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# A NOVEL OPTICAL FIBER SENSOR FOR STEEL CORROSION IN CONCRETE STRUCTURES

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## Abstract

For reinforced concrete structures, steel corrosion resulting from the penetration of chloride ions or carbon dioxide is a major cause of degradation. The objective of the present investigation is to develop a low-cost sensor for steel corrosion, which is based on a very simple physical principle. The flat end of a cut optical fiber is coated with a thin layer of iron. Light is then sent into a fiber embedded in concrete and the reflected signal is monitored. Initially, most of the light is reflected by the iron layer. When corrosion occurs to remove the iron layer, a significant portion of the light power will leave the fiber at its exposed end, and the reflected power is greatly reduced. Monitoring of the reflected signal is hence an effective way to assess if the concrete environment at the location of the fiber tip may induce steel corrosion or not. In this paper, the principle of the corrosion sensor and its fabrication are first described. Then, preliminary experimental results are presented to illustrate the feasibility of the sensing principle. An ongoing test to compare the sensor with a conventional corrosion detection method is described. A plausible packaging approach of the sensor is also discussed.

## INTRODUCTION

Reinforced concrete structures make up a large portion of the physical infrastructure of the world, and their durability is an issue of great concern. Steel corrosion is a major culprit for the degradation of concrete members. In order to perform proper maintenance which can extend the lifetime of concrete structures, techniques for steel corrosion detection need to be developed. Within the alkaline environment of concrete, steel is in a passivated state, with negligible corrosion rate. However, when carbon dioxide and chlorides penetrate through the concrete cover to reach the steel, depassivation occurs and the corrosion rate becomes significant. One approach to assess the corrosion of steel is hence to measure the carbonation depth or the chloride profile in the concrete structure. The conventional approach is to perform chemical analysis on samples cored from the concrete structure. A detailed description can be found in [1]. For carbonation, phenolphthalate solution is often applied to the sample to identify the depth where color change occurs. However, since the pH at which color change occurs is not the same as the pH below which steel corrosion may occur, some subjective judgment is required for interpreting the results. For chloride penetration, the cored sample is further sliced into thin sections, and each section is ground into powder for

chemical analysis. While this can provide an accurate chloride profile in the structure, a major limitation should be pointed out. The chloride concentration does not have a direct correlation with steel corrosion [2]. The critical chloride concentration beyond which steel is depassivated depends also on the pH of the concrete, and this exact relation is not known. Indeed, different researchers ([3], [4]) have come up with different relations between the critical chloride concentration and pH. As another major drawback, taking cores from a large concrete structure at critical locations is often difficult and costly. As a result, the coring operation can only be occasionally performed.

Embeddable corrosion sensors have been developed and installed in concrete structures. The most notable example is the 'ladder' sensor developed in Germany [5]. Parallel steel rods are fixed across two parallel rails to form a small ladder. The ladder is then placed inside a concrete structure in such a way that the rods are at different depths from the surface. By comparing the potential of each rod with a reference electrode, one can assess if corrosion has occurred at the level of a particular rod. The penetration of the corrosion front is then obtained. Note that a major advantage of this technique is the actual assessment of corrosion activity, rather than measuring a variable (such as chloride concentration) for indirect inference of whether corrosion has occurred. A disadvantage of the technique is the relatively high cost associated with the sensing system, and the fact that the 'ladder' sensor is only applicable to new structures. Recently, a cylindrical sensor, based on the same principle has been developed [6]. The cost is still relatively high. Also, when a hole is cored in an existing concrete structure for installing the cylinder, the prevention of preferential chloride penetration along the sensor/concrete interface is an important issue that needs to be further studied.

Optical fiber sensors for chloride detection have also been developed [7]. A particular chloride sensitive solution or indicator paper is brought into contact with concrete. Broad-band light is then sent from one optical fiber through the solution (or paper) to another fiber. In the presence of chlorides, formation of precipitates in the solution or color change of the paper will lead to changes in the intensity or spectrum of the transmitted light. For this sensor, an ingenious installation technique, which allows the sensor to be changed over the life span of the structure, has been developed. A limitation of the sensor is that it cannot be applied to existing concrete structures. Also, it is quite large in size, so if a large number of sensors are to be employed to monitor chloride profile at various locations, the installation becomes very inconvenient. Another optical fiber sensor was developed by [8]. The cladding of the optical fiber is made with a special polymer that is sensitive to the environment. Change in chloride concentration will lead to a change in properties of the fiber cladding. The corresponding change in the evanescent wave can be monitored through optical spectroscopy. While this is certainly a powerful technique, the principle is rather complicated, and specialists are probably required to perform the interpretation. Also, both optical techniques suffer the limitation that the measurand is the chloride concentration, which does not have a one-to-one relation with corrosion activity [2].

