Corrosion induced strain monitoring through Fibre Optic Sensors

SKT Grattan¹, PAM Basheer¹, SE Taylor¹, W Zhao², T Sun² and KTV Grattan²

¹ School of Planning, Architecture and Civil Engineering, Queen’s University Belfast, David Keir Building, Belfast, BT9 5AG
² School of Engineering and Mathematical Sciences, City University, Northampton Square, London, EC1V 0HB

E-mail: sgrattan02@qub.ac.uk

Abstract. The use of strain sensors is commonplace within civil engineering. Fibre optic strain sensors offer a number of advantages over the current electrical resistance type gauges. In this paper the use of fibre optic strain sensors and electrical resistance gauges to monitor the production of corrosion by-products has been investigated and reported.

1. Introduction
It is well known that the corrosion of steel reinforcements can produce waste products with an increase in localised volume. In general these waste materials occupy between two and six times the volume [1] of the original steel. This increase in volume would therefore be expected to generate a localised strain. It is this volume increase that leads to the formation of cracks and other defective consequences within the structure. An additional concern is the loss in cross sectional area of the rebar and this has a detrimental effect on the durability of the reinforcement and therefore the structure itself. The aim of this experiment was to attach both strain-monitoring Fibre Optic Sensors (FOSs) and standard Electrical Resistance Strain gauges (ERSs) to a steel rebar, embed them in concrete and cross-compare their performance. It would then be determined whether or not it is possible to measure/monitor effectively the induced localised strain.

2. Fibre Bragg Grating (FBG) Technology
The FBG works on the principle that light from a UV laser shining on a coating-stripped fibre can induce refractive index modulation of the fibre core [2]. For an FBG this modulation has a period of ~0.5 to 1µm whereas for a Long Period Grating (LPG) is would typically be >100µm [3,4]. These changes, through the use of phase or amplitude masks, can be predetermined and the masks fabricated to a required specification. The equation used to determine the central reflected wavelength, \( \lambda_B \), is defined by what is known as the Bragg condition, \( \lambda_B = 2n_e \Lambda \), where \( n_e \) is the effective refractive index and \( \Lambda \) is the periodic spacing of the grating [5].

Therefore the way that light behaves is dictated by the spacing between each refractive index interface and the effective refractive index of the fibre core. Light of a particular wavelength (\( \lambda_B \)) is reflected from these interfaces and can be measured. When there is a change in the environment around the fibre, there will be a resulting shift of this wavelength, for example, when a strain is...
imparted onto the fibre. Through calibration, this shift can be related back to the parameter that is under investigation, such as strain, temperature etc. as shown in Figure 1. By using the shift in wavelength rather than using a property related to the power of the signal there is an increase in the repeatability of these sensors. Any change in light source power will have no effect on the measurement.

![Figure 1: Schematic of optical characteristics of a FBG](image)

There are numerous advantages of FOS over current technology for this particular group of applications and these may be summarised as follows. For this type of fibre optic testing, the sensor approach:

- is wholly non-destructive, unlike many of the currently available systems
- can be designed to be installed as part of the manufacturing process and thereby minimising setup complications
- offers increased sensitivity compared to currently employed techniques
- is unaffected by high radiation dosages
- allows the user access to a large amount of vital data which can be used to flag issues/problems early or to monitor a particular environment
- uses light-weight components, yet can be designed to deal with almost any environmental conditions
- can ensure that the sensor itself will not interfere with the element which is monitored, this prevents loss of materials or introduction of adverse safety issues
- is not affected by electromagnetic radiation
- has no associated human error, unlike many of the traditional techniques that rely on a level of expertise with the equipment

3. Corrosion tests
Two concrete blocks of identical dimensions were created using the same mix of concrete, to avoid any variation in the sample, as shown in Figure 2. In one block FOS devices were attached to the rebar and in the other ERS devices were attached. Results were periodically taken from both samples and compared. The geologger ensured that a result was taken from the ERS every 6 hours, whereas the FOS had to be connected and a result taken manually. As far as possible this was carried out on a daily basis.
Passing a current through a steel rebar is known to increase the rate at which corrosion will occur. An additional bar was placed beside the rebar with the sensors attached to complete an electrical loop. When the positive terminal of the power supply is attached to the bar (in this case the bar with the sensors) it forces it to become anodic. As this process occurs, the metal atoms move into the solution as positive ions and the excess free electrons move through the electrolyte to the cathode. Once the concrete had been allowed sufficient time to cure and the readings had stabilised the current was applied and the corrosion process was monitored from this point on. The concrete mix was also altered to ensure that the conditions were suitable to accelerate the process.

