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Performance of an Innovative SHM System for RC Flexural Members under Normal and Adverse Environmental Conditions

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ABSTRACT: Structural health monitoring (SHM) techniques are often used for detecting damage and diagnosing the structural conditions. There are many issues related to installation and constructability of SHM systems and in-situ installation of fibre optic sensors (FOS) on rebars in reinforced concrete (RC) elements. Here, a solution is provided for installation of a FOS strain sensor by mounting it on a supplementary bar *a priori* and then attaching it to the main reinforcing bar of interest at the construction site prior to concrete pouring. Such innovative deployment system for FOS is particularly advantageous for developing a practical SHM system for infrastructure. However, the performance of such systems under various loading and climatic conditions is not very well known. The objective of this research is to assess the performance of the said system used in concrete beams reinforced with FRP (fibre-reinforced polymer) bars, under normal and adverse environmental conditions such as, immersion and cyclic immersion in alkaline solution. The results show that the proposedFOS system is efficient and useful in capturing the real strain in control and the wet and dry condition. Electric strain gauges were found to perform poorly in adverse conditions.

1. INTRODUCTION

Periodic visual inspection is a common method for detecting problems in concrete infrastructure, particularly bridges. These inspections can only detect deterioration after it has reached certain levels. The lack of real time assessment of the behavior of structures for different impacts such as gusty wind, earthquake, settlement, heavy traffic loading, deterioration, stress relaxation, makes it important to assess the effectiveness of the current practice. A better understanding of the real behavior of a structure can be achieved by an appropriate monitoring system that can be easy to adopt. Increased usage of fiber-reinforced polymers (FRP) in structural concrete applications is due in part to their high resistance to deterioration, light weight and high strength. However, although research has been performed regarding various aspects of this relatively new composite material, further research is needed to confirm serviceability and safety of these materials. Due to concern over these issues, application of structural health monitoring (SHM), particularly in bridges made of FRP, is increasingly used to continuously assess the structure's performance. Monitoring methods are not standardized and present some issues.

Fiber optic sensors (FOS) present an improvement and accuracy in monitoring over electrical stain gauges. However, they are difficult to install as the bare fibre sensor is very fragile and brittle. In this research, a method of monitoring was investigated that incorporates mounting both fiber optic sensors (FOS) and electric strain gauges (ESG) on a supplementary bar to protect them which is connected to the main bar just prior to pouring concrete. The installation of the FOS sensors on a supplementary bar will represent an improvement in construction practice as the bar pre-installed with FOS can be installed quickly attachedto thereinforcements on site prior to concrete placement in a minimal window of time and adequate protection the sensor and accessories. Such an innovative deployment system for FOS is particularly advantageous for developing a practical SHM system for durable civil infrastructure such as bridges. The supplementary bar with FOS strain sensor installed on it would be attached to a reinforcing bar (referred to as the main bar here) in order to measure its strain. This system was originally proposed by Bagchi et al. (2007), and the preliminary results on the performance of such systems in FRP-reinforced concrete beams under static load were presented. Further extensive study on such systems with different length and diameters for the supplementary and main bars, and for different attachment methods has been reported by Torkan, 2010, which shows the viability of such systems, and also establishes important design parameters.

Given that concrete placed in field conditions is subject to varying exposure conditions, it is important to know how these conditions affect the FRP and sensors as well as the bond between the two and with the concrete. FRP embedded in concrete is exposed to high alkalinity. The hydroxyl ion concentration in fresh concrete is mainly due to calcium hydroxide. Higher pH values are due to the hydroxyl ions from sodium and potassium hydroxides (NaOH and KOH). Concrete quickly attains a pH of about 12.4 or 12.5 due to the development of a saturated solution of calcium hydroxide. But as the solubility of $Ca(OH)_2$ is not high, the calcium hydroxide precipitates, forming portlandite, and the pH rise due to the influence of the hydroxyl ions from sodium and potassium hydroxide. If the pore solution of recently hardened concrete is measured, the pH is over 13.Resins used in FRP are susceptible to alkaline attack, however they have good resistance to water, but in real structures, the presence of groundwater, soils and concrete pore water all contribute to creating a natural condition of alkalinity. Transformation of water and alkaline materials in concrete and resulting chemical reactions with FRP bar will affect shear resistance and bond strength. It is predicted to see more severe effects in cyclic exposures (Davalos et al., 2008).

