The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

EVALUATION OF A RUGGED FIBER OPTIC SENSOR SYSTEM FOR MONITORING REINFORCED CONCRETE STRUCTURES

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Abstract

For Structural Health Monitoring (SHM) of civil infrastructure, Fibre Optic Sensors (FOS) are regarded to be more durable than the conventional sensors. However, the installation of FOS needs a significant level of care and efforts as the bare fibres are brittle and vulnerable to alkaline attack when they are embedded in concrete. To avoid such problems, these sensors are often coated with protective materials such as acrylate or polyimide. They are also ruggedized in various protective devices such as a Fibre Reinforced Polymer (FRP) patch with pre-embedded FOS, or FRP bars with FOS embedded in them. The performance of such sensors would depend on how they bond to concrete and the main reinforcing bars. This paper presents an experimental study on the performance of Bragg Grating FOS embedded in the epoxy filled groove in supplemental FRP bars which are attached to the main reinforcing bar at the midspan of simply supported reinforced concrete beams. For comparison, electrical strain gauges are attached to the supplemental FRP bar and the main rebar at the same longitudinal location. The strain recorded by the electrical stain gauges and the rugged FOS shows a good agreement considering the effect of shear lag between the main and supplemental bars and the variation in their positions.

INTRODUCTION

As the structural health monitoring (SHM) technologies are evolving, more and more new, innovative and cost effective sensors are becoming available. This brings new challenges from the constructability, practicality, and durability points of view. Installation and management of an SHM system needs multidisciplinary collaboration among Civil, Electrical, and other Engineering disciplines, giving rise to a new field called Civionics [1], which can be viewed as the application of Electro-Photonics in Civil Engineering with a similar scope as Avionics in the Aerospace industry. Effective and durable sensors are very important for an SHM project. Fibre Optic Sensors (FOS) has many advantages over conventional sensors in terms of durability, inertness to electromagnetic interference, and measurement accuracy [2, 3]. A number of bridges and other structures in Canada have been instrumented with FOS over the last decade or so [3-7]. FOS's are made of glass fibres and work on the principle of optics. There are a number of different varieties of FOS, and are available for use in the SHM implementation in a

civil engineering structure. The common varieties include Bragg Grating, Fabry-Perot, and Distributed Brillouin Scattering FOS. These sensors differ in their operational techniques, and some of the details are available in [2]. Fibre Bragg Grating sensors are considered in this study. A typical bare-fibre Bragg Grating sensor is shown in Figure 1.

Figure 1. Bare fibre Bragg Grating FOS

The FOS data readout equipment sends a light signal to the sensor and receives the reflected light from the gratings. When a structure deforms, the length of the sensor attached to it changes, which affects the properties of the light received from the sensor. The readout equipment detects the change in optical wavelength and correlates it to the appropriate strain or displacement value. FOS are regarded to be more durable than the conventional electrical strain gauges (ESG), provided they survive the installation and the construction processes. Significant care and efforts are necessary for installation of the bare fibre sensors as they are brittle and often susceptible to alkaline attack if embedded in concrete. To mitigate these problems, they are often coated with acrylate or polyimide. A preliminary study on the tension behaviour of coated Bragg Grating FOS on steel coupons suggests that a standard needs to be developed for these sensors [8]. ISIS Canada Research Network, A Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures, has developed a set of guidelines on SHM systems for civil engineering structures [9] and the deployment of FOS in such cases [2]. Based on the experience with FOS and innovative structural applications, ISIS has recently come up with some guidelines in the Civionics Manual [9] for installing and protecting the FOS, SHM equipments, and accessories.

Figure 2. FOS integrated in supplemental bars

In order to make the sensors rugged, they are sometimes protected by embedding in a composite patch [11] or in a supplemental Fibre Reinforced Polymer (FRP) bar as shown in Figure 2. These supplemental bars containing FOS can be attached to the main reinforcing bars in a beam as indicated in Figure 3. The examples of various protective mechanisms for FOS currently being developed or considered in the industry include, *(i)* FRP patch with embedded

FOS, *(ii)* FRP bar with FOS embedded in epoxy filled grooves, *(iii)* FOS integrated to an FRP bar, and *(iv)* FOS mounted on the surface of a supplemental bar.

The performance of such sensors will depend on how they bond to concrete and the main reinforcing bars to capture accurate strains. So far, there is no comprehensive study to compare the static, dynamic, and fatigue behavior of these systems. The paper presents an experimental study on the performance of Bragg Grating FOS embedded in epoxy filled groove in a supplemental FRP bar which is attached to the main reinforcing bar in FRP-reinforced concrete beam specimens. Two beam specimens have been tested in three-point bending with monotonically increasing loads. The study presented here is preliminary in nature and only static tests have been performed under a load level similar to the service load conditions.

Figure 3. Deployment of a rugged FOS system

EXPERIMENTAL SETUP

Two reinforced concrete beam specimens of 900 mm span, 200 mm width and 300 mm depth have been tested in three-point bending as shown in Figure 4.