This investigation reports preliminary work on the development of a novel optical fiber corrosion sensor. In the following, the physical principle is first explained, and preliminary experiment results are presented to illustrate the feasibility of the sensing concept. Ongoing experiments to compare the corrosion capability with existing methods will be described, and issues related to sensor packaging for practical applications are discussed.

## PHYSICAL PRINCIPLE

The novel corrosion detection method is based on the simple principle of light reflection illustrated in Fig.1. An optical fiber is stripped and cut with a cleaver to produce a flat surface at its end that is perpendicular to the fiber axis. Using the ion sputtering technique, a thin iron film (thickness around several hundred nanometers) is deposited on the cut fiber surface. Light is then sent through the optical fiber and the reflected power is monitored as a function of time. Initially, the iron film at the end of the fiber acts like a mirror and all or most of the light is reflected (Fig.1(a)). As corrosion occurs, the film thickness decreases with time. Consequently, the reflected signal also drops (Fig.1(b)). Ultimately, after the film is completely removed, the reflected power will show a large decrease, as most of the light energy is now able to disperse thorough the fiber end to the surroundings.

Compared to other corrosion sensors, the 'reflection' sensor possesses a number of advantages. Since the principle is very simple, interpretation of results is easy and direct. It is applicable to corrosion induced by either chloride penetration or carbonation. The technique does not require the use of special optical fibers, and low-cost single mode telecommunication fibers can be employed. In the sputtering process, a large number of fibers can be placed

in the sputtering chamber and coated at the same time. Mass production of the sensor at low cost should therefore be possible. Moreover, with the small size of the sensor, it can be retrofitted to existing structures. Two plausible ways to install the sensor are illustrated in Fig.2. For a bridge with a boxed section, a hole of

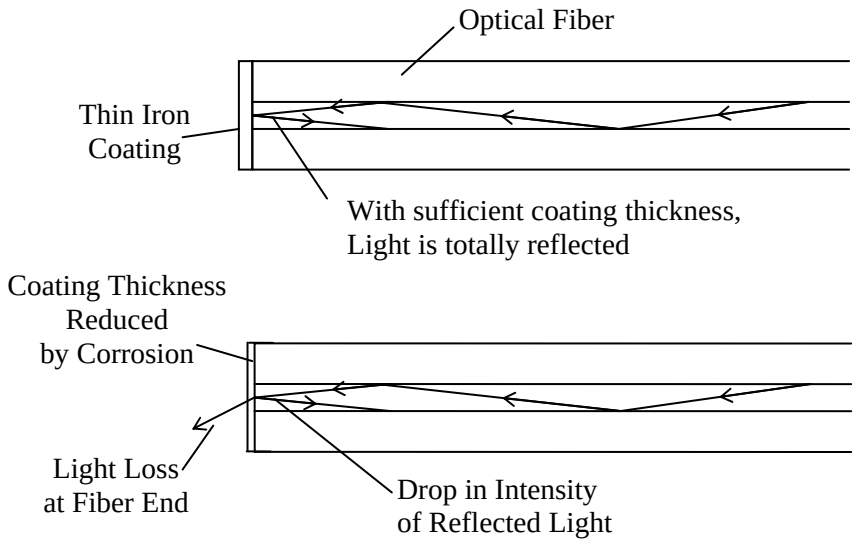


Figure 1. Illustration of the corrosion sensing principle.

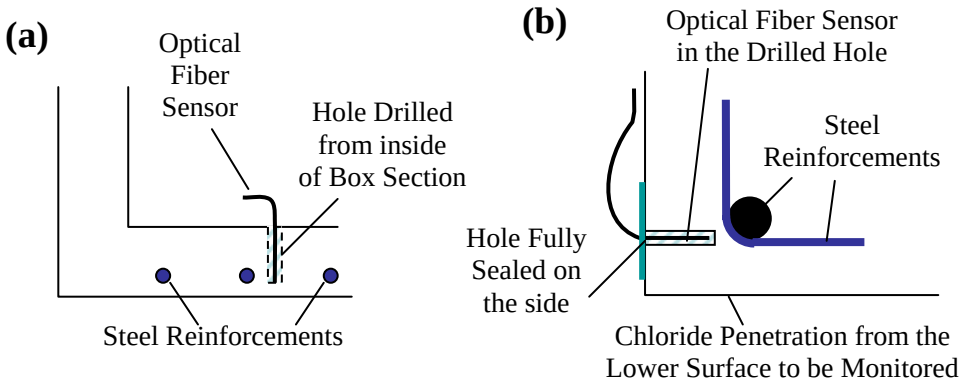


Figure 2. Plausible ways for installing the sensor on an existing structure with (a) boxed section, (b) solid section.

