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ASSESSMENT OF FIBRE OPTIC STRAIN GAUGES FOR FIELD USE IN INDIA

ABSTRACT

The commissioning and evaluation of a fibre optic strain sensor system for the structural health monitoring of a prestressed concrete post-tensioned box girder railway bridge in operational use in Mumbai, India, is described. Preliminary laboratory trials to identify the most appropriate sensor system are detailed followed by a description of the load tests on the actual bridge which were undertaken in collaboration with Indian Railways. Results from the load tests using the optical system are compared with similar results obtained using electrical resistance strain gauges. Conclusions are drawn concerning the integrity of the structure and for the future use of the sensor system for monitoring bridges of this type. Crack width measurements obtained during the load tests are also summarised.

KEYWORDS

Fibre optic strain sensors, load tests, railway bridges, structural health monitoring.

INTRODUCTION

There is an increasing need for improved structural health monitoring of civil engineering infrastructure such as, for example, bridges, buildings, tunnels and dams. Unnoticed degradation of these structures will cause major disruption, possible loss of life and, almost certainly, incur major expense when remediation measures are implemented. Consequently, civil and structural engineers are seeking better and more reliable systems which can be used cheaply, quickly and effectively for the structural health monitoring of such structures in order that problems can be identified as early as possible in their service history. Often this monitoring has to be undertaken in climatic conditions which are alien to sensor performance as, for instance, extremes of temperature, humidity, dust and electro-magnetic interference all pose considerable challenges to the developers of reliable and robust sensor systems.

The development of Fibre Optic Sensors (FOSs) has represented a major opportunity for structural health monitoring, especially of civil engineering structures and in particular bridges, due to their relatively small size, ease of use and potential to be multiplexed over long lengths. Over the last 15-20 years, research groups around the world have instrumented various types of bridges (e.g. steel (Lee et al., 1999), concrete (Chan et al., 2006), and composite (Kister et al., 2007)) and these studies have demonstrated the potential for data from FOS measurements to be a valuable aid in the structural health monitoring process.

The prime focus has been on strain measurement which, for civil engineers, is a key parameter. Various optical techniques have been developed for this purpose where the most common are using Fabry-Perot cavity-based sensors, Fibre Bragg gratings (FBGs) or Brillouin scattering (Li et al., 2004). Most attention has been devoted to the use of FBGs due to their unique property among FOSs to encode information in the wavelength domain which makes them less noise-sensitive. Although fully distributed measurements using FBGs are not possible and there are constraints on the wavelength spacing of the gratings themselves,

these limitations can be overcome in practical applications and considerable work has been done in this area by the authors using conventional techniques (Bai et al., 2009; Banerji and Chikermane, 2011) and by using optical fibre sensors (McPolin et al., 2009). However, it is essential that expertise is shared between the sensor *developers* and the sensor *users* if opportunities for innovation in the design and application of the sensors are to be fully exploited. Unfortunately, this is not often the case and thus was one of the motivations for the work reported in this paper.

In this work, the authors collaborated on a project to design and commission a fibre optic based strain measurement system for use in the structural health monitoring (in this instance load testing) of a prestressed concrete post-tensioned box girder railway bridge in Mumbai. The project, a collaboration between the Indian Institute of Technology Bombay, Durham University, City University London and Queen's University Belfast, formed part of the UKIERI (UK-India Education and Research Initiative) programme funded jointly by the governments of the UK and India and administered through the British Council. The site was identified by Indian Railways as one where there was an urgent need for monitoring of this type to take place. The work was in two parts, firstly the laboratory evaluation of suitable fibre optic strain sensors followed by use of the selected system in a series of load tests on the bridge itself both during normal daytime traffic conditions and with loading provided by heavy locomotives during a night-time closure of the railway over the bridge. A feature of the field work was opportunity to trial the use of the monitoring system in the hot, dusty and humid environment of the Indian summer with the added challenge of the electrical interference introduced by locomotive traction motors and signaling systems

Sensors can be embedded in a structure or mounted on the surface. Embedded sensors are suitable for new constructions since they can be readily installed during the building phase whilst surface mounted sensors are more appropriate when assessing the performance of an existing structure. Consequently, surface mounting was chosen for monitoring the bridge in Mumbai.

