Commissioning and Evaluation of a Fiber-Optic Sensor System for Bridge Monitoring

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***Abstract*— This paper describes the design, commissioning, and evaluation of a fiber-optic strain sensor system for the structural health monitoring of a prestressed concrete posttensioned box girder railway bridge in Mumbai, India, which shows a number of well-documented structural problems. Preliminary laboratory trials to design the most appropriate sensor system that could be readily transported and used on site are described, followed by a description of load tests on the actual bridge undertaken in collaboration with Indian Railways and using locomotives of known weight. Results from the load tests using the optical system are compared with similar results obtained using electrical resistance strain gages. Conclusions are summarized 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 described.**

***Index Terms*— Fiber-optic strain sensors, load tests, railway bridges, structural health monitoring.**

I. Introduction

THE need for the better monitoring of the key infrastructure in and surrounding our major cities has never been greater as loss of service can cause major disruptions, costs of many millions of dollars and loss of life. With the proliferation of such infrastructure worldwide, civil and structural engineers are seeking better and more reliable systems which can be used cheaply, quickly and effectively for such tasks. In this paper, with the motivation described above, the authors have collaborated on a project to design and commission a fiber 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. This paper, a collaboration between the Indian Institute of Technology Bombay, Durham University, City University London and Queen's University Belfast, formed part of the UKIERI (U.K.-India Education and Research Initiative) program funded jointly by the governments of the U.K. 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. This paper falls into two parts, the first being the design and evaluation of a system built around a prior, laboratory-based, evaluation and performance optimization of suitable fiber optic strain sensors, with the second part building directly on the results of the first by undertaking a series of load tests on the bridge itself both during normal traffic conditions and with loading provided by heavy locomotives during a closure of the bridge.

The use of fiber optic strain sensors for structural health monitoring is not, of course, new and considerable work has been published by some of the authors and others for work done under a range of field applications [1]–[15] over a considerable period. This paper was different in that, in cooperation with the owner of the bridge, specific loading tests were planned and carried out during a closure of the structure. The principal aim was to give confidence to Indian Railways that, as a relatively recent technology and being dependent on a completely different system of measurement from electrical resistance strain gage sensors, high quality measurements could be taken that were within the ranges expected (and hence a comparison with the outputs of electrical resistance strain gages was used). In addition, considerable care must be taken in the use of the sensors and the design of the experiments employing them to allow that confidence to be developed and this paper shows the processes by which this was built up.

In order to undertake the work on the bridge in the very limited time-window available, it was decided not to use 'unmounted' (i.e. bare fiber) Fiber Bragg Grating (FBG)-based sensors as had been used in previous work on actual bridges by some of the authors [1], [2] as they were more liable to breakage and the strain transfer ratio was more difficult to evaluate in the short time that the bridge was available to the experimenters. Thus commercially available fiber optic strain sensors were chosen for this application. These are now available in a range of gage lengths but required evaluation and optimization prior to use on the bridge. With such sensors, there is a choice of either gluing or mechanically fixing (bolting or welding) them to the test piece.

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The choice of gage length and mounting type can be problematic when measuring concrete surface strains as it is important to ensure optimum and consistent strain transfer to the sensor (this, of course, being a constraint for any type of sensor used, not just optical fiber devices). This was particularly important in the context of the proposed bridge monitoring with the constraint of the availability of the bridge since the sensors would have to be surface mounted on an existing structure rather than being embedded during the construction of a new structure. As a consequence, and to minimize time wasted at the actual bridge site itself, it was decided to undertake a laboratory evaluation to determine the most appropriate sensor mounting arrangement before moving onto site. Thus the work at the bridge itself was preceded by a series of laboratory tests in which a number of fiber optic strain sensors were mounted on the surface of a reinforced concrete beam which could be loaded such as to simulate the loading of the bridge. The readings obtained from the surface mounted fiber optic sensors could then be compared with reinforcement strains measured using a previously instrumented reinforcing bar and with surface strains measured using a mechanical strain gage, giving confidence to the outputs from the fiber optic sensors when they were used in-the-field. Descriptions of this trial, the conclusions drawn from it, and the actual work on the bridge now follow in the subsequent sections.

