Development of a Long-gage Optical Fiber Sensor for Monitoring of Corrosion Environment

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ABSTRACT

This paper reports the development of a long-gage Fiber Optic Sensor (FOS) reinforced with carbon fiber polymer (CFRP) wire and pre-tensioned after inserting into a corrosion sensitive metal tube for monitoring corrosion environment. The CFRP-wire along with the optical fiber was fixed on the ends of the tube to transfer the prestress to the metal tube. The tube length represents the sensing zone and the strain sensing within the sensing zone is uniform with reasonably high accuracy. The experimental results show that the residual strain of the preloaded optical fiber decreases when the corrosion sensitive metal tube is corroded. The residual strain reduces to zero when the tube is fully corroded. These results demonstrate the feasibility of using optical fiber corrosion sensors for monitoring corrosion environment in civil structures.

Key words: CFRP, long-gage FOS, residual strain.

INTRODUCTION

The degradation by corrosion of industrial plants or other types of metallic structures, corrosion of the reinforcing bar or of the concrete of the civil infrastructures is a very real hazard and the risk of accidents is often linked to a sudden failure or collapse of the structure.Thus, there exists a strong demand for developing non-destructive, in situ and cost-effective techniques to give an early indication of corrosion without significant disassembly, reducing the cost of corrosion maintenance [1,2]. Sensors embedded in or attached to the structures, which could give an early indication of corrosion without significant disassembly, could reduce the cost of maintenance. Several reliable systems to serve this purpose are available in the market. However, the main draw back of these sensors is the incapability of detecting the corrosion distributedly. Since corrosion is a very local phenomenon, distributed sensing of the corrosion environment will help detect it and probability of detection will be increased accordingly.Optical fiber based sensors are good for this purpose due to their small diameter, flexibility and feasibility of remote sensing.

Fiber optic sensors present a promising tool for distributed sensing such as strain, temperature, acceleration etc. Among fiber optic sensors, such as Brillouin back scattering based sensors, Fiber Bragg Grating (FBG) sensor in nature hold better precision and measuring stability, which is more suitable and feasible at present to implement to structural assessment strategy [3].There exists a good number of different examples of the use of optical fibers for in situ monitoring of the durability of materials and structures. The research on optical fiber corrosion sensors fabricated by electroplating an Fe–C alloy film onto an optical fiber core within the sensing region have been reported in references [4,5]. Metalised optical fibers have been developed in order to monitor corrosion in aeronautical structures [2]. Benounis et. al. [6] have developed an optical fiber corrosion sensor by an electroless copper film deposited onto an optical fiber core within the sensing region. Maalej *et al.* [7] developed a corrosion sensor using embedded Fabry–Pé rot fiber optic sensors to detect and monitor the propagation of cracks and delamination within concrete beams induced by corrosion of the reinforcing bars. Lo and Xiao [8] have developed a single pitch Bragg grating corrosion sensor by coating a thin copper shell onto a pre-strained optical fiber at the grating region. The principle of the sensor is that environment corrosion would change the thickness of the coating, and eventually cause the changes of residual strain inside the grating region. Researches regarding the developement of the FOS for monitoring the corrosion are cited above. These sensors primarily focused the detection of corrosion of steel or metalized structures . However, manufacturing of these sensors requires complex equipments and moreover the incapability of measuring the corrosion distributedly motivates for development of a sensor which will be easy to manufacture and will be capable to sense distributedly.

This paper describes the development of a long-gage fiber optic sensor for monitoring of the corrosion environment. This optical fiber sensor was fabricated by pretensioning a CFRP-wire reinforced FBG and fixing the end of the sensing region after inserting the fiber into a corrosion sensitive metal tube. Any change in the residual strain of the FBG sensor indicates the presence of the corrosion environment. The important feature of this sensor is the long gage-length which will help detect the corrosion distributedly.

SENSING PRINCIPLE

The concept of structural damage detection based on distributed long-gage strain sensing technique has been addressed by Li and Wu [9]. Since FBG has high precision and measuring stability over other types of FOS, it was selected for the development of the proposed sensor. The potential for using FBG for measuring the corrosion has been highlighted by some researchers e.g. Lo and Xiao [8]. Within the gage length of the FBG sensor, the stress or strain is not influenced locally by the local change of the stress or strain to be measured by it. This feature of uniform strain sensing within the gage-length favors the concept of long-gage distributed sensing.