In order to measure the actual strain experienced by the bridge several important factors had to be carefully considered. The first was how to attach the sensor to the surface as the quality of the measurement would depend on optimising the degree of strain transfer from the structure to the sensors – a problem common to all surface mounted sensors. The second was the gauge length of the sensor since if this was too short its measurements would be influenced by local surface strains and thus not be fully representative. Finally, ensuring that the system was able to monitor up to the maximum anticipated strain level was also an obvious requirement.

Access to the bridge for sensor installation plus the amount of time when the bridge could be closed for load testing (it is on a busy passenger route) were both subject to very tight time constraints. Thus it was necessary to select an appropriate and high performing sensor which could be installed quickly and easily for immediate use in the field. Use of bare fibre sensors was deemed inappropriate since it would be impossible to prepare all the surfaces properly and then mount these sensors satisfactorily in the very limited time available. Fortunately, however, these problems could be eased by using commercially available packaged sensors specifically designed for mounting on test pieces.

An in-fibre FBG is a periodic modulation of the refractive index of the core of a photosensitive fibre where the modulation of the refractive index is induced by UV light from

a laser source. The periodic modulation acts as a filter reflecting one wavelength, the Bragg wavelength, which is expressed by the following formula:-

$$\lambda_B = 2n_e \Lambda \quad (1)$$

where n_e is the effective refractive index and Λ is the period of the grating.

A variation of the period of the grating or the effective refractive index (caused in this case by strain (and temperature) change) induces a shift of the Bragg wavelength. It is known that temperature variations induce a change of refractive index and grating period, while longitudinal strain mainly induces a change in Λ . The temperature or strain induced wavelength shift can be modelled by the following equation:-

$$\Delta\lambda = S_{strain}\Delta\varepsilon + S_T\Delta T \quad (2)$$

where S_{strain} and S_T are the strain and temperature sensitivities, respectively. $\Delta\varepsilon$ and ΔT are the strain and temperature variations respectively.

Equation 2 highlights the temperature dependence of strain measurement which is a well recognised feature of FBG based strain sensors so, in order to have a meaningful determination of the actual strain, it is important to have an accurate value of the temperature in the vicinity of the FBG plus a record of how the temperature changes during the course of the measurements. This would be particularly important during field trials in Indian conditions.

LABORATORY TRIAL

As discussed earlier, a series of laboratory trials was carried out prior to the installation on the bridge itself to ensure optimum use of the very limited time when the bridge would be available for the load testing.

Two types of packaged sensors were selected for trial in the laboratory, optical strain gauges and optical strain sensors. The two optical strain gauges (designated OSG1 and OSG2) had a gauge length of 250 mm and, being designed for field applications, were relatively robust (Figure 1). They contained two fibres, one for strain measurement and one for temperature compensation. The three optical strain sensors used (designated OSA, OSB, OSC) each had a gauge length of 22 mm and were normally intended for laboratory use (Figure 2). Consequently, they were much less robust and did not include provision for temperature compensation. (Fortunately, temperature measurements taken during the laboratory trial indicated that conditions in the laboratory were very stable thus obviating the need for temperature compensation.) The geometrical characteristics and properties of the sensors are summarized in Figure 3.

Different mounting techniques were used to simulate the sort of conditions that could be expected in-the-field and thus test the sensors' strain transfer capability and robustness under load. The mounting techniques used were as follows:-

- Optical strain gauge with temperature compensation OSG1 used mounts which each had a lug glued into a pre-drilled hole in the concrete (Figure 4, right hand pair).