2. Experimental investigation

As a part of the present study, experiments were carried out on FRP-reinforced concrete beams with a plan to investigate the flexural behavior and to determine the ultimate failure load and strain captured at the main and supplemental bars. Three different beams have been tested to failure under the third-point loading. The beam's dimensions were 150 mm×250 mm×1750 mm with reinforcement as shown in Figure 1. The FRP reinforcing consisted of two longitudinal bars of 19 mm diameter and two top and supplemental bars at 6 mm. It was previously found that a smaller supplemental bar is necessary to have best strain capture (Torkan,2010). Sufficient steel shear reinforcement prevented any shear failure.

In a previous study (Torkan, 2010),the performance of Fabry-Perot and Fiber Bragg Grating (FBG) strain sensors was compared, and it was found that while both types of sensors show excellent performance up to a certain level of strain; and the Fabry-Perot sensors could not record strain values beyond 3000με.For that reason, FBG strain sensors have been used in the current study along with the conventional electrical strain gauges (ESG) for comparison. Seven sensors are placed at the level of the main bars; two FBGs and five ESGs. Three ESGs are installed along the length of the main bar and the data from these ESGs should provide the strain profile along the length of the bar to compare with the theoretical values of the strain (one is at mid-span and two are at quarter-span). Figure 2 shows a general scheme of the instrumentation. The supplemental bars was connected to the main bar by carbon fibre wrap and plastic “zip” ties, as shown in Figure 3.