II. Laboratory Trial

A. Sensor Selection

The fiber optic sensors were purchased already packaged (i.e. supplied ready for mounting on the test specimen) and thus were easier to use than the unmounted 'bare fiber' sensors, especially in the field. Two types were trialled, optical strain gages and optical strain sensors. The two optical strain gages (designated OSG1 and OSG2) had a gage length of 250 mm and, being designed for site applications, were relatively robust. They contained two fibers, one for strain measurement and one for temperature compensation. The three optical strain sensors used (designated OSA, OSB, OSC) each had a gage length of 22 mm and were normally intended for laboratory use. Consequently, they were much less robust and did not include provision for temperature compensation (which was unnecessary in the laboratory). The geometrical characteristics and properties of the sensors are summarized in Table I.

Different mounting techniques were used to simulate the sort of conditions that could be expected in-the-field and thus test their strain transfer capability and robustness under load. Overall, this exercise permitted an assessment of the practicality of these sensors for field application. The mounting techniques used were as follows:

1) Optical strain gage with temperature compensation OSG1 used mounts which each had a lug glued into a pre-drilled hole in the concrete [Fig. 1(a)]. (The lug cannot be seen from the photographs).
2) Optical strain gage with temperature compensation OSG2 used mounts which were screwed into fixings in the concrete [Fig. 1(b)]. 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. 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.
3) Optical strain sensor OSA was glued directly onto the beam [Fig. 1(c)].
4) 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.
5) Optical strain sensor OSC was glued to two metal plates which had previously been glued to the beam [Fig. 1(d)]. 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.

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 under the circumstances of a test lasting several hours because their sensitivity to temperature excursions could mask relatively small excursions in strain, due to the relative sensitivities. Thus an additional temperature sensor

TABLE I
Properties of the Optical Strain Gages and Optical Strain Sensors Evaluated in This Paper

	Optical Strain Gages OSG1 and OSG2	Optical Strain Sensors OSA, OSB, and OSC
Strain sensitivity	~1.2 pm/microstrain	~1.4 pm/microstrain
Temperature sensitivity	23.8 pm/°C	Not applicable
Gage length	254 mm	22 mm
Operating temperature range	−40 to +80 °C	−40 to +120 °C
Strain limits	±2500 microstrain	±2500 microstrain
Wavelengths (measured at 22 °C)	1542/1546 nm 1552/1556 nm	1527 nm 1535 nm 1563 nm

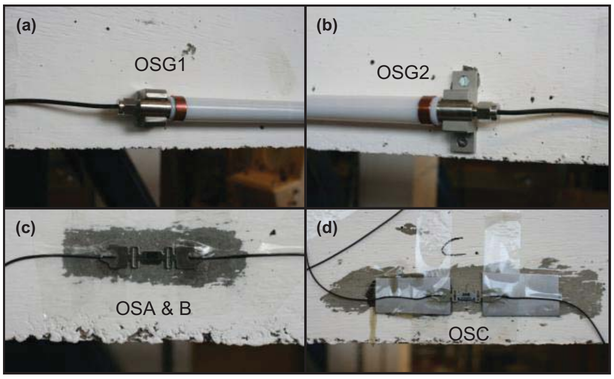

Fig. 1. Mounting details for optical sensors on the test beam in the laboratory. (a) OSG1. (b) OSG2. (c) OSA and OSB. (d) OSC.

Fig. 2. Test beam in the laboratory.

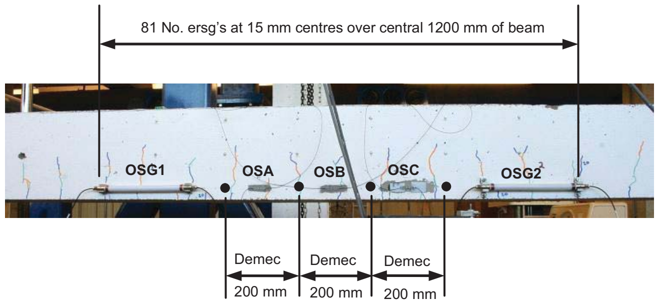

Fig. 3. Layout of sensors on the test beam in the laboratory.

in the vicinity of these sensors would be needed in order to remove the temperature effects on the sensors and so estimate real strains and both optical and conventional techniques are available to provide such compensation. Fortunately, due to the controlled environment of the laboratory, temperature compensation could be omitted in this test. During the test, the temperatures both outside the beam and inside the beam (the latter measured using previously cast-in thermocouples) were monitored and a variation of less than half a degree was recorded. For the sensors used, a variation of half a degree creates an error in the wavelength measurement which is equivalent to a maximum of 5 microstrain. This was seen as a tolerable error in this test but for "in-the-field" measurements where the temperature change is much greater, it is important that adequate temperature compensation is included, otherwise temperature changes could be construed as strain changes, thus creating an unacceptable error in the actual strain measurement.