The developed sensor consists of two main parts, namely the corrosion sensing part and the corrosion detecting part. The corrosion sensing part is a corrosion sensitive metal tube and in this experiment an aluminum tube was used. The corrosion detecting part is a CFRP-wire reinforced FBG. The corrosion sensitive metal tube serves two functions. Firstly, it is used to receive the environmental corrosion if there is any such environment. It also houses and protects the corrosion detecting part. Construction of the sensor system is very simple and is described in the experimental investigation section.

Working principle of the sensor is very similar to that of a prestressed tensile member. A FBG cable was preloaded and the two ends of the sensing region were fixed after inserting into a corrosion sensitive tube. The corrosion sensitive metal tube if exposed to the environment will receive corrosion if there is any such environment. Any corrosion of the metal tube will change the stress of the tube thus in turn will change the strain of the FBG sensor.

EXPERIMENTAL INVESTIGATION

At first, an optical fiber was pretensioned after inserting into a corrosion sensitive metal tube. For our experiment we used aluminum and steel tubes. The length of the metal tube is equal to the gage-length or the length of the sensing zone. For the experiment, a gage-length of 20cm was selected. Two ends of the sensing zone of the optical fiber were fixed on the ends of the tube. Thus the stress was transferred to the tube. Electrical corrosion was given to the metal tube according to the experimental setup shown in Fig.2. The tube receives corrosion and its stiffness gets reduced as the time progresses. Corrosion of the tube is recognized by the reduction of the residual strain of the FBG. Fig.3 shows the change in residual strain of the FBG during the corrosion process. A sudden drop of the residual strain can be seen in Fig.3. It is obvious that this sudden change in residual strain is due to the sudden breaking of the tube which was caused by the electrical corrosion. Very high ratio of the stiffness of metal tube to that of FBG is the primary cause of this hindrance in monitoring the whole corrosion process. Therefore, stiffness of the optical fiber should be increased to detect the corrosion process continuously. A CFRP-wire is used to serve this purpose.

CFRP-wire was made up of carbon fibers. Epoxy was impregnated onto the carbon fibers and was twisted to make a wire of about 1.2mm diameter. It was kept at least for 24 hours at room temperature to get hardened. The FBG was laid onto the surface of the CFRP-wire and the selected sensing zone was bonded using epoxy. The CFRP reinforced FBG was kept for curing for 24 hours at room temperature. The CFRP reinforced FBG was inserted into a corrosion sensitive metal tube and pretension was given by pulling the CFRP-wire from both ends. Both ends of the CFRP reinforced FBG was next fixed onto the ends of the metal tube to transfer the prestress to the metal tube. The details of the sensor packaging is given in Fig. 1. Accelerated electrical corrosion was given to the metal tube. Strain distribution over the gage-length is considered uniform before and after the initiation of corrosion in the metal tube.

The corrosion process of the tube can be affected by many factors, e.g. rate of current flow, solution strength, tube material, etc. However, rate of current flow and solution strength were considered as the primary controlling factors for the experiment and the electrical corrosion at different rates was given by varying these two controlling parameters. Pretension for different specimen were at a varied level and this factor was not considered responsible for the monitoring of the corrosion process with time. Primarily, aluminum and steel were chosen as the tube materials. The experimental controlling factors for different specimens are listed in Table 1. The loss of tube material