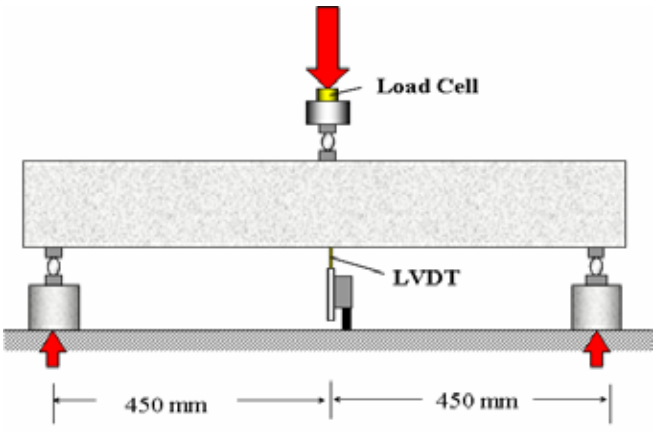


Figure 4. The experimental setup

The cross sectional details and the sensor locations are shown in Figure 5. Each beam has been reinforced in tension with 3 #3 GFRP bars. A supplemental FRP bar containing an FOS strain sensor is attached to the rebar at the middle, while an electrical strain gauge (ESG) is attached to the supplemental bar itself (SG 2) and another ESG is

attached to the middle rebar (SG 1) at the same longitudinal locations as the FOS. An LVDT is installed at the midspan of the beam specimens to measure the vertical displacement.

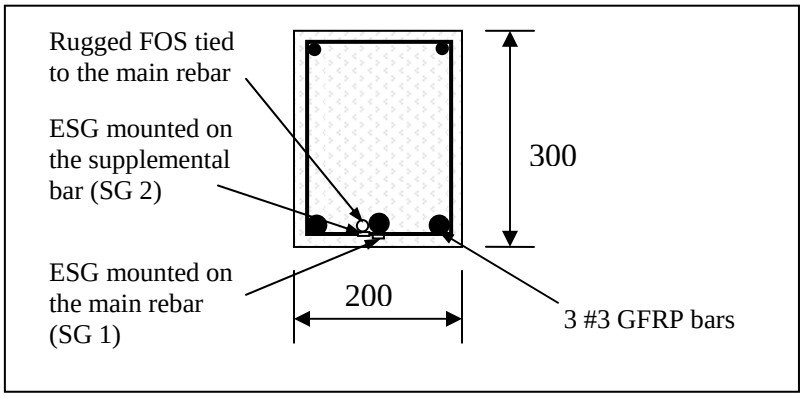


Figure 5. Cross sectional details of the beams

(a) (b)

Figure 6. Experimental setup

Two beam specimens have been tested. Monotonically increasing point loads were applied at the midspan of the beam using a 1000 kN capacity closed loop servo-controlled MTS load frame as shown in Figure 6, at W.R. McQuade Heavy Structures Laboratory at the University of Manitoba.

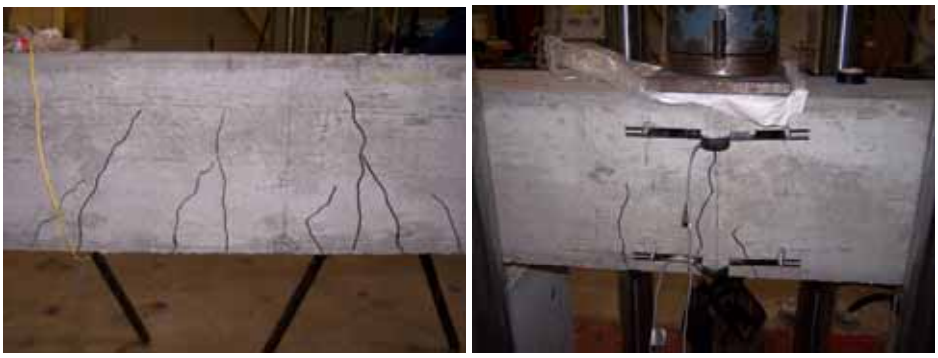
The ESG and LVD data were acquired using a National Instruments [12] Data Acquisition System which is connected at the desktop computer indicated by "A" in Figure 6(a), while the FOS data were collected using IDERS SHM System [13] as shown in Figure 7.

(a) (b)

Figure 7: FOS Readout unit (IDERS SHM System): (a) setting up, (b) snapshot of data as acquired