- Optical strain gauge with temperature compensation OSG2 used mounts which were screwed into fixings in the concrete (Figure 4, left hand pair). Later in the test program these mounts were modified by replacing the screws with threaded rods glued into the holes to which the mountings were then firmly bolted (Figure 5). OSG1 and OSG2, being designed for field use, could be removed from their mountings for safety when not in use, or for use elsewhere if needed.
- Optical strain sensor OSA was glued directly onto the beam.
- Optical strain sensor OSB was also glued onto the beam but the beam surface was first prepared with a film of glue before gluing of the sensor itself was undertaken.
- Optical strain sensor OSC was glued to two metal plates which had previously been glued to the beam. The intention was to increase the contact surface between the sensor and the beam. It was also hoped that this might be more robust than gluing directly to the concrete as there was metal-to-metal contact between the sensor and the plates rather than the metal-to-concrete contact of OSA and OSB.

It was appreciated that the lack of temperature compensation in sensors OSA, OSB and OSC was likely to be a major hindrance to their use in the field and would necessitate the installation of additional sensors purely to measure temperature effects.

All the sensors were connected to an interrogator box which allowed simultaneous monitoring of the Bragg wavelength changes (from which the strain data were obtained) for all five mounted strain sensors.

The reinforced concrete beam (Figure 6) used to simulate conditions on the bridge was 5200 mm long overall (4870 mm between simple supports), 250 mm deep and 300 mm wide. The main tension (bottom) reinforcement comprised three 16 mm diameter high yield reinforcing bars (one of which was internally strain gauged) and the top reinforcement comprised two 12 mm diameter high yield bars. The internally strain gauged reinforcing bar was included to provide very detailed measurements of the longitudinal reinforcement strains for comparison with readings from the optical sensors. This bar contained 81 electrical resistance strain gauges (ersg's) mounted in a central machined duct which ran the full length of the bar using a technique described in detail by Scott and Beeby (2005) and Scott and Whittle (2005). The gauges were spaced at 15 mm centres over the central 1200 mm of the bar.

Surface strains on the concrete were measured using a demountable, mechanical strain gauge (a "Demec" gauge) in conjunction with a grillage of steel studs glued to the surface of the concrete. The studs were at 200 mm centres at three levels over the central metre of the test beam, the level of most interest being that which coincided with the main tension reinforcement. Although this approach would only measure average strains over each 200 mm gauge length it provided a useful independent back-up to readings from the strain gauged bar and the optical sensors.

As shown in Figure 7 the fibre optic strain sensors, strain gauged reinforcing bar and the Demec points were all positioned at the same level on the beam (i.e. the level of the tension reinforcement) thus enabling easy comparison between the readings from all the strain measurement devices.

The beam was loaded in four point bending which provided a constant moment zone of 2500 mm. Since strains on the bridge in Mumbai were likely to be low, the beam was first

subjected to a series of load cycles in its uncracked range following which it was loaded to its fully cracked condition in order to assess sensor performance under more extreme conditions. A full set of readings was taken from all sensors at each load stage.

Perhaps predictably, the optical strain gauges (OSG1 and OSG2), with their mechanical fixings to the test specimen, performed much better than the optical strain sensors (OSA, OSB, OSC) which were glued to the specimen. The glued sensors performed badly during the early load cycling and then failed completely when more load was applied to the beam. The mechanically fixed sensors (OSG1 and OSG2) performed satisfactorily under all loading conditions although it was found that it was important to ensure that they were secured tightly in their mountings to avoid slip and hence under-reading. Basically, the tests confirmed that OSA/B/C were completely unsuitable for use in the conditions anticipated on the bridge site. OSG2, with its revised mounting system, performed best of all and generated very reliable data under all loading conditions which compared well with the readings from the gauged reinforcing bar and the Demecs. It was thus decided at the conclusion of the laboratory evaluation to use optical strain gauges on the bridge and mount them using threaded rods glued into drilled holes (i.e. the modified technique used for OSG2 as shown in Figure 5) as the beam test showed this technique to be particularly effective.