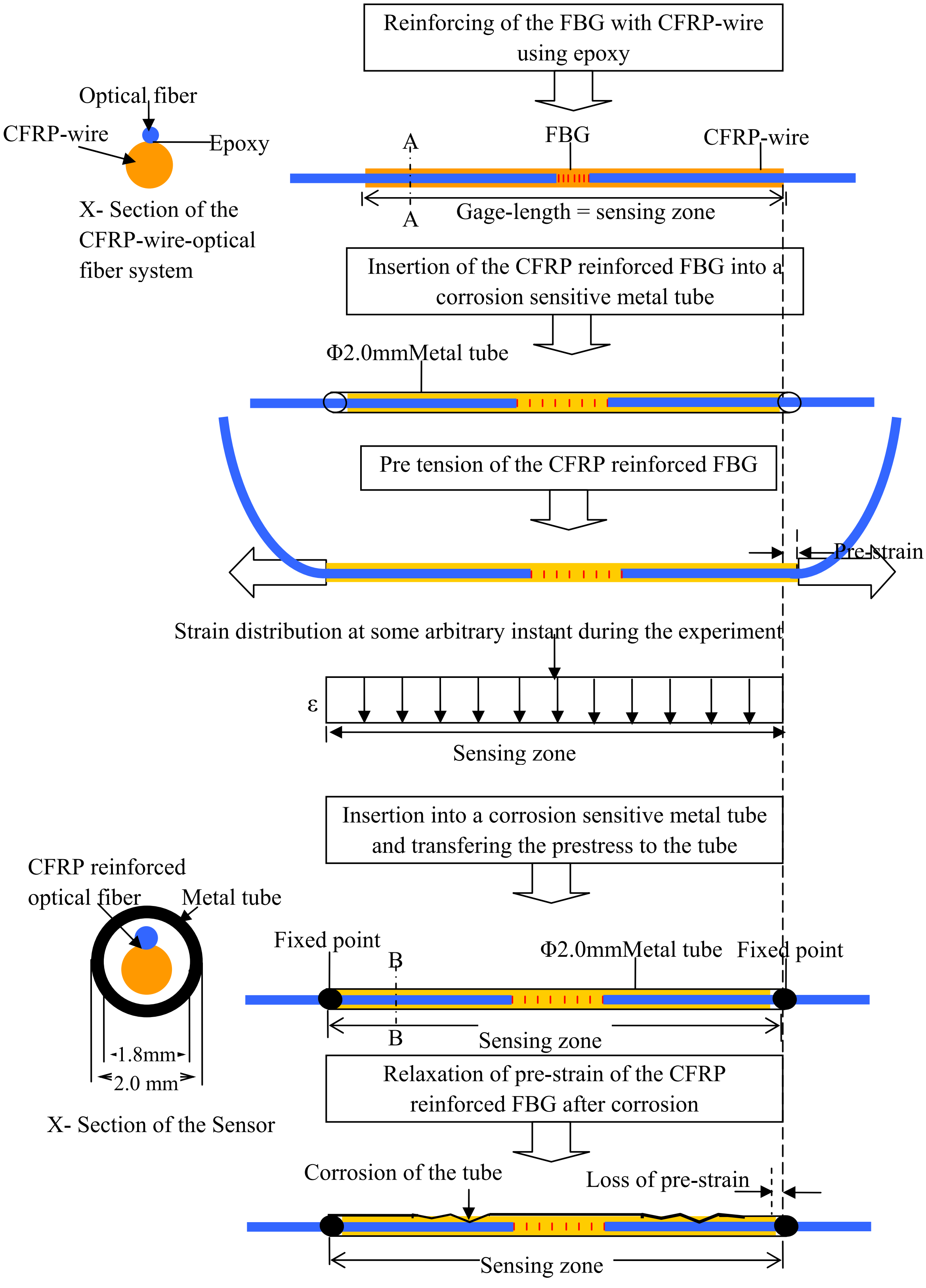


Figure 1: Packaging of the sensor.

which is the measure of the corrosion environment was detected by the reduction of the residual strain of the optical fiber. The residual strain of the CFRP-reinforced was found decreasing as the corrosion progresses with time. The experimental results are explained in the results and analysis section.

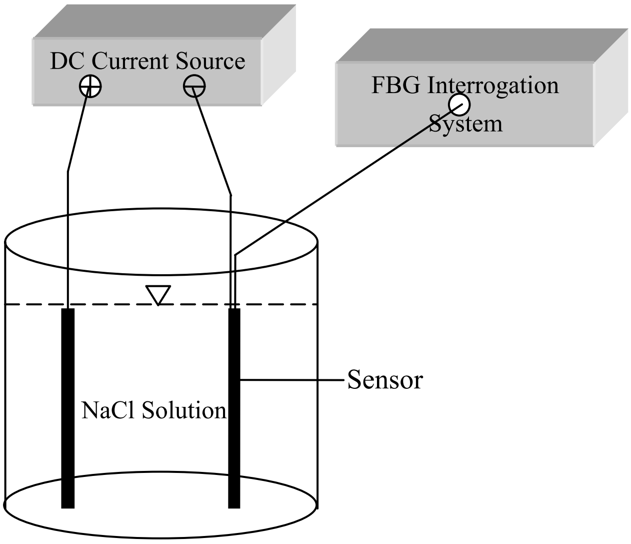


Figure 2: Experimental setup.

Table 1: Controlling parameters of the specimens.