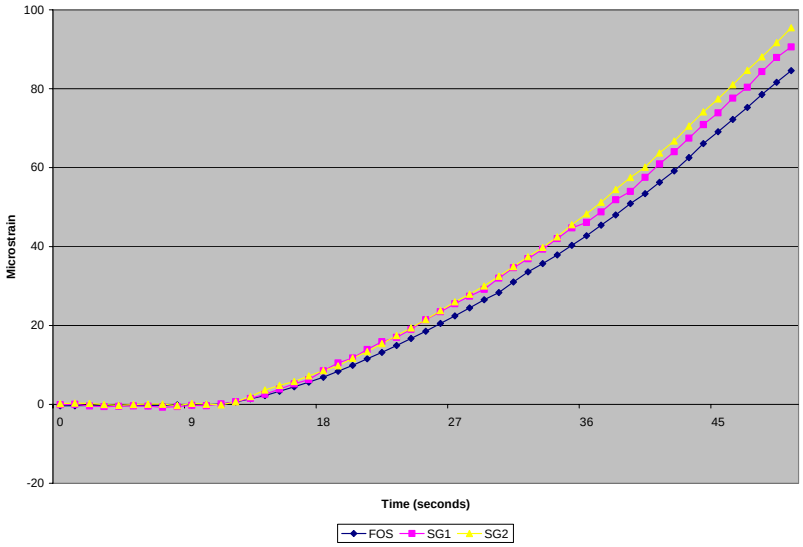
PRELIMINERY RESULTS

The beams were loaded gradually and the rate of loading was controlled by the midspan displacement, which was increased at a step of 1.5 mm until the strain in the FOS was about 100 με. The beams developed typical flexural cracks as shown in Figure 8.

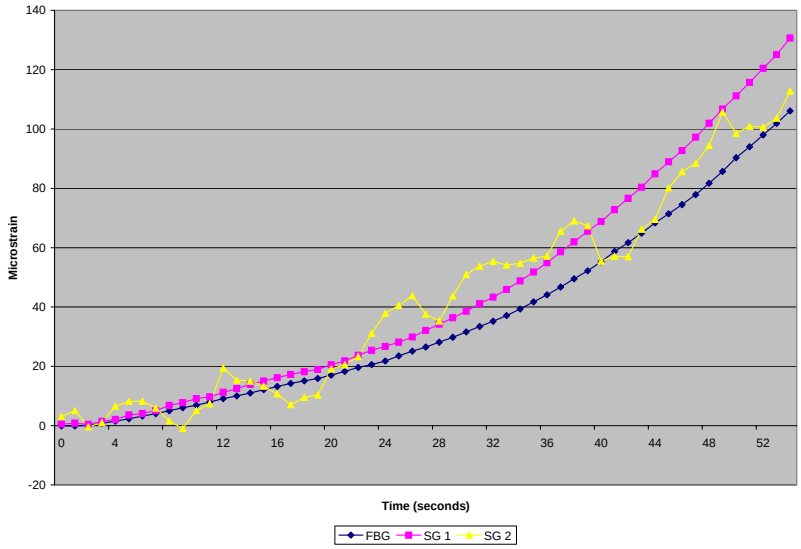


(a) (b)

Figure 8. Crack pattern: (a) Specimen 1, (b) Specimen 2



(a)



(b)

Figure 9. Strain-time plots (a) Specimen 1, (Specimen 2)

The strain measurement over the loading period has been shown in Figure 9. As indicated earlier, SG1 and SG2 are electrical strain gauges, installed on the main reinforcing at the middle and on the supplemental FRP bar, respectively. For both samples, the strain values recorded by SG1 and the FOS embedded in the supplemental FRP bar follow the same trend and there is a small shift between these values. The shift is expected and it is possibly due to the effect of shear lag between the supplemental bar and the main rebar, and a slight difference in the vertical positions of these sensors. These results indicate that the supplemental bars are well bonded in concrete and are capable of developing a similar strain pattern as in the main rebars when the beams are subjected to service loads. As an additional validation, SG2 data are also presented in Figure 6. The strain measurement from the FOS shows a very good correlation with SG2 in Sample 1. The strain pattern recorded by SG2 in Sample 2 appears to be somewhat erratic, which may be due to malfunctioning of the gauge.

DISCUSSION

FOS is believed to be very advantageous for structural SHM of Civil Engineering Structures. However, installation of the bare fibre sensor is difficult for its brittleness. A preliminary experimental study was conducted to explore the feasibility of ruggedizing the fibre optic sensors by integrating them with supplemental FRP bars of very short length which can be attached to the main reinforcing bars in concrete structures. The study as presented here indicates that this mechanism provides a strain pattern comparable to that in the corresponding reinforcing bar. The results are encouraging as the mechanism can provide a rugged and easily deployable solution for FOS for SHM of reinforced concrete structures. It is possible to integrate the FOS in supplemental bars in a controlled environment and tested before deploying them in the field. It should be noted that the length of a supplemental bar exceeds the required development length so that it can bond properly to the concrete. Of course, the study presented here is too limited to provide any guideline for the use of this mechanism of FOS deployment. Further study with a larger number of samples and different levels of loadings including static, dynamic and fatigue tests will be necessary to develop such guidelines. The study should also include the mechanisms where an FOS is integrated to an FRP patch to be installed on the surface of a structure. Such patches can be beneficial in the cases when FRP sheets are used for rehabilitation of existing structures.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Avensys Inc., Montreal for donating the FOS used in this study. After constructing the reinforcing cage and installing the sensors, the beam specimens were cast at the Winnipeg plant of Lafarge SA, and the materials and labour provided by Lafarge are gratefully acknowledged. Special thanks to Dr. Maria Onofrei and Mr. Moray McVey at ISIS for their help. The Postdoctoral Fellowship awarded to the first author by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the resources provided by the SHM Support Centre at ISIS Canada Research Network are also gratefully acknowledged.

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