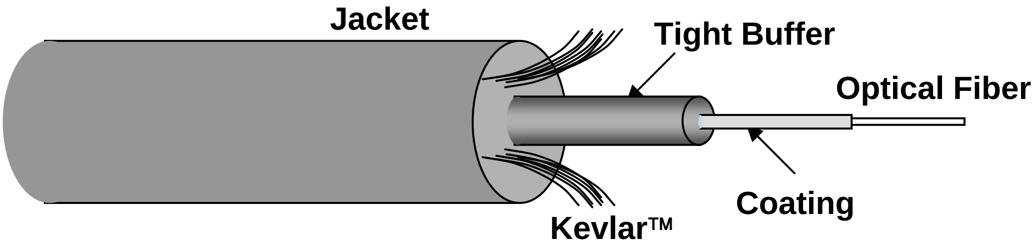

Figure 1. Optical cable basic construction (Diagram not to scale).

5 EXPERIMENTAL PROGRAM

The FBG sensors were installed in a Glass Fiber-Reinforced Polymer (GFRP) bar used as internal reinforcement of a beam. Two beams have been tested under a four points loading. The strains obtained by the FBG sensors are compared to electrical resistance strain gauges. The two types of sensors were installed at the same location on two different bars in the same beam to ensure the same testing conditions.

5.1 Fiber Bragg Grating (FBG) Installation

The Fiber Bragg Grating sensors were installed on V-ROD GFRP bars No. 6 and No. 8. The FBG sensors were spaced at 500 mm with a total of five sensors installed on each GFRP bar. Figure 2 shows the location of the FBG sensors. The bars were provided by Pultrall Inc. in 4.2 m long prepared for FBG sensor integration. Thereafter, the FBG sensors (Provided by ITF Labs) were installed at the University of Sherbrooke by ITF's trained personnel and following ITF's commercial process. It is important to mention that the sensors are completely integrated in the bar and covered with filling material. The FBG sensors integrated process developed by ITF Labs have been tested by University of Sherbrooke team and pass all tests including resistance to humidity and temperature cycling. The FBG strain gauge factor is determined from FBG theory and where a percentage deviation from theory is applied (equation 1). The percentage deviation factor is determined from a fixed load applied on the sensor. Comparative results are presented previous paper (Tremblay et al. 2009). Figure 3 shows the GFRP bars after the installation of the FBG sensors.

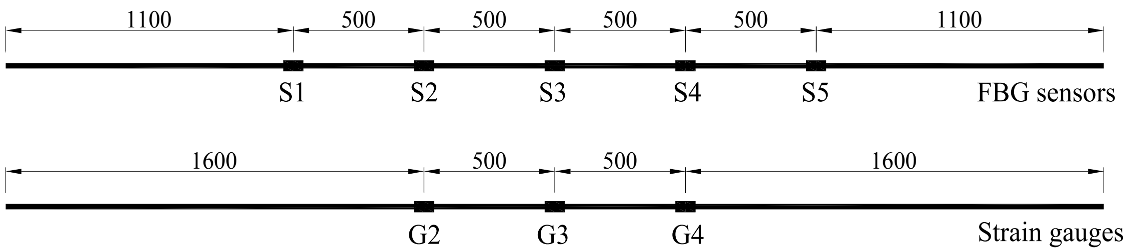

Figure 2. Locations of the FBG sensors and electrical resistance strain gauges on the V-ROD GFRP bars No. 6 and 8.

5.2 Beam Specimens

The instrumented V-ROD GFRP bars No. 6 and 8 were used in beam specimens as main reinforcement. In addition to the FBG instrumented GFRP bars, another bar with strain gauges attached at the same locations of the FBG sensors was used so that their readings can be compared. The details of the two beams that were prepared and tested (Beam 1 and Beam 2) as well as the locations of the electrical resistance strain gauges and FBG sensors are shown in Figure 4. The main reinforcement in Beam 1 was 2 GFRP bars No. 8 and that of Beam 2 was 3 GFRP bars No. 6. In each beam, one bar was instrumented by FBG sensors and another one was instrumented with electrical resistance strain gauges.