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.

B. Test Beam

The reinforced concrete beam (Fig. 2) 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 was three 16 mm diameter high yield reinforcing bars (one of which was internally strain gaged) and the top reinforcement comprised two 12 mm diameter high yield bars. The internally strain gaged 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 gages (ersg's) spaced at 15 mm centres in a central longitudinal duct over the central 1200 mm of the bar (further details of this technique are given in references [16] and [17]). The ersg's had a gage length of 3 mm and an upper strain limit of 3%. A three wire system was used for the gage wiring and the data logger used provided double constant current energisation to each gage in turn.

Surface strains on the concrete were measured using a demountable, mechanical strain gage (a "Demec" gage) 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 meter of the test beam, the level of most interest being that which coincided with the main tension reinforcement. Obviously, this approach would only measure average strains over each 200 mm gage length but this was deemed a useful independent back-up to readings from the strain gaged bar.

As shown in Fig. 3, the fiber optic strain sensors, strain gaged 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. Manually pumped hydraulic jacks were used and the loads applied were measured using load cells incorporated in the loading system. A full set of readings was taken from all the sensors at each load stage during the tests.

It was anticipated that strains on the bridge in Mumbai induced by the test trains would be low. Consequently, the test program simulated this by concentrating on loading the beam in its uncracked condition with a number of load cycles being performed to obtain a good indication of repeatability. The beam was then loaded close to onset of yield in the reinforcement to investigate the performance of the sensors on a cracked section and thus obtain a good indicator of their robustness.

C. Test Results

Perhaps predictably, the optical strain gages (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 failed completely in the early stages of loading to reinforcement yield. The mechanically fixed sensors performed satisfactorily under all loading conditions although it was found that it was important to ensure that they were secured tightly in their mountings as this was essential to avoid slip and hence under-reading. For all practical purposes the tests confirmed that OSA/B/C were completely unsuitable for use in the conditions anticipated on the bridge site. OSG2 performed best of all and generated very reliable data under all loading conditions which compared well with the readings from the gaged reinforcing

Fig. 4. General view of Vasai Creek Bridge.

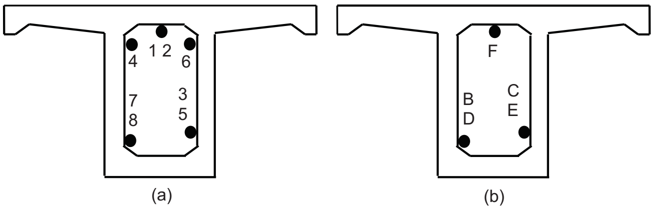

Fig. 5. Instrumentation layout at midspan. (a) Optical devices (optical strain gages). (b) Electrical strain gages.

bar and the Demecs. It was thus decided at the conclusion of the laboratory evaluation to use optical strain gages on the bridge and mount them using threaded rods glued into drilled holes (i.e. the modified technique used for OSG2) as the beam test showed this technique to be particularly effective.

III. Vasai Creek Bridge

A. Instrumentation

Fieldwork was performed on Vasai Creek Bridge, a 28 span prestressed concrete post-tensioned box girder railway bridge located just north of Mumbai in India. The bridge was constructed in the mid 1980's with all spans (length 28.5 m) simply supported. The bridge actually consists of two parallel and adjacent lines of concrete boxes each of which support a single line of railway. Sensors were mounted inside the western (uptide) end span at the southern end of the bridge. Fig. 4 shows a general view of the bridge, Fig. 5 shows the layout of the sensors at mid-span of the end box and Fig. 6 shows the inside of the box with the instrumentation in place ready for testing.

