Novel sensor design using photonic crystal fibres for monitoring the onset of corrosion in reinforced concrete structures

Colum McCague, Matthias Fabian, Mohammad Karimi, Mikel Bravo, Leszek R. Jaroszewicz, Pawel Mergo, Tong Sun and Kenneth T. V. Grattan

***Abstract*— In this paper, a novel sensing technique has been designed and investigated for the direct, *in-situ* detection of steel corrosion distributed in reinforced concrete structures. At present, structural health monitoring (SHM) in reinforced concrete structures is generally focused on monitoring the corrosion risk of the reinforcing steel. It is of significant importance, however, to inform industry of both the onset of corrosion and the corrosion rate as these are key contributors to structural degradation and thus evaluating the service life of the structures. This paper aims to address the above challenges by describing a novel corrosion sensor design using birefringent photonic crystal fibres (PCFs). The technique exploits fully both the birefringence of the fibres for force/pressure measurement and their very low temperature sensitivity to detect the onset of corrosion. This new type of sensor not only determines the onset of corrosion but also allows for better monitoring along the length of a reinforcement bar.**

***Index terms*— Optical fibre sensors (OFSs), photonic crystal fibre (PCF), pressure sensor, fibre loop mirror, structural health monitoring**

I. INTRODUCTION

Over the past century, reinforced concrete has become the most widely used construction material in the built environment [1]. One of the key challenges facing the industry is to design reinforced concrete that will stand the test of time while retaining its integrity during the expected lifespan. One of the main pitfalls of concrete as a construction material is its inability to fully prevent corrosion of the reinforcing steel. While much advancement has been made in terms of protecting against corrosion (i.e. improvements in concrete durability), there is always the risk that corrosion may occur. As a result, corrosion monitoring in concrete structures has now become a major component of the design process. The importance of this was properly recognized in the late 1970s [2], after the degradation of reinforced concrete structures by corrosion was seen as a reality.

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At present, a number of techniques are available to assess the likelihood of reinforcement corrosion in concrete structures [3-5]. These include electrochemical techniques which, under normal working conditions, can give reasonably accurate information relating to parameters such as the steel corrosion rate and the chloride ion concentration. However, with each of these techniques it is difficult to achieve continuous measurement and in most cases rigorous surveys must be carried out manually, on site.

Optical fibre sensors (OFSs) are now becoming increasingly popular in the field of structural health monitoring (SHM). Compared to conventional electrochemical sensing techniques, OFSs have many characteristics which make them more favourable for SHM including: small size and light weight, immunity to electromagnetic interference, stability of material and good multiplexing capabilities [6]. The concept of SHM using OFSs has been recognized for some time although the industry has been very slow to implement and standardize many such proven forms of measurement. This is mainly due to the high cost of the existing OFS systems and some key issues which require to be addressed to meet industrial standards, such as durability and long term stability.

Over the past decade, the potential for using OFS techniques to monitor the corrosion of metals has been explored. The most popular method has been to replace part of a fibre cladding with the metal under study and monitor changes in transmitted power due to corrosion [6, 7]. This technique simulates what may happen with nearby steel reinforcement, however, no information of the actual rebar corrosion is provided. In addition, the sensing principle is usually intensity-based, which is known to suffer from limitations of low signal-to-noise ratio and inaccuracy due to fluctuations of the light source. The long period grating (LPG)-based technique has also been reported for monitoring the corrosion of reinforcement in concrete [8, 9] which takes full advantage of fibre sensitivity to the refractive index variation of the surrounding environment caused by the changes in ion concentrations [10, 11]. More recently, strain measurements using Fibre Bragg Gratings (FBGs) have been reported, in an attempt to directly monitor the corrosion at the steel-concrete interface [12-17].

However, the above OFS techniques can only be used to monitor corrosion at discrete locations where the sensors are installed, but the initiation of corrosion may occur at any point of the rebar, even at locations where there is no sensor installed. Therefore, there is a real need for a monitoring system which is able to alert the onset of corrosion irrespective of its location. This paper aims to address this challenge by using a pressure sensing technique based on the polarization characteristics of a polarization-maintaining (PM) photonic crystal fibre (PCFs), in an attempt to accurately determine the onset and development of corrosion along embedded reinforcement bars.

