Distributed Fibre Optic Strain Measurements for Pervasive Monitoring of Civil Infrastructure

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ABSTRACT: In order for the monitoring of civil infrastructure to become pervasive it must be both cost effective and provide useful data for infrastructure managers and engineers. Brillouin optical time-domain reflectometry (BOTDR) has the potential to meet both of these criteria as the fibre optic cabling that forms 'the sensors' can cost as little as €0.25/m and the longitudinal strain profile along any line in a structure can be acquired. However, the robustness of the inexpensive cable is questionable, especially if it is exposed to harsh environments such as being cast in concrete. More durable fibre optic cables have been developed that offer considerable gains in terms of robustness but the associated cost penalty is also considerable as these cables cost up to 50 times more than their less robust counterparts. In order to determine whether it is possible to use the low cost fibre optic cables in a civil engineering environment, and thus take a step closer to pervasive monitoring, six prestressed concrete beams for a new road bridge in Cambridge, UK were instrumented with these cables. This paper will outline the installation of the cables and the success of using the inexpensive cables will be evaluated by using the initial distributed strain results. The practicality of installing the fibres will also be addressed with reference to the installation time and associated costs. The potential of using BOTDR on bridge structures will then be discussed to determine if this technique provides useful data that bridge managers and engineers can use to adequately assess structures.

1 INTRODUCTION

Civil infrastructure in Europe is both expanding in extent and deteriorating in condition with time. This is juxtaposed against limited government infrastructure budgets. In order to manage the maintenance, repair and ultimately the decommissioning of these structures in a cost-effective and efficient manner, which will hopefully allow the service life of these structures to be extended, managers and engineers require data about their performance. One way to acquire this data is through the use of sensors. For existing structures this may mean the installation of external sensors that form a comprehensive monitoring system but for new structures there is also the possibility of embedding sensors within the structure during the construction phase. Fibre optic cable-based strain sensors are an example of a technology that lends itself to embedment as the ends of the fibre optic cable can extend beyond the structure allowing for measurements of the internal strain state to be taken.

There are several methods of employing fibre optic cables as strain sensors with the two most common techniques being fibre Bragg gratings (FBGs) and Brillouin optical time-domain reflectometry (BOTDR). FBGs allow the strain to be determined at discrete locations along the length of the cable with a resolution of approximately 1με and a precision of ± 5με (Gebremichael et al. 2005). The number of discrete strain measurement locations, or sensors, that the cable can have is a function of the strain range required for each sensor (Gebremichael et al. 2005). BOTDR on the other hand allows the strain to be measured along the full length of the cable, however this distributed measurement technique leads to a reduced resolution. The random error of a typical BOTDR analyser corresponds to normal distribution with a standard deviation of 15με (Klar et al. 2006).

Ideally these monitoring systems should be pervasive if the management programs they support are to be effective in providing managers and engineers with a complete picture of the performance of infrastructure under their control. In order to be pervasive a monitoring system should (i) be inexpensive, (ii) produce useful data and (iii) be user-friendly. If monitoring systems are expensive they will consume valuable resources that would have a greater impact if spent on the actual infrastructure. However there is an inevitable trade-off between robustness and cost. In terms of fibre optic cables it is possible to spend anywhere from €0.25/m for mass produced cables used in the telecoms industry to €13.00/m for cables specifically designed for strain measurements in harsh environments. One of the aims of this project was to determine if inexpensive fibre optic cables could be installed inside reinforced concrete beams to measure the strain using the BOTDR technique. Previous work (Klar et al. 2006) has shown that more robust and expensive cables can be used in pile foundations to measure the strains using the BOTDR technique. This paper will deal with the installation of inexpensive cables and try to gauge their robustness from the initial installation phase before the concrete was cast through to placement of the beams in the bridge. The relevance of the data is also an important consideration as though it may be possible to install fibre optic cables, if they do not produce data that is useful for the management of the structure then there is little value in using them. Similarly the ease with which the data can be interpreted and manipulated is also crucial if the end users are to implement it effectively into their management systems. Thus the relevance and application of the data from the BOTDR measurement system will also be discussed.