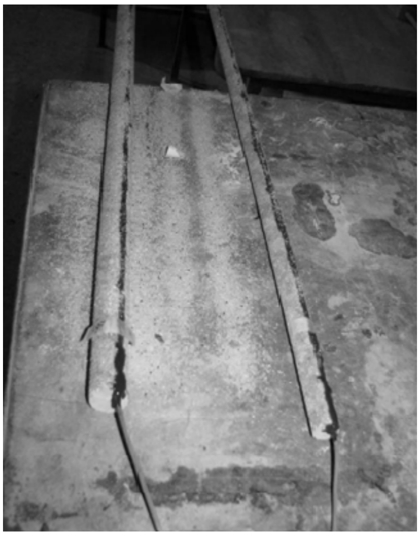

Figure 3. Bars after the FBG sensors installation.

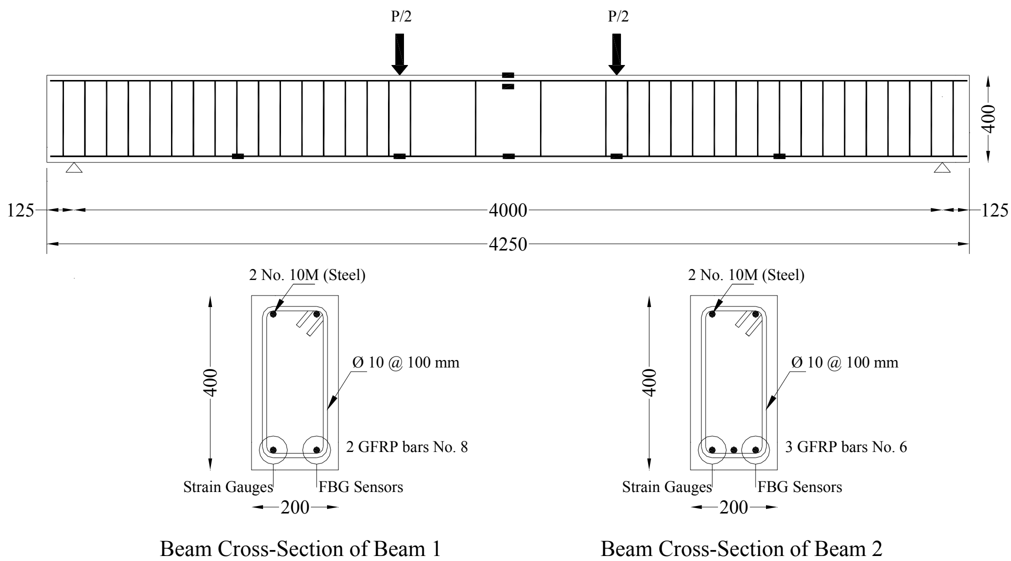

Figure 4. Details of the beam specimens.

The reinforcing cages of the beam specimens were assembled using the instrumented GFRP bars and placed into the formwork. Thereafter, the concrete was cast and the surface was adjusted. After casting and curing for seven days, the beam specimens were stored in the laboratory till the day of testing.

5.3 Testing of the Beam specimens

The beam specimens were tested under four points bending over a clear span of 4.0 m using the test setup shown in Figure 4. The electrical resistance strain gauges that were attached to the reinforcing bars were connected to a data acquisition system to get their readings. On the other hand, the FBG sensors were connected to the readout unit which was connected to a computer for recording the signals. The beams were tested under an increasing load till the failure.

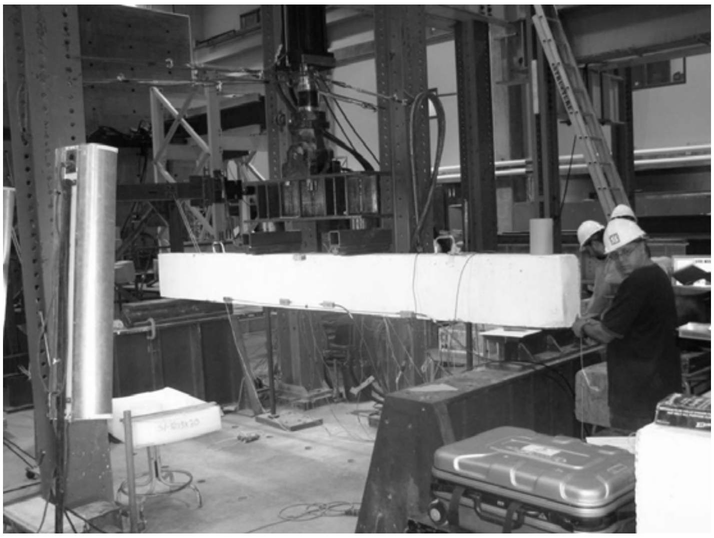

Figure 5. Test setup for beam testing.