II. SENSING PRINCIPLE

Corrosion is an electrochemical process involving chemical reactions and the flow of current between anodic and cathodic sites on the metal surface. When steel corrodes in concrete, rust is deposited at the anodic site (area of steel that has a more positive potential in relation to the cathode) and can occupy a volume many times the volume of the original metal [18]. The expansive forces can eventually exceed the tensile strength of the surrounding concrete, leading to cracking and degradation of the structure. This work is focused on the development of a fully distributed sensor system using a birefringent PCF which is able to capture the expansion force/pressure caused by this rust-forming process.

The sensitivity of birefringent PCFs to changes in applied lateral pressure was recently investigated by some of the authors [19, 20]. Fig. 1 shows the experimental setup, in which an interferometric fibre loop mirror (FLM) is used to convert the birefringence variation of the fibre as a result of the change in lateral pressure into interference pattern shift which is monitored by an optical spectrum analyser (OSA). The peak shifts can be measured and therefore translated into changes in pressure.

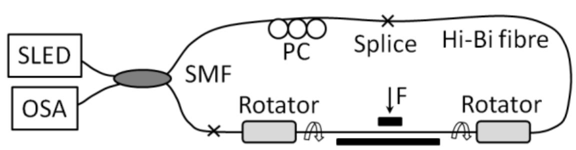

Fig. 1 The setup for characterizing different PCFs based on changes in lateral pressure [19]

The setup consists of a superluminescent light emitting diode (SLED) with emitting wavelength being centered at 1550 nm, a 3dB coupler made on singlemode fibre (SMF) which splits the input signal into two waves that counter propagate along completely identical paths and thus experience the same loss. The FLM configuration has shown low insertion loss, polarization independence to input light, broad spectral bandwidth and high resistance to environmental changes as the two waves propagate through identical paths. The extinction ratio of the interferance can be maximized using a polarization controller (PC) within the loop. Rotators allow the adjustment of the fibre orientation until an evenly distributed, maximum sensitivity is achieved. Compared to conventional HiBi fibres (such as the panda type), HiBi PCFs are less sensitive to changes in temperature making them more suited for environmental applications [21].

The OSA application gives the possibility for measuring the output transmission spectrum T of an optical FLM is described by [22] as:

$$T = [cos(\varphi/2)\ sin(\theta_1 + \theta_2)]^2 \tag{1}$$

where θ_1 and θ_2 denotes the angle of rotation of the polarization state when propagating light enters the HiBi PCF and $\varphi = 2\pi LB/\lambda$ is the phase difference, where λ is the guided wavelength, L is the sensor fibre length, $B=n_x(\lambda)-n_y(\lambda)$ is the birefringence, and $n_x(\lambda)$ and $n_y(\lambda)$ are the effective refractive indices of the fast and slow fibre axis, respectively.

The phase difference φ in equation (1) changes in response to fibre length and birefringence of which both are affected by mechanical load variation and temperature. Therefore, the wavelength shift $\Delta\lambda$ in the detected transmission spectrum due to temperature and transverse mechanical load variation can be written as:

$$\Delta\lambda \approx \left(L\frac{\partial B}{\partial T} + B\frac{\partial L}{\partial T}\right)\Delta T + (L\frac{\partial B}{\partial F} + B\frac{\partial L}{\partial F})\Delta F \tag{2}$$

where ΔT is the temperature variation and ΔF the mechanical load variation. $\partial L/\partial T$ and $\partial L/\partial F$ describe the elongations of the fibre due to the temperature and mechanical load variation, respectively. These are, however, negligible parameters [23] compared to birefringence change under the force. As PCFs are highly insensitive to temperature variation [21], equation (3) can thus be re-written as:

$$\Delta\lambda \approx L_f \frac{\partial B_F}{\partial F}\Delta F \tag{3}$$

where L_f is the fibre length and $\partial B_F/\partial F$ is the birefringence variation coefficient introduced by the measured lateral mechanical load. $\partial B_F/\partial F$ remains constant depending on the material properties including photoelastic coefficients, Young's modulus and Poisson's coefficient. It is clear from equation (3) that the wavelength shift is directly proportional to the transverse mechanical load.

III. SENSOR FABRICATION AND INSTRUMENTATION

For this study, the HiBi PCF type 070107P2 (B = 1.446 x 10^{-3} at 1550 nm, Ø = 96 µm, d = 1.4 µm, D = 2.7 µm, Λ = 3.1 µm where d - small hole Ø, D - large hole Ø and Λ - distance between adjacent holes) (UMCS, Poland) was chosen due to its higher sensitivity and sharp interference pattern at relatively short lengths. The setup devised by Karimi *et al* [19] was employed for aligning the sensing fibre before mounting on a steel rebar. A HiBi PCF (250 mm Ø) of L = 170 mm was fusion spliced to two lengths of single mode fibres (SMFs) and inserted into the rotators. A schematic of the alignment process is shown in Fig. 2.