Access to the bridge was only possible for a very limited period and so, building on the results of the laboratory trials, at mid-span, pairs of optical strain gages were positioned in the centre of the soffit (underside of roof) and at the bottom of each web (side wall) of the box (Figs. 5 and 6). 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 gage (ersg: gage length 120 mm) was placed next to each optical sensor (Fig. 7) in order to achieve corroborating strain readings.

The optical strain gages were clamped to the surface using the grouted stud technique developed in the laboratory tests.

Fig. 6. View inside the box girder showing the scale and the environment in which the sensors are mounted.

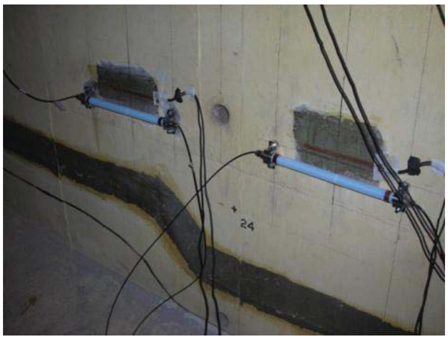

Fig. 7. View of typical strain gage configuration mounted on the bridge itself (lower left: Fig. 6).

Fig. 8. Multiple unit suburban train on the test span.

The ersg's were bonded directly to the concrete after surface preparation.

Additional ersg's were installed in the top corners of the box at mid-span. Further ersg's were installed at the end of the box to investigate possible torsional restraints effects at the supports.

All the fiber 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.

All the box sections of the bridge exhibited significant longitudinal cracking in the webs plus some diagonal cracking at a number of locations in the span. Consequently, Indian Railways normally permit only multiple unit suburban trains

Fig. 9. Crack width sensor used in the bridge tests.

Fig. 10. Locomotives for load testing (design train) that is made available for the tests carried out.

(Fig. 8) to use the bridge while all locomotive hauled traffic, which has considerably higher axle loadings, uses a pair of adjacent, newer bridges. Thus, as an addition to the main test program, crack widths were monitored at five locations using commercially available sensors. These consisted of an arch-shaped spring plate which was strain gaged and bolted to the concrete across a crack. Fig. 9 shows one of the sensors in position across a crack. Sensors 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 noted that all instrumentation, optical, ersg and crack width, could only record changes in loading on the bridge. Measurement of self-weight effects was, unfortunately, impossible, of course.

B. Load Tests

Load tests were carried out during the limited period made available which included 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 (Fig. 10) 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

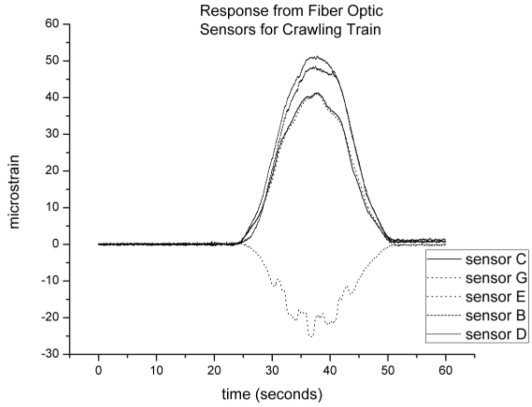

Fig. 11. Strain measurements from the five fiber-optic sensors operating [Fig. 5(a) for positional details].

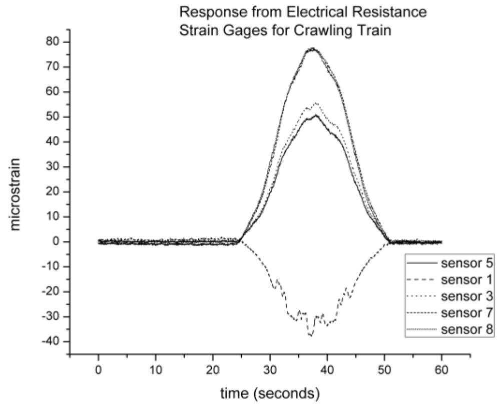

Fig. 12. Strains from the five electrical resistance strain gages [Fig. 5(b) for positional details].

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). In addition, continuous recording was undertaken over a 24 h period to monitor all normal traffic on the bridge provided by the regular succession of multiple unit suburban trains.

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.