required depth can be drilled from the inside of the box for placement of the sensor (Fig.2a). To monitor chloride or carbon dioxide penetration from a surface of a solid section, the hole can be drilled on a perpendicular surface and sealed. With these approaches, the drilled hole will not act as an easy diffusion path that will affect the monitoring results. Since the monitoring involves light intensity measurement, to avoid variations due to fluctuations in the light source, and changes in connector efficiency when fibers are disconnected and re-connected, the loss in reflected light power is best measured with an optical time domain reflectometer (OTDR). This method measures the relative power of light reflected at points along the fiber, and that at the fiber end. Since it is a relative measurement, results will not be affected by the variations mentioned above.

## VERIFICACTION OF THE DETECTION PRINCIPLE

Experiments have been performed to demonstrate the feasibility of corrosion detection with the approach described above. To form an iron film with controlled thickness on the cleaved end of the optical fiber, the sputtering deposition technique was employed. The fibers were placed inside a vacuum chamber, with the cleaved ends facing an iron target. The sputtering process involves the bombardment of target with energetic ions to induce the ejection of vapor particles. Inside the vacuum, the vapor will deposit as a thin film on the surface of the fiber. The film thickness depends on the distance of the fiber from the target as well as the deposition time. Before the coating of fibers, a calibration experiment was performed using a glass plate with a strip of thin tape bonded to its surface. The plate was placed at a distance to the target that was equal to the fiber/target distance in the actual sputtering process. Sputtering deposition was performed for different periods of time. After the deposition process, the tape was removed and the thickness of iron film was obtained from the surface profile measured along the coated glass plate. With the calibration experiment, the relation between film thickness and deposition time was found.

To perform the verification experiment, iron film of 100nm thickness was deposited to the end of optical fibers. As a first test of the sensing concept, the coated end of optical fibers were dipped into calcium hydroxide solutions (pH=13) with 0.1 mol, 0.5 mol and 1.0 mol of sodium chloride respectively. The reflected signal from the fiber end was monitored daily with an optical time domain reflectometer (OTDR). The variations of optical loss (in dB) with time (in days) under different chloride concentrations are shown in Fig.3. It should be pointed out that an optical fiber sensor has also been placed in alkaline solution with no sodium chloride added, and no change in optical power was observed after 2 months. Based on the test results, two observations can be made. Firstly, the presence of corrosive agent (chloride ions) leads to a drop in reflected optical power with time, which can be attributed to the gradual removal of the iron film on the fiber end. Secondly, the rate of power drop which represents the corrosion rate of the film increases with increasing chloride concentration. These findings demonstrate the feasibility of corrosion detection with the proposed sensing concept.

A second set of experiment was performed to investigate the corrosion sensing capability inside the actual concrete environment. Optical fiber sensors are cast inside

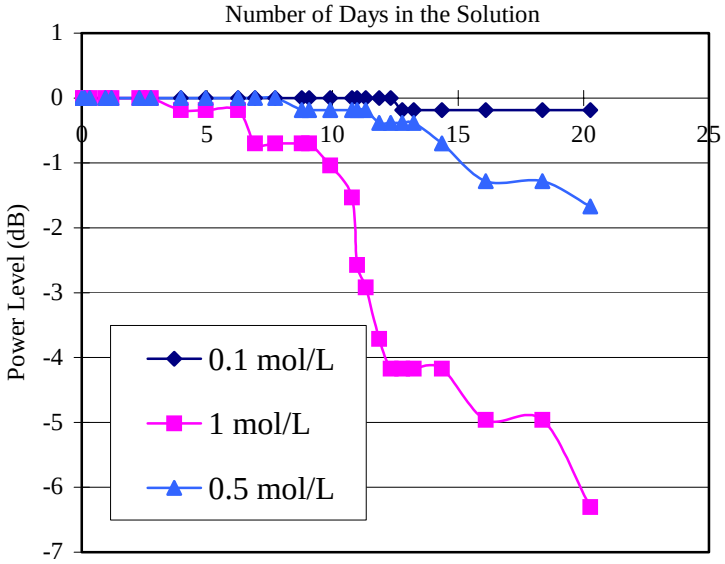


Figure 3. Effect of chloride concentration on corrosion sensor output.