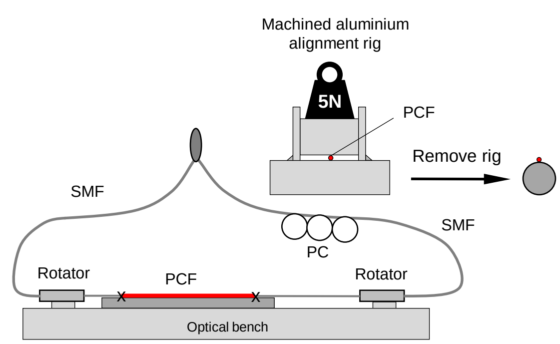

Fig. 2 Schematic of the alignment rig used in this work

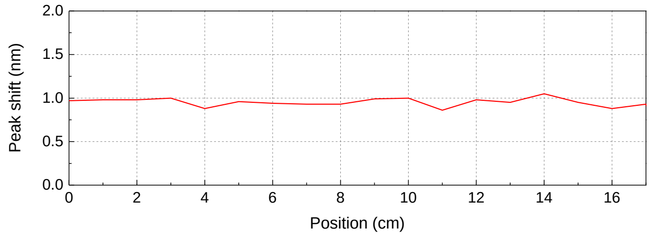

Fig. 3(a) Sensor alignment at a constant load of 5N before mounting on the rebar

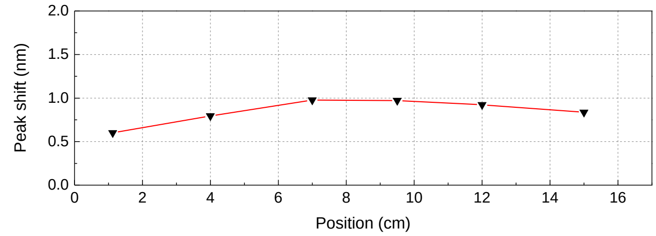

Fig. 3(b) Sensor response to 5N after mounting to rebar

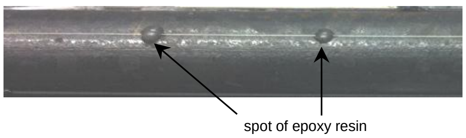

Fig. 4(a) Instrumated rebar with unprotected sensor

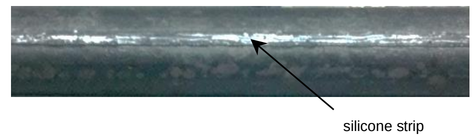

Fig. 4(b) Instrumented rebar with sensor protected by a thin layer of silicone

It was found that a 5 N weight applied along 4 cm of PCF produced a peak shift of 1 nm (0.125 N/mm → 1 nm). Fig. 3(a) shows the wavelength shift of the sensor when a fixed load of 5 N is positioned at any point along the length of the sensing fibre. It is noted that the force sensitivity of this distributed sensor is constant irrespective of the location of the force/pressure.

When the alignment was achieved, the rebar was gently positioned underneath the sensing fibre and spot-glued using rapid set epoxy. The sensor response after mounting on the rebar was evaluated by balancing the 5N weight at positions between each of the epoxy points. It was found that the sensitivity had reduced slightly near the ends of the sensor as shown in Fig. 3(b). This loss in sensitivity was likely due to an effect induced by the hardened epoxy covering the end splices. Fig. 4 shows the rebar instrumented with a bare (unprotected) sensor and a sensor protected by a thin layer of silicone. The protected sensor did not respond to the 5 N check due to the reduced sensitivity as a result of the protection, however a positive response occurred by manually exerting additional pressure.

For each sensor, a hairpin loop was made with one of the free SMF ends, directed back to the top of the rebar and fixed into position using epoxy. Isolating heatshrink was used to confine the corroding area of the rebar to the sensing length. All splices were coated with a thin layer of epoxy and located underneath the heatshrink (outside the corroding zones).