FIELD TRIALS: SENSOR LOCATION AND LOAD TESTS

Following discussions with the Indian Railways authorities, Vasai Creek Bridge (Figure 8) was kindly made available for field trials of the optical strain gauges. Vasai Creek Bridge is located just north of Mumbai on the very busy electrified commuter route which originates from Mumbai's Churchgate terminal station. Traffic over the bridge consists of a regular succession of multiple unit passenger trains typically formed of two four car sets. Vasai Creek Bridge consists of two parallel and immediately adjacent lines of post-tensioned prestressed concrete box girders each of which supports a single line of railway. It was constructed in the mid 1980's and has 28 simply supported spans each 28.5 m long. It is thus a very substantial structure but all the box sections exhibit significant longitudinal cracking in the webs plus some diagonal cracking at a number of locations in the span. Consequently, all locomotive hauled traffic, which has considerably higher axle loadings than the multiple unit passenger trains is routed over a newer bridge built around ten years ago immediately adjacent and broadly similar to the older structure.

Sensors were mounted inside the western (uptide) end span at the southern end of the bridge since access to this span was readily available from the bank of the creek. Funding and time constraints for installation meant that only six optical strain gauges could be purchased so considerable thought was given with regards to their positioning particularly as access to the bridge would be possible for only a very limited time period. The priority was to measure the maximum tensile and compressive flexural strains so, since these would occur at mid-span, pairs of optical strain gauges were positioned in the centre of the soffit (underside of roof) and at the bottom of each web (side wall) of the box at the mid-span location (Figure 9). Sensors were placed in line to provide redundancy in the event of one failing as there would be insufficient time to procure and mount replacements. An electrical resistance strain gauge (ersg: gauge length 120 mm) was placed next to each optical sensor (Figure 10) in order to achieve corroborating strain readings (fortunately, two of the authors already possessed considerable experience of using ersgs for bridge monitoring under Indian conditions).

The optical strain gauges were clamped to the surface using the grouted stud technique developed in the laboratory tests. The ersg's were bonded directly to the concrete after surface preparation and additional ersg's were installed in the top corners of the box at mid-span. In addition, ersg's were installed at the end of the box to investigate torsional effects at the supports due to the possibility of some end restraint occurring in the nominally simply supported span. All the fibre optic sensors used were connected to a Micron Optics sm130 interrogator box capable of recording data at 1000 Hz and which allowed simultaneous monitoring of the Bragg wavelengths of all six optical strain sensors used in the tests. The instrumentation for the ersg's allowed for simultaneous monitoring of up to eight sensors.

In view of the significant cracking present in the span and as an addition to the main test programme crack widths were monitored at five locations using commercially available sensors (Figure 11). These consisted of an arch-shaped spring plate which was strain gauged and bolted to the concrete across a crack (Figure 12) and were calibrated such that bending in the sensor caused by crack movement (opening and closing) was output as a crack width reading.

It should be emphasised that all instrumentation, optical, ersg and crack width, could only record *changes* in loading on the bridge. Measurement of self-weight effects was, unfortunately, not possible, of course.

Continuous monitoring of the regular passenger traffic over the bridge was conducted over several days but load tests were carried out during the limited period made available by a night-time possession of the bridge when all timetabled traffic was suspended. To facilitate the tests, Indian Railways provided a pair of electric locomotives coupled together (the "design train") for accurate load testing of the instrumented span during the night-time possession. The combined weight of the two locomotives was about 250 tonne, close to the maximum loading permitted by Indian Railways in view of the condition of the bridge. The locomotives were used to excite the span under static and moving load conditions. For the static tests they were halted at mid-span while, for the moving load conditions they were driven across the span at constant velocities of 5 kmph (crawling run), 20 kmph (medium speed run) and 65 kmph (design speed run).

Most of the data were sampled at 200 Hz except for some portions of the locomotive moving load conditions where the sampling rate was increased to 1000 Hz.