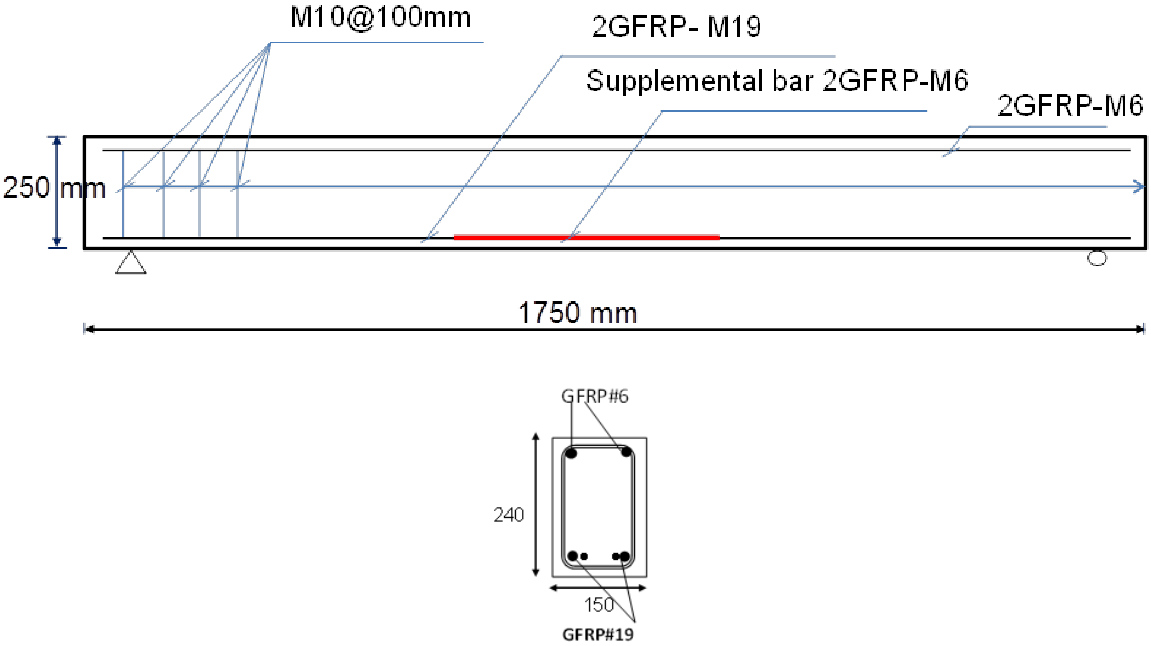

Figure 1: Reinforcing details

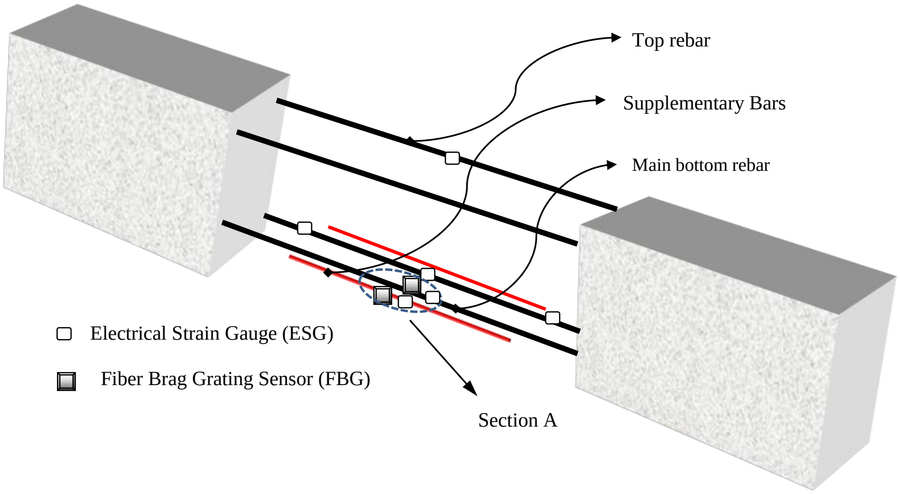

Figure 2: Sensor locations

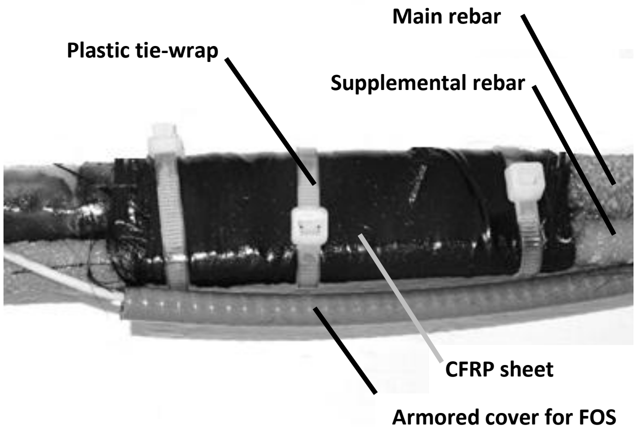

Figure 3: Detail of main and supplemental bar connection (Section A)

All the beam specimens are of normal density concrete, designed for 46MPa compressive strength (CSA, 2006 and ISIS, 2007). The beams were exposed to three conditions at 28 days after casting the concrete. The first beam (control) was left in the lab at ambient temperature and humidity. An alkaline solution meant to simulate concrete pore solution and previously been used by Chen et al. (2005) as given in Table1 was used in the research for the remaining two beams. The initial pH was measured to be 13.2. However, the pH of the solution increased and after 6 months, it surpassed the limit of the pH meter.

Table 1: Details of the alkaline solution

Chemical Materials	$NaOH$	KOH	$Ca(OH)_2$
Alkaline solution(g/L)	2.4	19.6	2.0

For simulating the wet and dry (cyclic immersion) condition, the following plan was adopted which consists of three days immersion followed by four days drying, which provides enough time for the drying of the surface pores in the concrete and enhances alkaline solution absorption in the subsequent cycles (Figure 4). Continuous and cyclic immersions were carried out for a period of 14 months.