IV. ACCELERATED CORROSION TESTS

Corrosion of steel in concrete *in situ* in many installations may take months to initiate, even if accelerated in the laboratory by exposing to either CO_2 or chloride. As corrosion is an electrochemical reaction, electrical methods can be used to force corrosion [24]. This can be achieved in the laboratory by immersing a concrete-steel specimen in a solution of NaCl and connecting to a current source as shown in Fig. 5. The experimental program thus developed has been divided into two phases:

1. *Demonstration of the sensing principle (Rebar 1)*
The purpose of this was to transfer the sensing principle demonstrated using laboratory weights, in which a rapid accelerated corrosion trial of the bare PCF on the instrumented rebar is necessary. For this part, an accelerating current is applied, disconnected, and reapplied again to demonstrate whether peak shifts correspond to changes in corrosion rate.

2. *Accelerated corrosion on protected and unprotected PCFs (Rebar 2)*
One of the major concerns with any sensing fibre is its durability when exposed to the wet and hardened concrete environment. Thus in this test, by mounting two sensors on opposite sides of the rebar (one bare, and the other protected using the approach illustrated in Fig. 4(a) and 4(b)), a direct comparison could be made between sensors to investigate the effect of using protection (thin silicone coating). The accelerating current would also be monitored throughout the experiment.

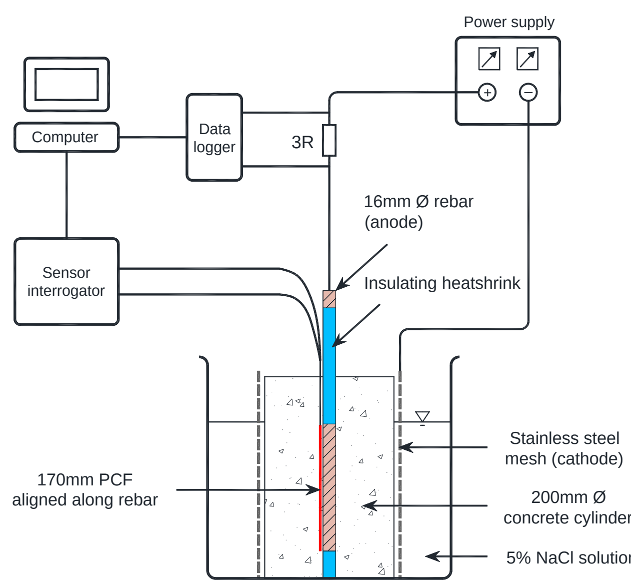

Fig. 5 Accelerated corrosion test setup

For the concrete, a typical mix was prepared with a cement:sand:gravel weight ratio of 1:2:2.25 and a water/cement ratio of 0.5 (for Rebar 2, salt was added during mixing). The concrete was poured and gently compacted into a prepared cylindrical mould with the sensor/rebar centrally positioned. Both ends of the SMF were connected to a coupler enabling connection to the sensor interrogator (Micron Optics SM125 which is used to replace the OSA and the light source shown in Fig. 1). As the SMF fibres are not polarization maintaining, it was necessary to adjust
the polarization conditions observed to generate the optimum spectral interference pattern (i.e. with maximum extinction ratio so that distinct peaks/valleys can be processed by the peak/valley detection and tracking algorithm). This was achieved by forming small loops with the SMF and arbitrarily adjusting the orientation (similar to the PC in Fig. 2) before fixing in position at the optimum pattern and peak tracking was initiated in the detection system. The concrete was cured at room temperature under moist conditions for two weeks, then demoulded and immersed in water. The peaks were then observed to test the stability under saturated conditions. After the signal had stabilized, salt was added to Rebar 1 and an accelerating voltage of 30 V was applied between the rebar and the mesh, as shown in Fig 5.

V. RESULTS AND DISCUSSION

Rebar 1

Almost immediately after the current was initiated, the peaks of the interference pattern began to shift dramatically and at a steady rate. To confirm that this was due to the corrosion acceleration effect, the current was switched off temporarily at 20 days (as can be seen from Fig. 6).

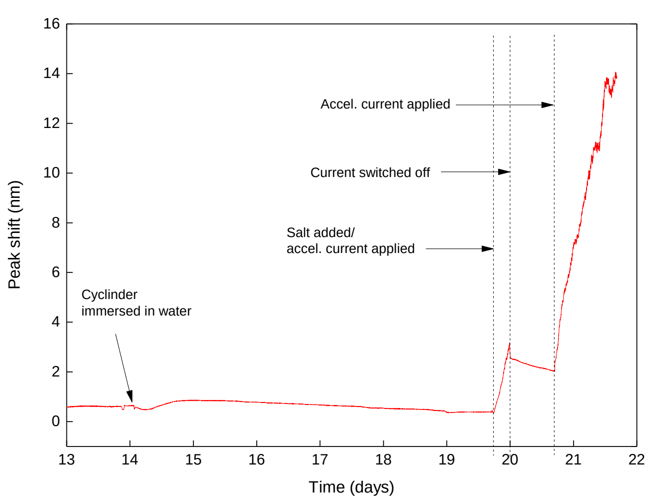

Fig. 6 Validation of sensing concept using the accelerated corrosion test (Rebar 1)