6 TEST RESULTS AND DISCUSSON

In this section, the strains measured by the FBG sensors as well as the strain gauges are presented and compared. Only the results of the Beam 2 are presented due to similar responses of the two beams tested. The strains measured in Beam 2 (reinforced with 3 GFRP bars No. 6) for different FBG sensors are shown in Figure 6 and in Figure 7 for electrical resistance strain gauges. In those figures, it can be noticed than the curves of all FBG sensors and strain gauges can be represented by two straight lines. The first line represented the uncracked stiffness of the beam while the second line, less steep, represented the cracked stiffness of the beam. The intersection of the two lines occur when the tension at the bottom of the beam exceed the tension strength of the concrete. The similar results of the sensors S1, S2 and S3 as the gauges G2, G3 and G4 are due to the constant moment in the beam between the two loading points. The sensors S1 and S2 also have similar behavior due the symmetry of the beam. The cracking moment is reach at a higher applied load at the locations of sensors S1 and S2 due to their positions more away from the loading points.

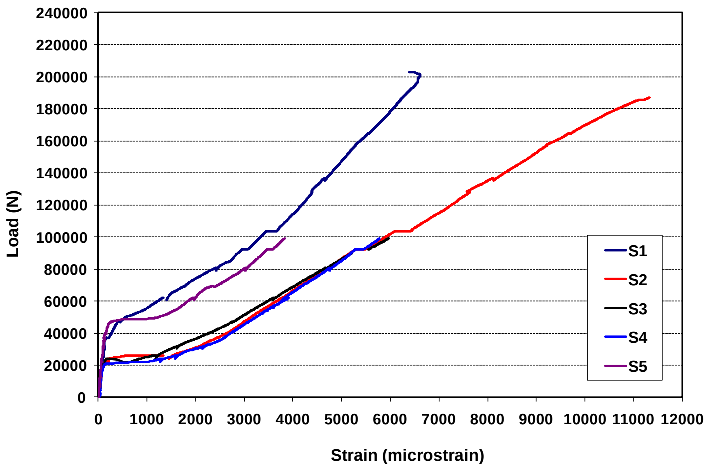

Figure 6. Load-strains relationship using the FBG sensors.

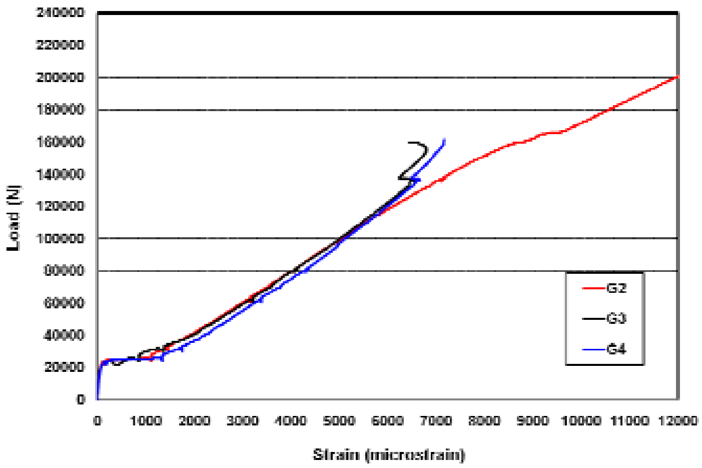

Figure 7. Load-strains relationship using the strain gauges.

Figures 8 to 10 show the comparison of the strains in the FBG sensors and the electrical resistance strain gauges for a same location. It can be noticed than the FBG sensors have very close response to the strain gauges for the uncracked stage of the beam and up to around 1000 microstrains. After this point the optic sensors show slightly higher strain than the strain gauges. However, the overall trends of the FBG sensors are similar to the electric strain gauges.