Specimen No.	Tube Material	Solution Strength (%)	Rate of Current Flow (Amp)	CFRP Reinforced
A	Aluminum	3.00	1.0	No
B	Aluminum	3.00	1.0	Yes
C	Aluminum	3.00	0.5	Yes
D	Aluminum	1.25	0.5	Yes
E	Steel	1.00	0.3	Yes

RESULTS

Fig.3 and 4 represent the experimental results. Fig.3 shows the experimental result obtained by pre-tensioning the FBG without reinforcing. There is a sudden change in residual strain and the strain falls below 500μ from 2000μ. Time taken for full corrosion of the tube was about 1600 sec and the sudden drop of the residual strain was occurred at 1500 sec. There is no other clear indication of strain loss before this sudden drop in strain. The sudden change in strain was caused by the breaking of the tube. Since the tube did not break suddenly, however, it was corroded continuously; the sensors should be able to detect the process continuously. The change in strain is proportional to the change in tube material. However, very low stiffness of the fiber optic cable in comparison with the stiffness of the tube hinders the continuous detection process. The sensor responded only at the verge of breaking of the tube where its stiffness is almost reduced to the stiffness of the fiber optic cable. To improve the sensor performance for detecting the corrosion process and its progress with time, stiffness of the FBG should be increased.

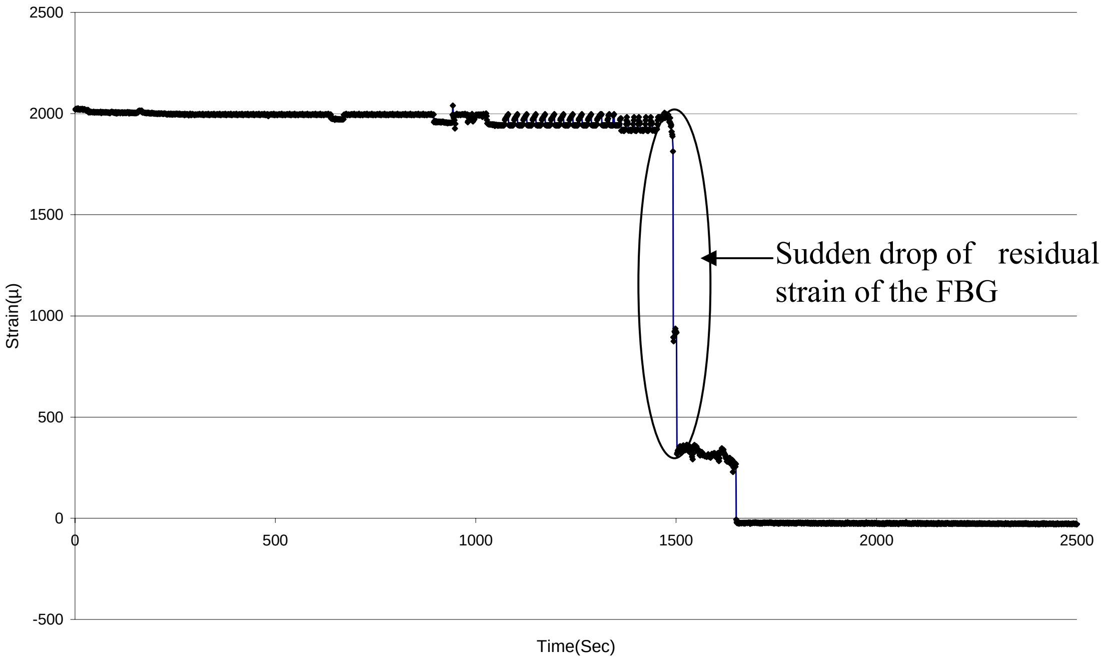
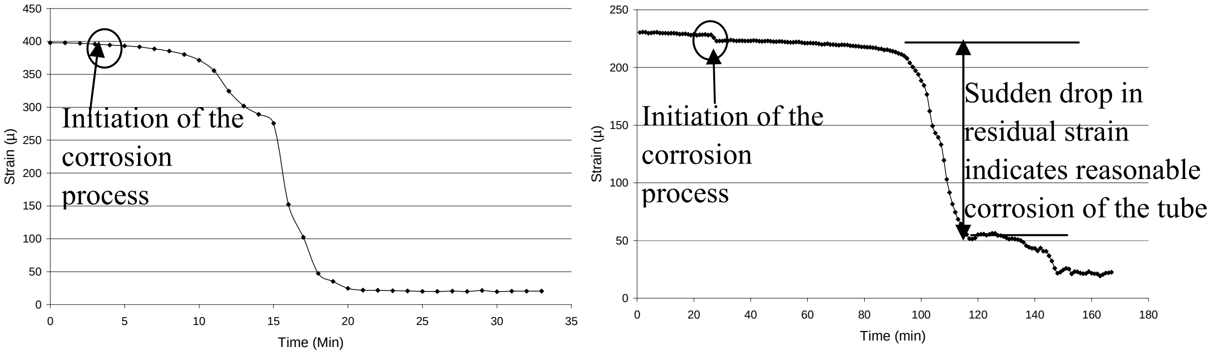


Figure 3: Change in strain during corrosion process of FBG without CFRP reinforcing (Specimen A).