1.1 Brillouin optical time-domain reflectometry

BOTDR as mentioned previously provides a distributed strain profile along the length of the fibre optic cable. To do this the end of the cable is attached to an optical strain analyzer, which provides the required light source, measurement and analysis capabilities. A pulse of light is sent down the fibre and some of this light is reflected back or back-scattered from each point along the fibre. The frequency distribution of this back-scattered light is dependant on the strain in the cable. The location of this strain along the fibre is dependant upon the time of arrival of the back scattered light. Thus by measuring both the frequency distribution and time of arrival the strain at any location can be determined. Unfortunately the intensity of the back-scattered light is very low and multiple readings must be taken and averaged at every point in order to get an accurate reading. As a result it takes approximately 10 minutes to take readings from a single fibre optic cable and the strain resolution is approximately 15με.

As with any strain measurements the effect of temperature must be determined in order to distinguish strains due to temperature from strains due to loading. This is done by embedding two fibre optic cables: one to measure total strain and one to measure temperature strain. The cable that measures total strain is bonded directly to the structure (in this case it was placed inside the beam before the concrete was cast ensuring good bond between the cable and the concrete). The fibre that measures the temperature sits within a gel filled tube in the cable so that when the concrete hardens the fibre floats freely in the gel meaning that the strain is purely due to temperature. The results from the temperature cable can then be used to adjust the total strain cable results to compensate for temperature.

1.2 Test bed

In order to determine whether inexpensive fibre optic cable could be used with a BOTDR strain measurement technique, cables were installed in six prestressed precast concrete beams. The beams were part of the western-most span of a three-span concrete road bridge designed by Atkins and being built in Cambridge, UK as illustrated in Figure 1. Each span contains 12 super-Y prestressed concrete beams and the beams in the western-most span were 29m long. They were manufactured offsite at the Tarmac precast concrete facility in Tallington, UK. They were then transported by road to site where they were lifted into place using a mobile crane by the contractor, Jackson's Civil Engineering. Concrete was cast at both ends of the beams to stabilize them and then finally the bridge deck was cast in three installments: first the eastern span, then the western span and finally the central span.

Figure 1. Three span precast concrete beam bridge.

2 FIBRE OPTIC CABLE INSTALLATION

The fibre optic cables were installed in each beam after the prestressing steel had been tensioned but prior to the casting of the concrete. In four out of the six beams (Beams 1, 2, 5 and 6) two fibre optic strain measurement cables were installed that ran in loops entering the beam at mid-height, travelling along one of the bottom tendons, up the end shear link and back along one of the top tendons before passing out of the beam mould at mid-height as illustrated in Figure 2. Two cables were used rather one for redundancy. In Beam 3 only one loop of strain cable was installed due to time constraints. In Beam 4 only one cable was installed along the top strands but this cable was of the more robust and expensive type intended for this application. A loop of the inexpensive fibre optic cable was installed in this beam along the bottom strands only. In all the beams a single loop of temperature cable was installed that followed the same path as the strain fibres in beams 1, 2, 5 and 6. Where the cables passed through the beam mould, they were inserted into 20mm diameter plastic pipes so that the end of the form could be removed without damaging the cables.

The cables were also attached to the underside of the prestressing strand so they would be protected from falling concrete during casting. In order to maximize the measurement sensitivity of the strain measuring fibres they were pretensioned during installation. This was done by attaching the cables to the prestressing strand at one end of the beam using a high strength epoxy and adhesive tape. The fibre was then pulled at the other end of the beam until an extension of approximately 75mm (equivalent to approximately 2500$\mu\varepsilon$) was put into the fibre and then it was affixed to the prestressing strand using the epoxy and adhesive tape. Once the epoxy had hardened the tape could be removed. Both the strain cable and the temperature cable were then taped to the prestressing strand at regular intervals along the beam to ensure that the cables did not sag (and to connect the temperature cable to the prestressing strand).