C. Results and Discussion

From an initial analysis of the data it was seen that optical strain gage F (Fig. 5) did not give consistent data and thus the results from this sensor were not used in the analysis. This fully justified the decision to use sensors in pairs to allow for redundancy as there would have been insufficient time to install a replacement once the tests had begun.

Results for one run of the design train at crawling speed are given in Fig. 11 for the optical strain gages and Fig. 12 for the ersg's. It can be seen that for, each sensor type, the values of the strains recorded for the two sensors applied for corroboration correlated with each other very well e.g optical strain gages B and D gave almost identical values and ersg's 7 and 8 gave almost identical values.

TABLE II

Peak Strain Values for Optical Fiber Sensors [Fig. 5(a) for Positional Details]

Sensor	Optical Strain Gages					
	B	C	D	E	F	G
Run 1	48.4	41.3	51.4	41.0	-	−25.2
Run 2	46.7	41.0	51.0	41.2	-	−24.7
Run 3	45.8	40.5	51.0	41.1	-	−26.3
Run 4	48.4	41.2	51.8	41.9	-	−25.8
Run 5	48.0	42.3	52.4	41.8	-	−26.4
Run 6	48.0	42.4	52.1	42.2	-	−25.5
Run 7	51.6	44.6	56.0	42.8	-	−28.3
Run 8	54.3	46.1	57.5	43.8	-	−27.0
Run 9	53.4	45.4	57.4	42.5	-	−28.3

TABLE III

Peak Strain Values for the ERSGs [Fig. 5(b) for Positional Details]

Sensor	Electrical Resistance Strain Gages					
	1	2	3	5	7	8
Run 1	−38.0	−40.6	55.9	51.0	77.1	77.7
Run 2	−39.6	−41.6	55.5	51.2	76.6	76.6
Run 3	−38.2	−40.8	55.7	50.7	77.3	77.7
Run 4	−38.7	−41.3	54.1	50.4	77.5	78.8
Run 5	−38.4	−41.5	54.8	51.1	76.9	79.5
Run 6	−38.9	−41.5	55.0	51.2	78.0	78.4
Run 7	−38.3	−40.9	56.0	51.2	77.6	80.4
Run 8	-	-	-	-	-	-
Run 9	−37.6	−41.1	56.1	51.1	77.0	79.8

The peak values for each design train run from the optical strain gages and the corresponding electrical resistance strain gages are tabulated in Tables II and III respectively. 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 gage F are omitted (see above) and ersg data recording for Run 8 were not available due to technical problems on site.

It is interesting to note that although the optical and electrical strain gages have identical time history patterns, in general optical strain gage values are slightly lower than the corresponding electrical resistance strain gage values. Comparisons of the two sensors at two different locations, as shown in Figs. 13 and 14, illustrate this point.

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

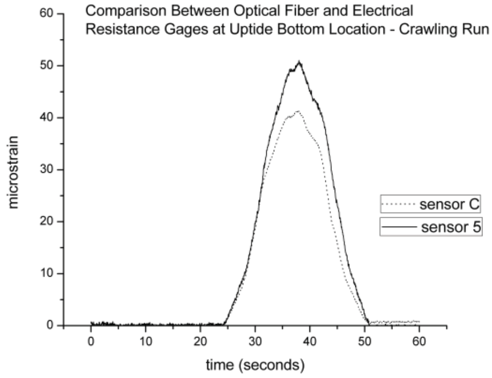

Fig. 13. Strain comparison at the web bottom location between the output of an optical gage (sensor C) and an electrical gage (sensor 5) during a crawling run.

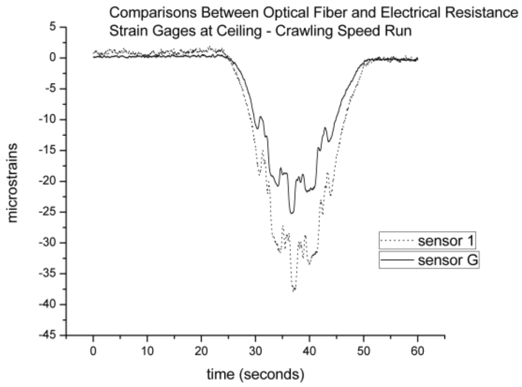

Fig. 14. Strain comparison at the soffit (ceiling) location between the outputs of an optical gage (sensor G) and an electrical strain gage (sensor 1) during a crawling run.