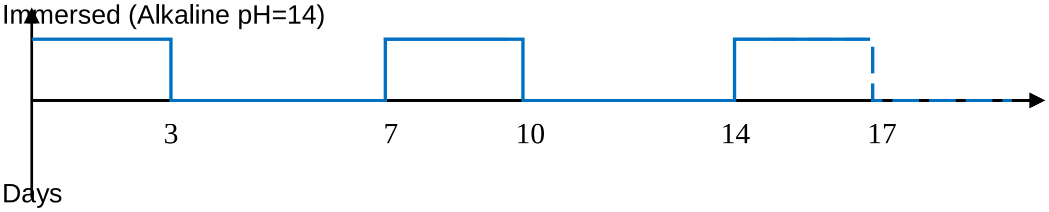

Figure 4: Wet-Dry Cycles

Pre-loading (equal to the amount of $P_{cr} = 37\ \mathrm{kN}$ or approximately 20% of the ultimate load) was used to create cracks in the beams before exposing them to different environmental conditions to have adequate alkaline penetration into concrete especially to the level of the FRP (Figure 5). The results from earlier similar tests on reinforced concrete beams show that pre-cracked samples results are more reliable (Green and Rosowsky, 1998).

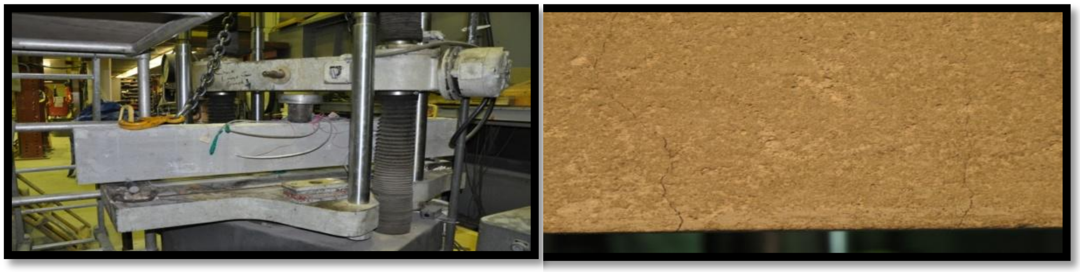

Figure 5: Pre-cracking by Tinius Olsen Jack (left). One mm width pre-loading cracks before environmental exposure (Right)