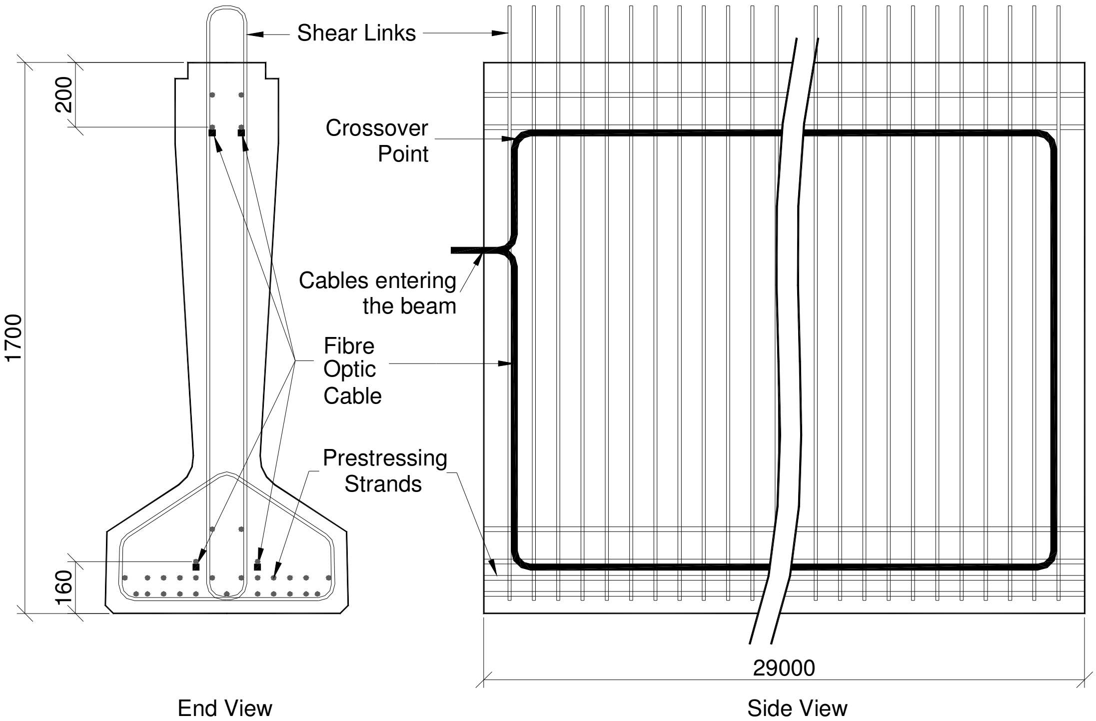

Figure 2. Fibre optic cable location in prestressed concrete beams.

Unfortunately the region where the cable crossed over from the prestressing strand to the shear link was vulnerable to damage due to its exposure to falling concrete during casting and so various techniques to protect the cables in this region were tested. In beams 1 and 2 the cables were taped to prestressing strands and the shear links but in the critical corner region they were left unprotected. In beams 3 and 4 the cables were reinforced with duct tape in this critical area. In beam 5 the cable was coated in epoxy at the crossover points making it completely rigid. Finally in beam 6 the cables were connected to 1mm thick by 5mm wide plastic strips with duct tape in this corner region. The cables that run along the top strands were also vulnerable to damage at the locations where the shear links were tied to the prestressing strands by wire ties. It was decided that the shear links would not be tied to the prestressing strands that the fibre optic cables were attached to, unlike for the other beams in the bridge, however if a tie was installed accidentally by the steel fixers this could potentially sever the fibre optic cable. This was not an issue for the cables at the bottom of the beam as the prestressing strands were not tied to the shear links at this level.

It took a team of three people approximately three hours per beam to install three cables. This time could be reduced with experience. It could also be reduced by using the more robust cable in order to avoid the need for the second redundant cable and for such careful handling of the cable. A further four days with a five person team was required on site to install the necessary protection for the cables in-situ, which significantly affects the economics of using the fibre optic cable as discussed later.