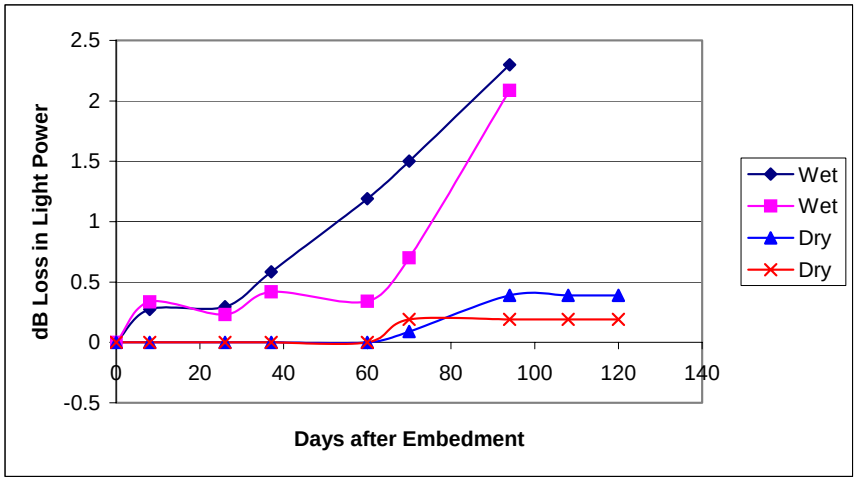


Figure 4. Output from sensor embedded in concrete under different environments.

small blocks of mortar with a water:cement:sand ratio of 0.5:1:2. Also, sodium chloride was added at 5% the weight of cement. After curing for 7 days, two specimens were placed inside a warm water bath at 30°C. Another two specimens were taken out of the curing room and exposed to the dry laboratory environment. For each specimen, reflection from the embedded optical fiber sensor was monitored as a function of time. The results are shown in Fig.4 for both the wet and dry specimens. When kept wet, corrosion (which is indicated by power loss) starts much earlier and occurs to a much larger extent. For the specimen in the laboratory environment, which is relatively dry but not completely dry, corrosion starts to occur after 2 months, and does not reach a high level. The experimental findings indicate that the sensor can detect chloride ions inside the concrete environment, and it can distinguish between the seriousness of corrosion activities under different environments.

In the above tests, the sensors are tested on their own to show that they can respond to chlorides in the environment. In real application, however, we would like to know if the sensor output can provide information on the corrosion of steel inside a concrete structure. In other words, if the sensor is attached to a steel reinforcing bar, on the side facing the concrete surface, would steel corrosion occur at about the same time (or slightly later) when the reflected power from the corrosion sensor starts to decrease? To address this question, the test illustrated in Fig.5 can be conducted. The set-up is a variation of the common set-up to compare the effectiveness various concrete in protecting steel against corrosion. A salt water reservoir is placed on top of a concrete prism, to provide a source for chloride ions that will penetrate into the concrete specimen. A steel reinforcement, 10mm in size, is placed near the top with a cover of 15mm. At the top of the steel reinforcement, an optical corrosion sensor is placed. Two additional steel rods are also placed close to the bottom of the member. During the test, the reflected power from the sensor is measured at different times. Also, the voltage over a resistor between the upper and lower reinforcements is measured to calculate the macrocell current. Since the bars at the bottom of the specimen should not corrode, an increase in macrocell current indicates the onset of corrosion at the upper bar. The corrosion initiation times obtained from the optical power drop and macrocell current can hence be compared. Using the set-up in Fig.5, several specimens have been prepared and monitored for more than 2 months. However, no change has yet occurred in both the optical power and the current. The test will be continued, and it is hopeful that some results will become available to be presented at the conference.

## PACKAGING OF THE SENSOR

The sensor employed in the above experiments is simply a bare fiber with iron coating. The installation of sensor into concrete has to be conducted with great caution to avoid fiber breakage. While this is achievable in the laboratory, field application of the sensor requires proper packaging to make it robust against the concrete casting process. A preliminary design of the packaged sensor is illustrated in Fig.6. A very thin and small plastic tube is placed on a flat surface, with its longitudinal axis along the vertical. A mortar made with sand less than 1 mm in size, and high water/cement ratio is used to fill