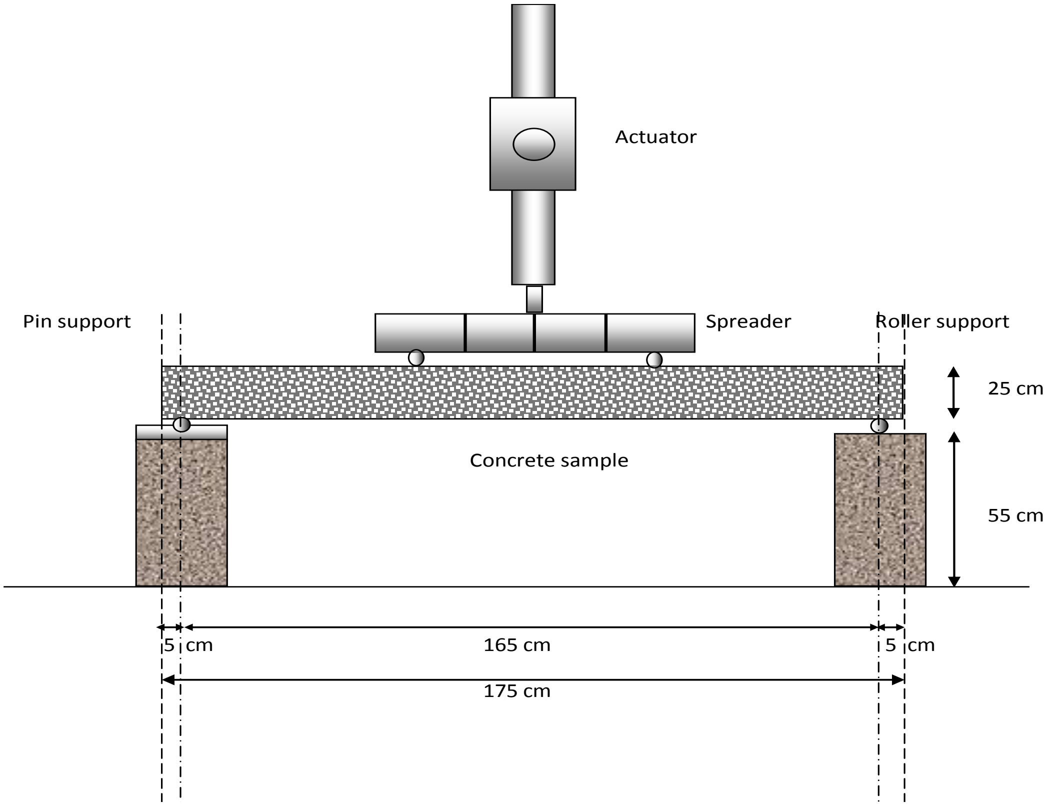

Figure 6: Loading setup

3. Strain Analysis

Figure 5 shows the test setup for the beam specimens. A third-point loading protocol has been used for testing the beams in flexure (ASTM, 2002). The rollers were inserted at two ends of the spreader beam to ensure the simply supported condition and concentrated loading. Three beams with the following treatments have been tested: untreated (control), immersion in alkaline solution, and wet and dry condition.

The beam samples were instrumented for measuring the vertical deflections at the mid-point of each sample by two types of potentiometers. The surface of concrete was carefully inspected for cracks developing on the concrete surface during loading. Testing was terminated when crushing of the concrete occurred and crack width excessively widened with the loading. The load displacement curves, ultimate load and force-strain were recorded for each specimen. Figure 7 shows the variation of mid-span deflection with applied load (F-Δ graph) for the three specimens. A finite element analysis of these beams showedclose agreement between the model and experimental results. Details of the numerical model with different parameters for strain level, displacement, and bond stresscan be found in Rahmatian et al.(2013). Figure 7 shows that the deflection trends are similar. The maximum mid-span deflection recorded by two different types of potentiometers are found to be 22.69 mm in the control, 21.2 mm in the beam with immersion, 21 mm in the beam with wet and dry condition .