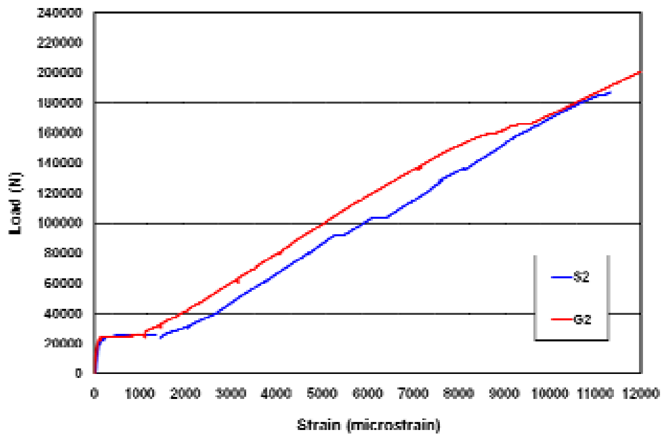

Figure 8. Comparison between the sensors S2 and strain gauges G2.

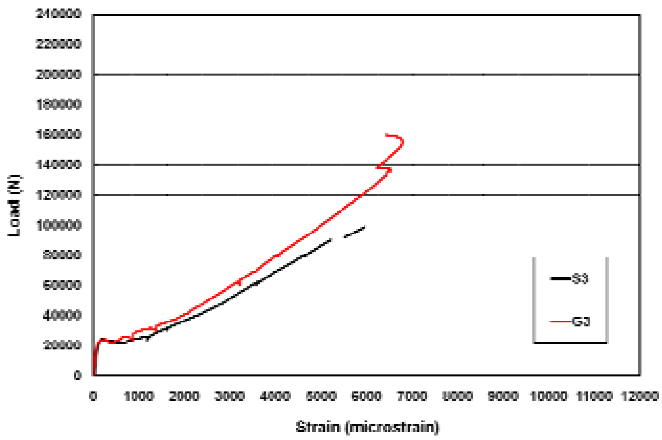

Figure 9. Comparison between the sensors S3 and strain gauges G3.

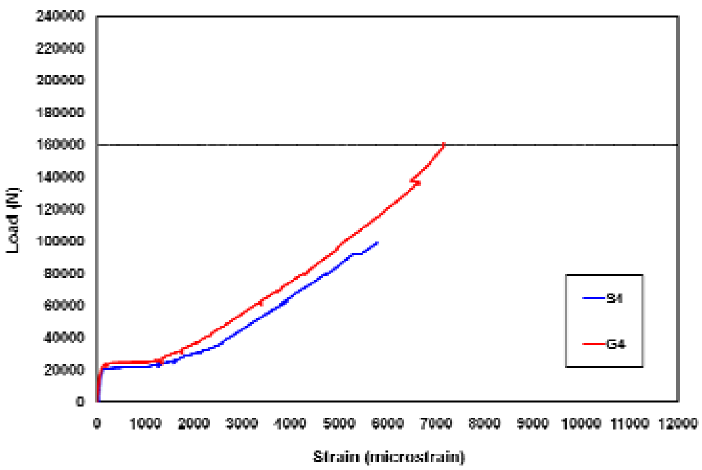

Figure 10. Comparison between the sensors S4 and strain gauges G4.

7 CONCLUSION

The following conclusions can be drawn based on the experimental results:

1. The FBG sensors provide an innovative solution for monitoring of the reinforced concrete structures when the strains at many closely spaced points are to be measured. This will enable capturing the strains at all the desired points which contributes to accurate prediction of the structural behavior of the reinforced concrete elements. Furthermore, those sensors can be used in field applications where the durability of the sensors is an issue.

2. The used FBG sensors were capable of capturing the strains in the GFRP bar at different locations during the beam testing.

3. There was acceptable agreement between the strains measured by the FBG sensors and that measured by the conventional electrical resistance strain gauges. However, the strains measured using the FBG were slightly higher than measured using the strain gauges in the cracked stage of the tested beams.

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