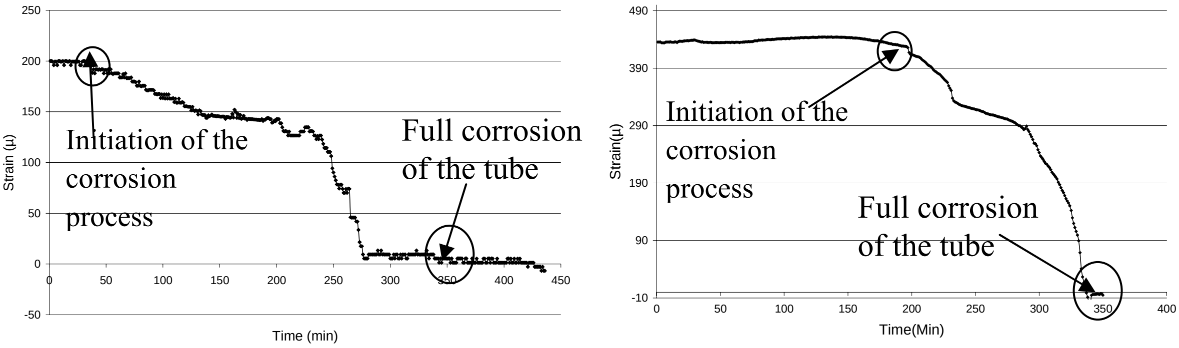
Fig.4 shows the experimental results obtained using the FBG reinforced with CFRP-wire. It is obvious that there is significant improvement in the corrosion monitoring process after reinforcing the optical fiber with CFRP-wire. Fig. 4(a) represents the result of the first introduction of the CFRP-wire with controlling factors similar to that used for specimen A. The initiation of the corrosion was detected by the sensor and the nature of the strain-time curve showing the corrosion progress. The corrosion rate was very high for this case and the corrosion rate was lowered by reducing the rate of current flow from 1 Amp to 0.3 Amp and the solution strength from 3.0 % to 1.0 % NaCl for the remaining specimens. Fig. 4(b) shows the result obtained using solution strength of 3% NaCl and a reduced current flow of 0.5 Amp. The residual strain was also reduced in this case and the sharp change in slope of the strain-time curve indicates the sensors drawback in detecting the initial corrosion of the tube. The corrosion rate was further reduced by reducing the solution strength and the initiation of the corrosion process was primarily detected as shown in Fig.4(c). Time taken for the initiation of corrosion process is about 40 minutes for this specimen which is greater than that of specimen C. This was caused by the lowered corrosion rate which indicates the agreement between the sensor performance and the corrosion rate. Fig.4 (d) represents the result obtained using the lowest corrosion rate used so far. Initiation of the corrosion process was detected by the sensor. Although the rate of corrosion was reduced the time taken to corrode the tube fully is not significantly higher than that for specimen D.

Time for full corrosion of the tube depends on the rate of corrosion and more time will be needed for the tube to be corroded fully if the corrosion rate is lowered. Experimental results reflect this fact. Time taken by specimen B, C, D and E for full corrosion is 30, 170, 340 and 350 minutes respectively. The corrosion rate was also at a decreasing order. This reflects the good agreement of the sensor performance with the reduction of corrosion rate. There is also good agreement between the initiation of the corrosion process and the corrosion rate. Time taken for initiation of the corrosion process for specimen B, C, D and E is 4, 30, 40 and 180 minutes respectively. Since the corrosion rate was at a decreasing order, time for the initiation of the corrosion process should be in increasing order.



(a) For specimen B

(b) For specimen C



(c) For specimen D

(d) For specimen E

Figure 4: Change in strain during corrosion process of the FBG reinforced with CFRP wire.

CONCLUSIONS

This study focused on the development of a fiber optic distributed sensor for monitoring of the corrosion environment. A sensor construction technique along with some experimental results has been presented in this paper which indicates the promising features of the sensor. The corrosion rate used for the experiment is still very high and there is a basic need for investigating the performance of the sensor to detect the low corrosion rate that a structure challenges normally. Along with this factor, detail analysis and the correlation between the sensed data and structural behavior are yet to be developed. These will be done in our future studies.

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