3 STRAIN MEASUREMENTS

Readings were taken using the BOTDR optical strain analyzer on all the beams at least twice: once at the precast plant after the beams had been cast and once when the beams had been lowered into their final position at the bridge site. In most cases more readings were taken in order to monitor the creep strains in the beams with time however these two measurements were key in terms of determining the robustness of the cables. Figure 3 shows a sample strain reading from beam 1 before it was removed from the prestressing bed. It should be noted that this initial strain reading is based on the initial prestress in the cable plus any effects from the casting, both of which cannot be determined with accuracy. The real value in this strain measurement system lies in the differential readings and thus the initial reading is simply a baseline against which change in strain over time is measured and so measurements are required at all critical stages.

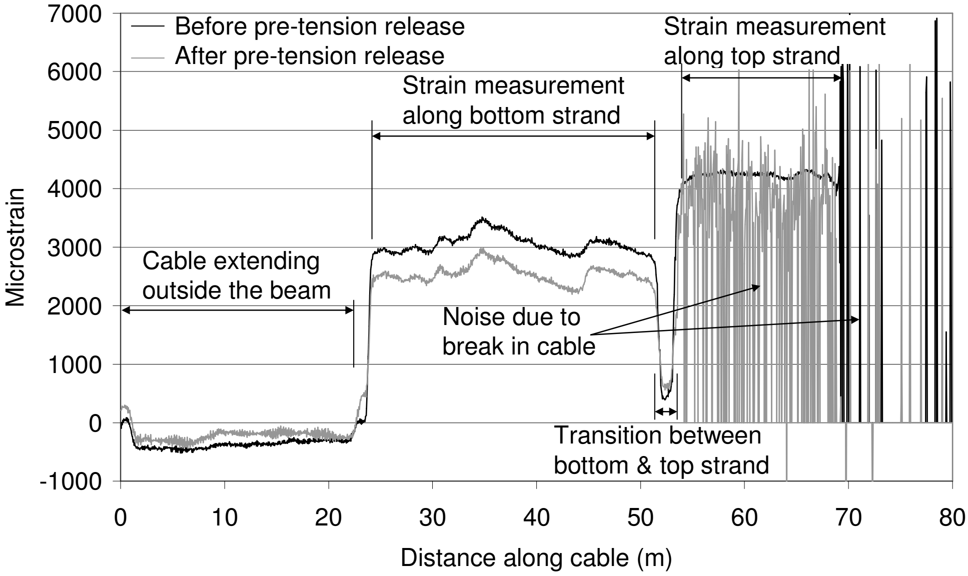

Figure 3. Strain in beam 1 before and after release of the pre-tensioning force.

Because the BOTDR technique measures back-scattered light, measurements only need to be taken at one end of the cable. So for every loop of strain fibre in the beam there were two opportunities to take measurements. Thus if there was only one break in the strain cable, measurements could still be taken over the full length of the cable by combining the results taken from either end. Unfortunately if there were two or more breaks (as was quite often the case) only the strain up to break nearest the end of the beam can be measured. The next section will discuss how many of the cables remained unbroken at the different stages of construction and could thus still be used for measurements.

4 ROBUSTNESS OF FIBRES

Table 1 indicates for each beam how many strain cables were still intact after (i) casting and (ii) transportation to site and placement at site. Not included in this table are the temperature cables as they are actually quite robust due to their protective coating. Only one of the temperature cables was damaged at a single location and this was overcome by the fact that measurements could be taken from the other end of the cable resulting in no data being lost.