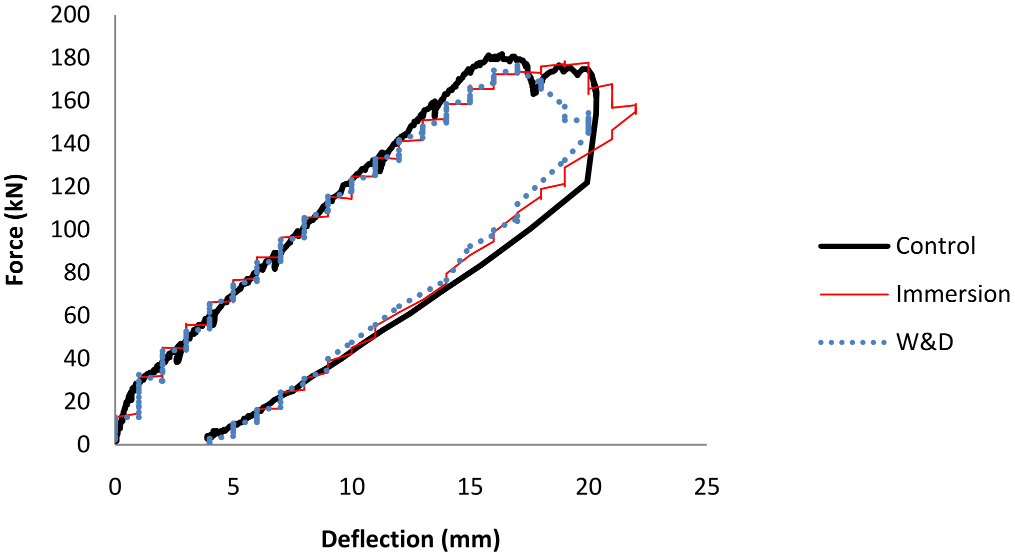

Figure 7: Force-Deflection relationships at mid-span

The failure load for control, wet and dry (W&D), and immersion (IMM) specimens are found to be 180kN, 176.5kN and 174kN, respectively. Figure 8 shows the strain values recorded by the FOS sensors installed on the main reinforcing bar and supplementary bar. It is observed from the figure that FOS performs well in all environments under static loads. The maximum strain values are 10,000 με, 8,800 με, 10,430 με, respectively.

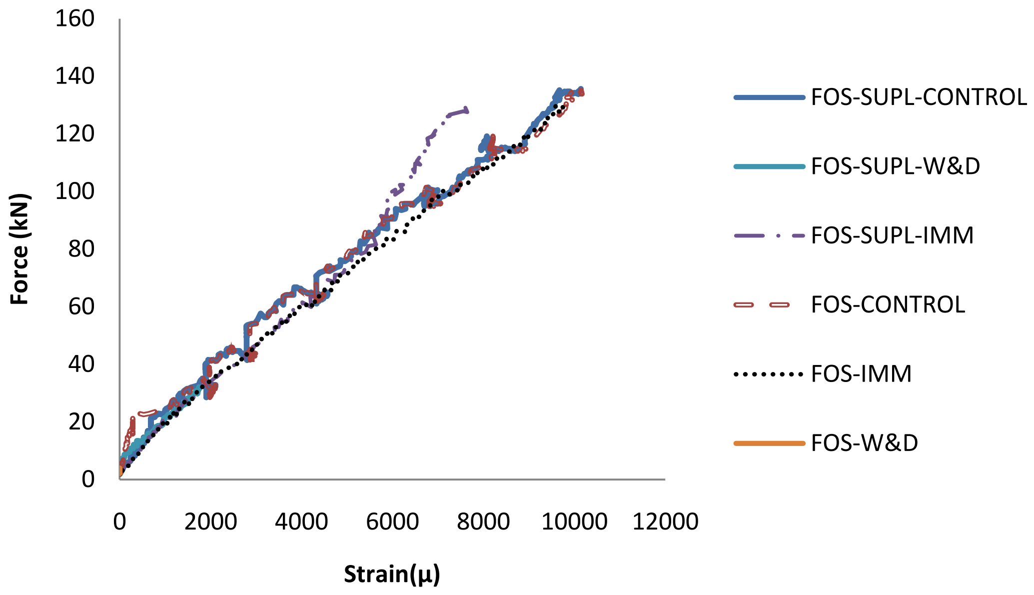

Figure 8: Strain in the supplemental bar and main bar for all conditions from FOS

In W&D, the strains in the supplementary bar and main bar are close with a small lag which is acceptable. In the immersion condition, the strain profile on the supplementary bar as captured by the FOS does not correspond to the main bar strain after 6000 µε. This may have happened due to probable bond failure in the supplemental bar under exposure of constant alkaline solution.

Currently, SEM (Scanning Electron Microscopy) investigations are being carried out by authorand confirmed penetration of alkaline in FRP and will be discussed in future papers. The deviation in ESG strain values from the control to both treated specimen indicates that unlike the FOS (refer to the strain pattern shown in Figure 9), the performance of the strain gauges are affected by the treatments appreciably.