TABLE IV

Ratios of the Peak Responses of the Optical Fiber Gages to the ERSG Over a Series of Runs Shown by Each Optical Gage (C Through D)

	Optical Strain Gage: ERSG Ratio					
	B	C	D	E	F	G
Run 1	0.629	0.809	0.661	0.733	-	0.663
Run 2	0.610	0.800	0.665	0.743	-	0.623
Run 3	0.592	0.799	0.656	0.738	-	0.689
Run 4	0.625	0.818	0.657	0.775	-	0.668
Run 5	0.624	0.828	0.660	0.763	-	0.688
Run 6	0.616	0.828	0.665	0.767	-	0.656
Run 7	0.665	0.870	0.696	0.764	-	0.739
Run 9	0.693	0.889	0.719	0.757	-	0.752
Mean	**0.632**	**0.830**	**0.672**	**0.755**	**—**	**0.685**

The results shown in Figs. 11–14 are typical for all runs of the design train at all speeds. The multiple unit suburban trains, which crossed the bridge at around

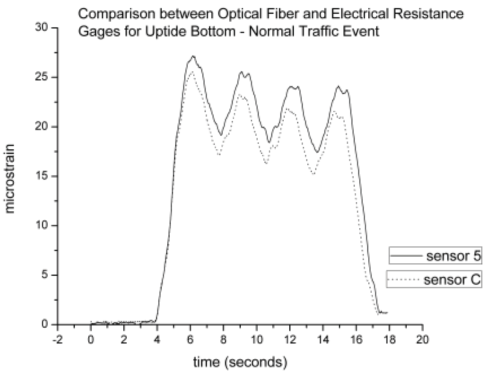

Fig. 15. Strain comparison between the outputs of the optical gage (sensor C) and the electrical gage (sensor 5) at the soffit for the suburban train as a normal traffic event.

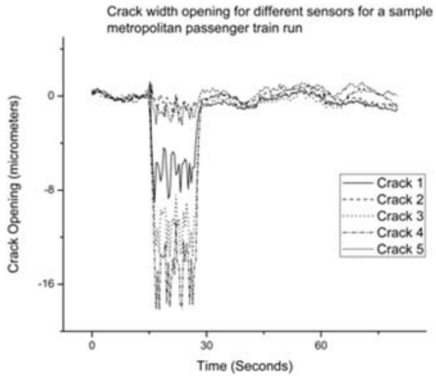

Fig. 17. Crack width movements showing the outputs of the five crack width sensors for the passage of a metropolitan passenger train.

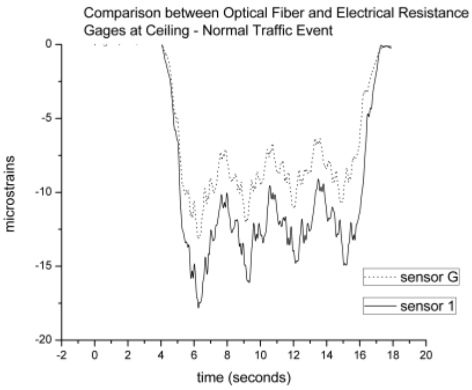

Fig. 16. Strain comparison between the outputs of the optical gage (sensor C) and the electrical gage (sensor 5) at the web (ceiling) for the suburban train as a normal traffic event.

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, maybe, to the dynamic effect of the first bogie providing additional excitation to the structure. This effect is shown in Figs. 15 and 16 which compare typical optical strain gage and ersg readings for the soffit and web.

The fiber 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 optical fiber 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 Fig. 17 (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.

IV. Conclusion

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 fiber optic gages and especially so when time on site for sensor installation was limited. However, the success of the research program undertaken emphasized the value of the planning and execution of the preparatory work in the laboratory from which it was possible to select the correct sensor type with regards to gage length and mounting technique and thus the use of packaged sensors would seem essential if a system sufficiently rugged for field use is to be obtained. Given these constraints, the research program described has shown that high quality measurements that are of value to the structural engineering community are eminently obtainable using the sensor system set up and evaluated in this paper even under the tight time constraints imposed by the limited availability of access to the bridge for the field test. A series of results of measurements taken under well controlled conditions has been reported and conclusions drawn which are highly relevant for future work.

Acknowledgment

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