It can be seen from Table 1 that the inexpensive cables are not very robust. Half of the possible measurements were lost after casting before any readings were taken. The breaks in the cable were usually located either just inside the beam or at the other end of the beam. This suggested that the weakest point in the cable could have been where it was no longer protected by the prestressing strand as previously mentioned. Unfortunately there does not seem to be an obvious way to effectively protect the cables in these crucial regions. For example, just as many cables survived in beam 2 after casting where no special measures were taken as survived in beam 6 which was reinforced with plastic strips and duct tape. It would seem that making the cables rigid at the crossover point is the least effective approach as no cables survived in beam 5. It should also be noted that the top cable in beam 4, which was the expensive reinforced strain cable, survived to site, one of only two top strain cables to do so. Another possibility is that the cables broke next to where they were glued to the prestressing strand as this area represents a fixed restraint. If the cables were pushed downwards by the falling concrete during casting, it would be at this critical location that they would be unable to move and thus be severed.

Table 1. Number of functioning cables

	At Precast Plant			At construction site after placement		
Beam No.	Functioning Bot. Cables	Functioning Top Cables	% of Total	Functioning Bot. Cables	Functioning Top Cables	% of Total
1	2	0	50	1	0	25
2	1	1	50	1	0	25
3	1	0	50	1	0	50
4	2	1	100	0	1	33
5	0.5	0	12.5	0	0	0
6	1	1	50	1	1	50
		% for all beams	50		% for all beams	28.5

Interestingly before beam 1 was removed from the pre-tensioning bed it was possible to read along the bottom cable and halfway along the top cable as illustrated in Figure 3. However after the beam was removed from the prestressing bed, where it was uniformly supported, and moved to the finishing area in the precasting plant, where it was only supported near the ends, the strain along the top cable could no longer be measured. This means that the strain cable actually broke within the beam after casting, which is an unexpected result as one would have assumed it was protected by the concrete at this point. It suggests that either the change in support from uniform to simple or the creep in the concrete when the pre-tension was released caused additional strains in the fibre optic cable resulting in a break. Unfortunately beam 1 was the only specimen for which measurements were taken in the prestressing bed so it is difficult to isolate which of the changes in the internal stress state caused the cable to break.

5 ECONOMIC CONSIDERATIONS

It is clear from these results that though the inexpensive telecoms fibre optic cables are appealing in terms of cost, they do not have the robustness required for civil engineering applications. However, this does not necessarily mean that fibre optic strain measurement cannot be used as part of a pervasive monitoring program. Despite the fact that the more robust cable costs an order of magnitude more than the cable used in this study, it would be several orders of magnitude less than the cost of the bridge. For example, in the case of this bridge the cost of having cables on the top and bottom strand of all 12 beams in all three spans at €13/m would have been €46800. The temperature cables would be an additional cost of approximately €2300 for the 36 beams. However this does not include labour costs. An initial estimate of these costs can be made by assuming a team of three will require an hour per beam at a rate of €10/hour (Bureau of Labor Statistics, U.S. Department of Labor 2008) to install the cables with a resulting cost of €1100. A further €4000 will be required for 5 people to complete the installation on site over 10 days. Thus the total installation cost would be around €53700, which when compared to the €5.7 million total cost of the bridge represents only ~1% of this amount. If the inexpensive cables were used this percentage would be reduced to < 0.2%. As such, if the cables can offer infrastructure managers and engineers critical data about structural performance, the impact of their installation on the cost of the project is negligible. One caveat is the cost of the spectrum analyzer which is approximately €65000. However it is envisioned that an analyzer could be bought by a group in charge of managing multiple bridges so as to average the capital cost over all of them as the analyzer can be moved between locations without any need for recalibration.

6 USE OF BOTDR IN BRIDGE APPLICATIONS

In the previous section it was determined that the cost of the cables should not be an impediment to their use in pervasive monitoring applications, however, one must also determine what benefit they offer in order to complete the analysis. This requires consideration of three important points: (i) the resolution of the BOTDR system, (ii) the static nature of the measurements and (iii) the use of BOTDR versus other strain measurement techniques.