FIELD TRIALS: RESULTS

Results for a run of the design train at crawling speed are given in Figure 13 for the optical strain gauges and Figure 14 for the ersgs. It can be seen that strains for each pair of sensors correlated with each other very well e.g optical strain gauges B and D gave almost identical values and ersg's 7 and 8 also gave almost identical values. (Unfortunately, optical strain gauge F (Figure 9) did not give consistent data and thus the results from this sensor were not used in the analysis but this at least justified the decision to use sensors in pairs to allow for redundancy as there would have been insufficient time to install a replacement once testing had begun).

The peak values from the optical strain gauges and the corresponding electrical resistance strain gauges are tabulated in Figures 15 and 16 respectively for all nine runs of the design

train. Runs 1 to 3 are crawling speed runs, Runs 4 to 6 are medium speed runs and Runs 7 to 9 are design speed runs. Data for optical strain gauge F are omitted (see above) and ersg data for Run 8 were not available due to technical problems on site. It is interesting to note that, although the optical and electrical strain gauges have identical time history patterns, in general optical strain gauge values are slightly lower than the corresponding electrical resistance strain gauge Figures 17 illustrates this point.

Optical strain gauge readings as a proportion of the peak electrical resistance strain gauge values for the nine design train runs are tabulated in Figure 18. These results indicate that there was consistent under-reading of strain values from the optical strain gauges compared with those from the ersg's possibly due to the ersg's being bonded directly to the concrete while the optical strain gauges were screwed into mounts which were themselves bolted into the concrete. Drilling holes in the concrete of the box, particularly in the soffit, during the limited period on site was not easy and screwing the gauges into the mounts had to be done with extreme care to avoid damaging them, all of which gave scope for "play" between the gauge and the concrete and possible under-reading when the concrete was stressed. This was an experimental technique problem which would be easily resolved by further practice.

The results shown in Figures 13, 14 and 17 are typical for all runs of the design train at all speeds. The multiple unit suburban trains, which crossed the bridge at around 80-100 kmph, consistently showed a pattern of four peaks as carriage bogies crossed the measurement point. The first peak was always the numerically largest due to the higher axle load imposed on the first bogie by equipment within the carriage. This effect is shown in Figure 19 which compare typical optical strain gauge and ersg readings for the soffit and web.

The fibre optic sensors were virtually unaffected by noise from the overhead electrical power supply to the trains, from the signal circuits or from interference generated by traction motors which illustrated the value of using optical fibre sensors for this particular application. Consequently, the data obtained were very "clean" and required very little post-processing. This was in marked contrast to the ersg's which picked up considerable noise from all these sources.

Readings from the crack width sensors for the multiple unit suburban trains, as illustrated in Figure 20 (negative values indicate crack opening), showed a similar pattern to the corresponding strain readings i.e. a pattern of four peaks with the first peak being the largest. The way that cracks in the boxes open and close with every passing train is an ongoing concern for Indian Railways and this monitoring, limited though it was, supported continuance of the weight limit currently imposed on the bridge.

CONCLUSIONS

A number of positive conclusions can be drawn, based on the success of the work carried out, as follows:-

1. The work described in this paper has shown that good quality and reliable data requiring minimal post-processing could be obtained in-the-field using fibre optic gauges and especially so when time on site for sensor installation was limited.
2. The success of the research program undertaken on site emphasised the value of the preliminary preparatory work in the laboratory making it possible to select the correct

sensor type with regards to gauge length and mounting technique. The use of packaged sensors would seem essential if a system sufficiently rugged for field use is to be obtained.

3. The research program described demonstrated that high quality measurements which are of value to the structural engineering community are eminently obtainable using the sensor system set-up described and evaluated in this paper, even under the tight time constraints and challenging environment imposed by the limited availability of access to the bridge for the field test plus the challenging climatic conditions of the Indian summer.
4. A series of results of measurements taken under well controlled conditions has been reported and conclusions drawn which are highly relevant for future work.

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