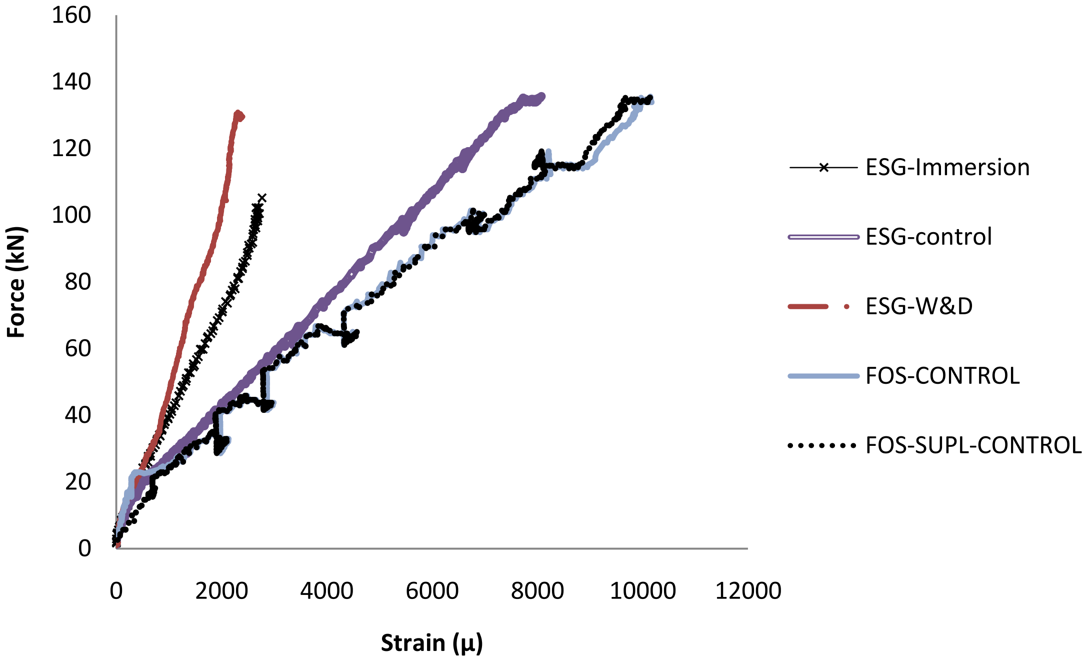

Figure 9:Comparision of FOS and ESG sensors

The main reinforcing bar strain profiles in the control specimen as recorded by FOS and ESGs are shown in Figure9. The maximum strain recorded from control specimen is 9000 (με) in ESG-control which is reasonably good agreement with that obtained using FOS. The mid-span strain recorded by FOS and ESG match quite well up to about 4000 με. For the two beams exposed to alkali solution, the strain as measured by the ESG significantly deviates from the FOS. (As all FOS sensors had similar results, only the results for the control specimen are shown for clarity.) The mass of the beams was measured after applying the treatments, prior to flexural testing. Absorption in immersion and in wet-dry (W&D) conditions was seen by an increase of mass by 1% and 0.5%, respectively. For both adverse conditions, the alkaline solution seems to have effective penetration to the surface of FRP and adhesion of sensor to FRP as the strain recorded deviates from that measured by FOS. The wet and dry cyclic exposure gave lower stains for the same stress when compared to the continuously immersed case. It is possible that the former case gave more alkali penetration to the level of the FRP reinforcement.

4. Conclusion:

The present study focuses on the performance of FBG type FOS in FRP-reinforced concrete elements under flexure. A set of three beams with different environmental exposures have been tested under static flexural loads. While one of the beams serves as the control, the second and third specimens have undergone immersion in alkaline solution and wet and dry condition, respectively. Fibre Optic Strain Sensor and conventional Electrical strain gauges were installed on the FRP rebars used in the beams. Additionally, an instrumented supplemental FRP bar of small length and diameter has been attached to both bottom rebars in each beam specimen to determine the efficiency of this system (i.e., the instrumented supplemental bar) to capture the strain corresponding to the main rebar. The supplemental bar is instrumented with both FOS and ESGs. The results of the present study indicate that FOS strain sensor performs well in all conditions. The conventional electrical strain gauges (ESG) do not perform reliably in these alkaline conditions. The supplementary bar mounted with FOS has been observed to capture the strain pattern of the main rebar quite well in both control and W&D specimens, while it fails to provide reliable information in the immersion condition at higher strains. Further study is necessary to identify the reasons for such failure and devise remedial measures.

Acknowledgement

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