The 10mm diameter rebars that were used in these experiments were cut to 400mm lengths. This length was chosen so that they would be longer than the slab and therefore allow the electrical connections to be made. They were then thoroughly cleaned so that there was no residual rust or dirt on their surface. To allow for the sensors and gauges to be attached three sections were ground to create a ‘flat’ on each bar. This process is required for the ERS which cannot be attached to any other surface than a flat one. The FOS on the other hand may be attached without such measures but it was felt that to continue the attempts to ensure that there was as little difference between the two samples as possible that this should be carried out for both.

The mix ratios and various other details for the concrete were taken from the work previously carried out by Basheer [6] where depths of chloride penetration were being investigated. The mould size used was 25cmx25.5cmx11.2cm in each section and the samples were as shown in Figure 3.

The mix ratios were as follows – 1 : 1.65 : 3 for cement : sand : aggregate respectively. The cement referred to is Ordinary Portland Cement, the sand is medium sand and 20mm Basaltic Coarse aggregate. The Water/Cement ratio was 0.55.
Where possible the pouring of the concrete was done so as to avoid it being applied directly on to
the FOS. Had it been possible the bar would have been rotated so that the sensor was facing away
from it; however there were sensors on both sides of the bar. The concrete was mixed and set in the
moulds initially. The traditional curing process of leaving the samples in water was not appropriate for
the FOS, so they were instead left on the bench to cure in air before having the voltage applied across
the bars.

The interrogation unit used with the FOS was left on permanently from the start of the experiment
until its end. The potential for variation in the readings due to the particular calibration method meant
that this step was necessary. It was important for the unit to stabilise and give a consistency in the
results.

The additional bar in the slab was to complete the flow of current being applied to the bar. The
voltage was applied from Day 23 (of the experiment) and it was set to 3V. This was then left
permanently on and the slabs themselves were not altered in any further way from this point. It was
found however that there was large resistance within both samples and so it was decided on Day 56
that the voltage should be increased to counteract this and create the accelerated corrosion conditions
required. The voltage was changed to 30V.

The FOSs were arranged so that sensor 8 was positioned towards the upper surface, the smaller of
the two depths of concrete cover, and sensor 6 was towards the bottom surface. The sensor that was to
be attached perpendicular to the bar did not survive the casting process.

From previous experimental work the conversion factor between the wavelength and the level of
the strain was known to be ~ 1 pm = 1.1 µε. The FOS were attached to a new version of the interrogation
unit (as shown in Figure 4) and as a result the Fabry Perot filter was a different series to that used
previously. This meant that the voltage range used for the Fabry Perot Filter was from -8 to +2 V.

![Figure 4: A close up of the FOS interrogation system](image)

4. Results

As shown in Figure 5, a substantial crack appeared in the block containing the ERS. The FOS
sample however did not produce such a distinct failure. There were more minor cracks but nothing as
clear as that of the ERS. The reason for this difference is unknown as there was a deliberate effort to
ensure that both samples were as close to identical as possible and after being cast they were both
treated in exactly the same way.
From the graph (shown in Figure 6) it can be seen that the results from the ERS were extremely stable until the voltage was increased. The initial setting of 3V was applied on Day 23, however by Day 56 there had still been no indication of corrosion occurring. The decision was made to increase the voltage to 30V as the resistance was found to be higher than would normally be expected. Shortly after this increase there was a sharp peak of strain to the gauges which was then followed by a huge reduction to the point of compression and beyond. The values actually dipped below what is accepted as a reasonable result for the gauges, as low as -26,000με. From previous experience this can normally be explained as a failure of the bonding of the ERS to the sample. It was not possible however to judge anything further until the sample had been split and examined more thoroughly.

By contrast, the FOS however provided readings until the end of the test. The applied voltage and all other conditions remained the same as for the ERS sample, however as stated previously there was no indication of cracking on the scale of that which was achieved with the ERS sample. Again there
was a sharp peak once the higher level of voltage was applied, for the FOS though this level was maintained with values of strain not dipping as low as the original values again. There was a great deal of variation in the readings after the initial increase in strain, but as already indicated these variations did not go against the trend that had been started. The measured strain from Sensor 6 started to decrease and it was felt that this could be attributed to a similar de-bonding as for the ERS, however again it would not be clear until after the sample was split.