As mentioned previously, the BOTDR system provides a resolution on the order of 15με. It is envisioned that the system will be used to determine the redistribution of strains due to creep in the beam, isolate potential areas of corrosion in the reinforcement and allow for future load testing of the bridge. In terms of measuring the creep strains, in the first 30 days after beam 1 was de-tensioned an overall change in strain of approximately 400με was measured suggesting that the resolution is adequate for capturing this behaviour. To isolate areas of corrosion the system should, at the very least, be able to identify if a steel prestressing strand has ruptured due to pitting corrosion. There are 27 strands in the bottom of each of the beams in this case. There are two potential conditions that must be considered: (i) the bottom of the beam (where the prestressing strands are located) remains in compression after the strand ruptures and (ii) this area is in tension after the strand ruptures. For the compression case, the maximum long-term compressive stress in the concrete due to the prestressing force at the centroid of the strands is predicted to be approximately 12MPa. This means that each strand contributes an average prestress to the concrete of 0.44MPa. Thus if a strand were to rupture the stress in the concrete would reduce by this amount and the strain in the concrete would increase by approximately 12με (using the predicted modulus of elasticity for the concrete of 36000MPa). This is right at the limit of the system's resolution and so it is possible a strand rupture in this case would not be identified. In the tension case, because the concrete does not contribute to the stiffness, the resulting increase in the strain in the remaining strands after one strand ruptures will be approximately 4%. The expected maximum strain in the strands, after long-term creep effects have been accounted for, is 5000με and so a 4% increase would represent 185με, which would be captured by the resolution of the system. Although complete rupture of a strand may seem too course a measure of corrosion, a 4% change in strand strain does not actually represent a significant reduction in the load carrying capacity of the beam. Thus decisions could be made about maintenance and repair before the issue became critical.

Finally it is hoped that the system can be used to determine if the bridge has enough capacity if the loading requirements are changed in the future. Based on the above calculation for strand rupture due to corrosion, the system may have the required resolution to detect increases in strand strain due to significant live loads although this will require further investigation. However, the drawback of using this system for loading testing is the period of time required to take measurements. The BOTDR technique measures the distributed strain profile over the full length of the beam which can be advantageous when, for example, trying to determine areas of localized corrosion however it also leads to lengthy measurement intervals. Since it takes approximately 10 minutes to measure a single cable this technique cannot be employed for dynamic analysis of a structure. If it were to be used for load testing, as suggested previously, the test vehicle(s) would have to be driven on to the bridge and left in place while the readings were taken. If the system is to be used for dynamic weigh-in-motion as has been done by Kobayashi (2004) then the FBG technique would have to be employed.

7 CONCLUSIONS

In light of the increased demands being placed on civil infrastructure as well as its deterioration due to age, there is a clear need to effectively monitor its performance. Managers and engineers will require data from pervasive monitoring systems to allow them to make cost-effective decisions about maintenance, repair and decommissioning. One possible component of a pervasive monitoring system is the use of a fibre optic cable-based strain measurement system. Such systems exist but in this project the Brillouin optical time-domain reflectometry (BOTDR) technique was investigated because it allowed the distributed strain profile over the full length of the bridge to be measured. If inexpensive fibre optic cables are used, these systems will only cost a fraction of the total cost of the structure thus meeting one of the key requirements of pervasive monitoring: cost effectiveness. Inexpensive fibre optic cables were installed in six prestressed precast concrete beams in the western-most span of a three span bridge. Unfortunately the cables proved not to be robust enough as less than a third of the cables installed were still working once the beams were placed on site. However, a much more robust type of fibre optic cable that was used in one of the beams survived the entire process and indicated that although these robust cables cost 50 times more the extra expense is worthwhile to ensure integrity of the data. Even if the more expensive cables were used, the installation of fibre optic monitoring still represented less than 1% of the overall cost of the structure. One must also consider whether the data produced by such a system is useful for the evaluation of the structure. Initial calculations suggest that the system does have the ability to indicate areas of localized corrosion and allow for the load carrying capacity of the bridge to be assessed over the lifetime of the structure. Other fibre optic systems namely, fibre Bragg grating, offer potential benefits over BOTDR in applications such as dynamic live load measurement. The BOTDR technique does have the potential to provide useful data for the management of the structure at a fraction of the cost of the structure itself.

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