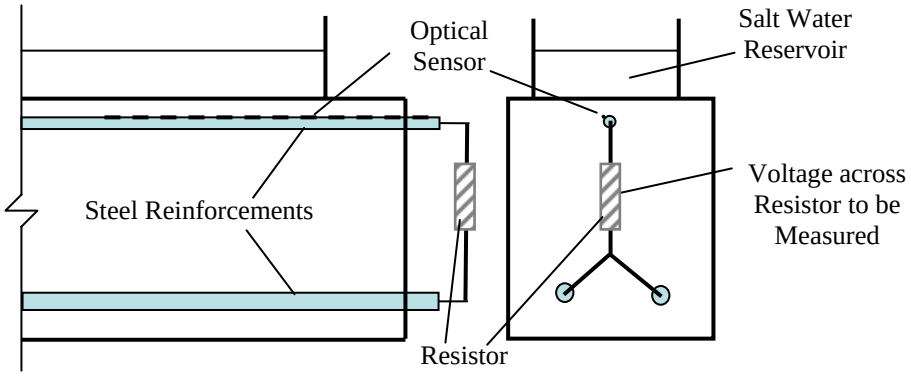


Figure 5. Set-up to compare optical sensor output with corrosion current of steel.

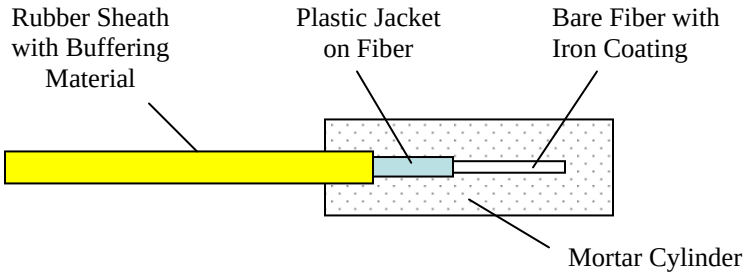


Figure 6. Fiber sensor packaged inside a mortar block.

up the tube. A coated optical fiber is inserted slowly into the fresh mortar until the part protected by the rubber sheath enters the mortar. The fiber is held in this position until the mortar hardens. The thin plastic tube is then removed to give a sensing head consisting of a cylindrical mortar block encasing the optical fiber sensor inside (see Fig.6). A high water/cement ratio mix is chosen for the mortar so chlorides and carbon dioxide can penetrate easily to reach the end of the optical fiber. Note that the optical fiber would not be attacked by the alkaline mortar, as all exposed glass surfaces are covered with iron film during the sputtering deposition process. We have packaged the sensor into 5mm diameter mortar cylinders and attached them to steel reinforcements before concrete is cast. They are found to be able to survive the casting process. In the future, the packaging method will be further developed to come up with sensing heads of different geometries and smaller size.

## CONCLUSIONS

In this paper, we have presented a new fiber optic sensor to detect if a particular environment is inductive to steel corrosion. The physical principle is based on the corrosion of a thin iron film at the end of an optical fiber, which will reduce the reflected power from the fiber end. Preliminary experimental results indicate that the sensor can detect the presence of chloride ions, either in solution or inside concrete. Also, the change in sensor output is dependent on the chloride concentration or moisture condition of the surrounding environment. While further work

is certainly necessary to fully verify the applicability of the sensor, the preliminary results do illustrate the feasibility and potential of the proposed sensing technique.

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## REFERENCES

1. Broomfield, J.P. 'Corrosion of Steel in Concrete' (E & FN SPON, London, 1997).
2. Bentur, A., Diamond, S. & Berke, N.S. Steel Corrosion in Concrete, (E & FN SPON, London, 1997).
3. Hausmann, D.A. 'Steel Corrosion in Concrete', Materials Protection, 6(11) (1967) 19-22.
4. Diamond, S. 'Chloride Concentrations in Concrete Pore Solutions Resulting from Calcium and Sodium Chloride Admixtures', Cement and Concrete Aggregates, 8(2) (1986) 97-102.
5. Schiessl, P. and Raupach, M. (1992) 'Monitoring System for the Corrosion Risk for Steel in Concrete', Concrete International, 14(7), (1992) 52-55.
6. Raupach, M. 'Corrosion Behaviour of the Reinforcement under On-Site-Conditions', Proceedings of 15th International Corrosion Congress, Frontiers in Corrosion Science and Technology, Granada, 2002, Art.096.
7. Huston, D.R. and Fuhr, P.L. 'Distributed and Chemical Fiber Optic Sensing and Installation in Bridges', in Fiber Optic Sensors for Construction Materials and Bridges, edited by F. Ansari, (1998) 79-88.
8. Ghandehari, M. 'Ingress Monitoring in Concrete Structures', Proceedings of the 15th ASCE Conference on Engineering Mechanics, New York, (2001), CD-ROM