An effect was seen immediately whereby the peaks initially stabilized and then slowly shifted downwards. On the assumption that the detected pressure was from the rapid buildup of hydrated ferric oxide (rust), it would be expected that the pressure would dissipate slightly as the products relax into the concrete pores. After a dormant period of 0.5 days, the accelerating current was reapplied and again positive shifts in the peak positions could be seen almost immediately. The constant pressure induced by the constant accelerating voltage was seen to lead to a linear peak shift response (as expected from Equation 3).

Rebar 2

As salt was already included within the concrete mix, a significant peak shift was detected by the bare sensor during the curing stage (a gradual peak shift by 6nm was seen) as shown in Fig. 7.

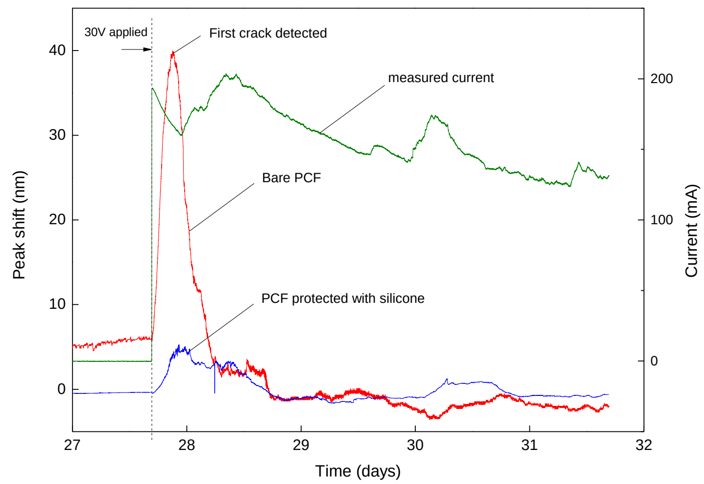

Fig. 7 Behavior of bare and silicone-protected PCFs under accelerated corrosion (Rebar 2)

Once the peaks began to stabilize, the accelerating current was applied. Within minutes, the peak began to shift at a rapid rate. The protected silicone PCF showed an increase in the peak shift at a lower rate compared to that seen for the bare PCF. However, the rate of increase was much greater than in the previous trial (rebar 1) which is likely due to adding salt at the mixing phase. While the sensitivity of the protected fibre is still seen to be lower, there was no delay in the reaction time. In Fig. 7, the measured accelerating current is also shown. The peak currents correspond to where the crack openings in the concrete are observed, as shown in Fig. 8.

Fig. 8 Photo of corroding cylinder

The opening of cracks allows more moisture/chloride to penetrate, which in turn leads to an increase in the corrosion rate. After the first main corrosion event, the bare sensor no longer responds to changes in corrosion rate, however, the protected fibre responds to subsequent increases in the corrosion rate (the peak is seen at ~30.5 days). It was subsequently found that the bare sensor was damaged after the first crack was formed, therefore it could not respond to any further cracking events. However, the protected sensor has been able to survive over the entire testing period and retain sufficient sensitivity to detect subsequent cracking in addition to the first.

VI. CONCLUSIONS AND FUTURE WORK

This preliminary study has demonstrated that HiBi PCF fibres show excellent potential for effective *in situ* monitoring of the corrosion of reinforcing steel in concrete from the point where such corrosion has been initiated. Very useful information can thus be obtained from the sensors, showing a direct relationship between the measured pressure and the corrosion rate of the rebar. This direct sensing approach not only provides information on the corrosion rate itself but also acts as an ideal sensor for crack detection. The data obtained also allows an analysis of the direct stresses induced by the expansive corrosion reaction, which enable a furtherance of the better understanding of many aspects of topical civil engineering research. With a constant sensitivity achieved over the whole length of the sensing fibre, there is significant potential to embed such sensors along an entire length of rebar at selected points to determine stresses and cracking that occurs.

Future work will evaluate these effects in greater detail, allowing correlations to be made to weight loss and the measured corrosion current. Other aspects of sensor development are ongoing with a particular focus on sensor protection, corrosion location identification and determination of corrosion arte, thus creating sensor design improvements to meet industrial needs.

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