Comparison of Results obtained from different sensors

The ERS devices uses have been shown to have failed at a critical stage in the experiment by returning results that were not acceptable. The suitability and durability of the ERS for embedding in concrete for these purposes is brought into question. The FOS, whilst giving a noisier output, have demonstrated a clear difference in pre and post corrosion readings. The aim of this test was to determine if such a distinction were possible and it has been shown that the FOS are able to achieve this.

It is also difficult to determine whether the noisier output from the FOS is actually an increased level of noise or an increased level of sensitivity within the confines of the concrete.

The reasoning behind the failure of the FOS to be attached perpendicular to the bar is clear. The width of the bar was less than the length of the stripped core region of the fibre and so this weakened area was not able to be supported properly.

The samples were split once it was confirmed that the results were not going to provide any further detail. Figures 7 and 8 below show the internal condition of the concrete and reinforcement bars. It can be clearly seen that there was genuine corrosion during this experiment, both from the corrosion of the bar and also the staining of the localised concrete area around the bar.

Figure 7: ERS bar extracted from the sample with corrosion visible on surface
Figure 8: Corrosion stained imprint of rebar in ERS sample

Figure 9 clearly shows that the ERS had become de-bonded from the bar. This shows the situation as they were found after being carefully removed from the sample and ties in with the erratic results being returned from the ERS after the voltage was applied.

Figure 9: ERS de-bonded from the rebar

Figure 10: Corroded bar from FOS sample
In Figure 10 above it can be clearly seen that there is a marked difference between the section of bar that was embedded and the section that was external of the sample. This again demonstrates the corrosion that has occurred.

5. Conclusions
As a result of the investigation carried out, the FOS demonstrated that they could be used for the required purpose of monitoring the localised corrosion on a rebar. The strain resulting from the corrosion can be distinguished from a standard strain, for example due to loading, by the fact that once the load is removed the strain will reduce, however with corrosion this will remain until the excess volume has reduced. Therefore a user would be equipped with suitable data to allow them to determine the difference through a simple examination of the structure. The readings would alert the user and they would be able to take suitable action to try and remedy that which has already started. The benefits of the chemical sensors are clear as they would prevent this stage from even being reached, however there is still the potential for such a strain sensor to be of use in the case of corrosion that is not distinguishable beforehand.

The sensor that failed perpendicular to the bar was, as explained earlier, not supported adequately. In future this could either be supported in some other way or else the length of stripped core reduced. The issue of the initial readings of the FOS prior to attaching the voltage will need to be researched further. Sensor 6 was reading values that reported a compressive force larger than would be imagined possible within the concrete due to the curing process. The method of attachment has come under question as the curing should normally only take around 28 days to complete. If the chemicals used to attach the FOS were actually reacting with its outer coating then this could be a possible explanation.

6. Acknowledgements
The authors would like to acknowledge the financial support of the UK Engineering and Physical Sciences Research Council (EPSRC) via a number of schemes and also the Department for Employment and Learning (DEL) in Northern Ireland.

References
[1] B L Ervin, J T Bernhard, D A Kuchma, H Reis, 2006, Estimation of corrosion damage to steel reinforced mortar using frequency sweeps of guided mechanical waves, Proc. of SPIE Vol. 6174 61740H-1 – 6174-15
[2] G. Meltz, W. W. Morey and W. H. Glenn, Formation of Bragg gratings in optical fibers by a transverse holographic method, Vol. 14, No. 15 Optics Letters, 1989
[3] S W James and R Tatam, Optical fibre long-period grating sensors: characteristics and application, Meas. Sci. Technol. 14 R49 - R61, 2003
[4] M. Vengsarkar, P. J. Lemaire, J. B. Judkins, V. Bhatia, T. Erdogan, and J. E. Sipe, Long-Period Fiber Gratings as Band-Rejection Filters, Lightwave Technology 14 (1) 58-65, 1996
[5] R. M. Measures, Structural Monitoring with Fiber Optic Technology, Academic Press, 2001
[6] L Basheer, PhD Thesis, The queen’s University of Belfast, Belfast, N.Ireland, 1994