Fibre Bragg Grating sensors for reinforcement corrosion monitoring in civil engineering structures

SKT Grattan\textsuperscript{1}, PAM Basheer\textsuperscript{1}, SE Taylor\textsuperscript{1}, W Zhao\textsuperscript{2}, T Sun\textsuperscript{2} and KTV Grattan\textsuperscript{2}

\textsuperscript{1} School of Planning, Architecture and Civil Engineering, Queen\textquoteright s University Belfast, David Keir Building, Belfast, BT9 5AG

\textsuperscript{2} School of Engineering and Mathematical Sciences, City University, Northampton Square, London, EC1V 0HB

E-mail: sgrattan02@qub.ac.uk

Abstract. Fibre optic strain sensors offer a number of advantages over the current electrical resistance type gauges, yet are not widely used in civil engineering applications. The use of fibre optic strain sensors (with a cross comparison with the output of electrical resistance gauges) to monitor the production of corrosion by-products in civil engineering concrete structures containing reinforcement bars has been investigated and results reported.

1. Introduction
Fibre optic sensors have a number of advantages over conventional sensors, yet they have not been widely used in civil engineering structural monitoring. Their passive nature and the absence of currents flowing at the sensor head, coupled with their ability to be retrofitted to existing structures gives credence to the claims of their particular value for monitoring the civil infrastructure. In this way, maintenance can better be planned and the losses associated with failure of structures can be minimized, important factors given the multibillion pound value of the civil infrastructure in the UK alone. The corrosion of steel reinforcements (\textquoteright rebars\textquoteright) used to provide structural strength to concrete can produce waste products which will result in an increase in localized volume, this often occupying between two and six times the volume \cite{1} of the original steel and thereby causing a localized strain arising from the volume change. Thus the formation of cracks and other defective consequences within the structure can occur over periods of time which vary from the short term to many years. An additional concern is the loss in the cross sectional area of the rebar and this effect can have a detrimental effect on the durability of the reinforcement and ultimately of the structure itself.

The work reported provides an evaluation and comparison of the outputs of both a strain Fibre Optic Sensor (FOS) and a standard Electrical Resistance Strain (ERS) gauge attached to a steel rebar and embed in concrete, with the aim of determining whether it is possible to measure/monitor the induced localized strain arising from the corrosion process occurring.
2. Fibre Bragg Grating (FBG) Technology

The optical sensor scheme uses FBG-based technology, which has been discussed in some detail elsewhere [2]. 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 [2]. Light of that particular wavelength ($\lambda_B$) is reflected from these interfaces and 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 under investigation, in this case the strain arising from the volumetric changes of the rebar. Any change in light source power will have no effect on the results.

3. Corrosion tests

To undertake the tests required to evaluate the performance of the FBG-based sensors for this application, two concrete blocks of identical dimensions were created using the same mix of concrete, (to avoid any variation) as shown in Figure 1. In one block several Bragg grating-based FOSs were attached to the rebar and in the other ERSs were attached. The aim was for a longer term evaluation (over a period of several months) and thus 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 to the ‘read out’ interferometer device and a result taken manually, where as far as possible, this was carried out on a daily basis.

In order to create the environment for accelerated tests, it was known that passing a current through a steel rebar increases the rate of corrosion and thus 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 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 so that they would be longer than the slab and therefore allow the electrical connections to be made. They
were then thoroughly cleaned before use, eliminating any 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 and, in particular, this process is required for the ERS which cannot be attached to any other surface than a flat one. To provide an environment for close comparison, the FOS was attached to a similar flat (so that as little difference between the two samples was created).

The mix ratios and various other details for the concrete were taken from the work previously carried out by Basheer [3] 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 2.

![Figure 2: The two slabs with the ERS (left) and FOS (right) embedded](image1)

The mix ratios were as follows – 1:1.65:3 for cement:sand:aggregate respectively where the cement used was Ordinary Portland Cement (OPC), the sand used is medium sand and the aggregate was 20mm Basaltic Coarse aggregate, with a water/cement (W/C) ratio of 0.55. Where possible the pouring of the concrete was done to avoid it being applied directly on to the FOS. Had it been possible the bar would have been rotated with the sensor facing away from it: however there were sensors on both sides of the bar. The concrete was mixed and set in the moulds but 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 wavelength interrogation unit used (Figure 3) with the FOS was left permanently during the experiment to provide stability. The FOSs were numbered for convenience of reference and arranged so that sensor 8 was 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 calibration factor between the wavelength and the level of the strain was known to be ~ 1µm=1.1µε.

![Figure 3: The FOS interrogation system and the concrete block in the laboratory](image2)
4. Results

As shown in Figure 4, 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.

The results obtained from the sensors were analyzed and from the calibration graph (shown in Figure 5) it can be seen that the outputs 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 -26,000 µε. 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.

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 – there was, however, no indication of cracking on the scale of that which was achieved with the ERS sample. There was a sharp peak once the higher level of voltage was applied, for the response of the FOS, although this level was maintained with the 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.
4.1 Comparison of Results obtained from different sensors – destructive testing of concrete samples

The ERS have been shown to have failed at a critical stage in the experiment by returning results that clearly were not physically credible and thus the suitability and durability of the ERS for embedding in concrete for these purposes is brought into question. The FOSs, whilst giving a noisier output, have demonstrated a clear difference in the pre- and post-corrosion readings obtained. 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. 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 experiment was over and Figures 6 and 7 below show the internal condition of the concrete and reinforcement bars. It can be clearly seen that corrosion has occurred during this experiment, evident from both the corrosion of the bar and the staining of the localised concrete area around the bar.

Figure 8 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 6: ERS bar extracted from the sample with corrosion visible on surface

Figure 7: Corrosion stained imprint of rebar in ERS sample

Figure 8: ERS de-bonded from the rebar
In Figure 9 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, demonstrating the degree of corrosion that has occurred.

5. Conclusions
The work has shown that FOSs can be used effectively for monitoring the localized corrosion on a rebar, distinguishing the strain resulting from corrosion from a standard strain, arising for example due to loading [4]. (Once the load is removed the strain will reduce, however with corrosion this will remain until the excess volume has reduced.) The sensor that failed perpendicular to the bar was not supported adequately and in future work this could either be supported in some other way or else the length of stripped core reduced. Sensor 6 was reading values that reported a compressive force larger than would be imagined possible within the concrete due to the curing process suggesting that the method of attachment will require further investigation. However the work has shown that the FOSs survive the embedding process and can be used for measurements on the sample – work is on-going to investigate these effects further.

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).

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. SPIE Vol. 6174 61740H-1 – 6174-15
[2] K T V Grattan and B T Meggitt, Optical Fibre Sensor Technology: Advanced Applications – Bragg Gratings and Distributed Sensors, Kluwer Academic Press, 2000
[3] L Basheer, PhD thesis The Queen’s University of Belfast, Belfast, UK, 1994
[4] R. M. Measures, Structural Monitoring with Fiber Optic Technology, Academic Press, 2001