Fiber Optic Strain Monitoring for Long-Term Evaluation of a Concrete Footbridge under Extended Test Conditions

Frederic Surre, *Member, IEEE,* Tong Sun and Kenneth T.V. Grattan

***Abstract*—An optical fiber sensor system that can be installed and used to give reliable and informative data has been developed, tested and evaluated, over an extended period of two years, on a redundant 50 year-old concrete foot bridge whose conditions of use were well known. The bridge now serves as an operational test-bed as it has been taken out of service, and recently has been subjected to different known environmental and loading conditions. Thus in this work, specific and controlled damage has been induced, the effects monitored and thus the changes induced to the bridge have been recorded, using the optical fiber sensor system over the test period. During this two year survey, issues relating to the installation, use, data capture and evaluation of performance not available in the present literature have been identified and addressed giving valuable information for the longer-term evaluation on the installation and use of optical sensors to assess better such concrete structures.**

***Index Terms*—Fiber Bragg grating, Optical fiber sensors, Strain sensors, Structural health monitoring.**

I. Introduction

SERVICEABILITY and whole life performance are critical to the more effective use and the better long-term monitoring of concrete structures, making it invaluable to ensure full structural capability and to minimize risks to the public from weakened structures. In order to understand more fully the needs and challenges of creating better infrastructure, effective assessment and monitoring systems that can give reliable and informative data are required and which have the confidence of the structural monitoring community. Fiber Optic Sensors (FOS), mainly using fiber Bragg gratings (FBG), have been demonstrated as being promising candidates for a breadth of such monitoring and tests and trials have been reported over several years by the authors and others. However, many of these studies have been made under laboratory conditions and often field tests have been limited by the availability of a real structure for evaluation, thus often to short-term monitoring of duration a couple of days [1]-[6]. Longer-term monitoring, which is vital to evaluate the robustness of fiber-optic systems and to give confidence to structural engineers in the veracity and stability of the sensor systems used, has often been performed using embedded sensors in newly built bridges. However, the majority of problems in infrastructure lie with existing bridges, built since the Second World War and it is more difficult to deploy this technique with such already-built structures, usually unless a program of repair is being planned or undertaken (and in which case there may be considerable and costly damage evident). For example, the study presented in the work of Kerrouche *et al* [7] shows one possible use of optical strain sensors embedded in the rebars used to strengthen an aging bridge. If no such repair program is planned, the only cost-effective solution is to use surface-mounted sensors. These techniques present issues regarding the most effective fastening of the sensors to give maximum strain transfer and the influence of environmental factors, such as from long term exposure to humidity and solar radiation. It is thus imperative to be able to identify damage (and thus potential weakness) as early as possible and effective tests under known and controlled conditions using high quality sensors offer the best way to do this.

To address the above, the present study arose because of access being given to a concrete footbridge which was being taken out of service, due to the refurbishment of a site. The study was thus able to test and evaluate installed FOS systems for a longer period of time than is frequently the case and to allow for the identification and resolution of issues linked to installation, use, and evaluation of performances under real condition over a multi-year period. To evaluate the system *in situ*, a series of loading tests has been performed before and after a planned regime of controlled damage has been performed on the bridge under test. These studies (and the performance monitoring using the FOS system) thus are designed to give an insight in the ability of the sensor systems used to detect the effects on the structure of the bridge, when a known level of damage is used. As a result, a long-term environmental monitoring study has been performed allowing structural engineers to identify robustness issues of the bridge and sensor specialists the integrity and performance of the

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F. Surre, T. Sun and K. T. V. Grattan are with the School of Engineering and Mathematical Sciences, City University London, London, EC1V 0HB, United Kingdom. Phone: 44-2070400127; e-mail: f.surre@ ieee.org).

system during the tests.

The paper presents representative data from the bridge under study and the fiber optic sensor system used for the evaluation taken at various times during the two-year period. It builds upon preliminary results presented in [8]. Thus in this report the outcomes of four specific loading tests typical of those carried out are presented and their results are critically discussed and compared with other data. Finally, conclusions drawn from the two years of environmental monitoring are presented, backed by the experimental results taken.

II. Footbridge Under Study

A concrete footbridge on the premises of the National Physical Laboratory (NPL), Teddington, UK, was the 'test-bed' for this work. The bridge, shown in fig. 1, was built in the early 1960s and is built from reinforced concrete. The deck is 20m long; the piers are 5m high and the total weight of the bridge is 15tonnes. It had been in use for more than 40 years before it had been moved to its present location after its decommission to allow the test work to be done. Prior to that, new purpose-built concrete foundations had been created to support the bridge. As it is no longer in active use, it could be used as a test specimen, allowing loading at levels beyond what would be permissible with a 'working bridge' and allowing for accelerated damage situations to be created with it.

As a result of prior work by structural engineers and arising from the fact that the bridge had been owned by NPL since construction, the condition and provenance of the bridge was as well-known as possible and prior extensive evaluations of the physical condition of the bridge have been undertaken and recorded. Furthermore, this assessment has been used to create data for a finite-element modeling of the structure undertaken by other groups but not part of this particular study although supporting the overall structural evaluation.

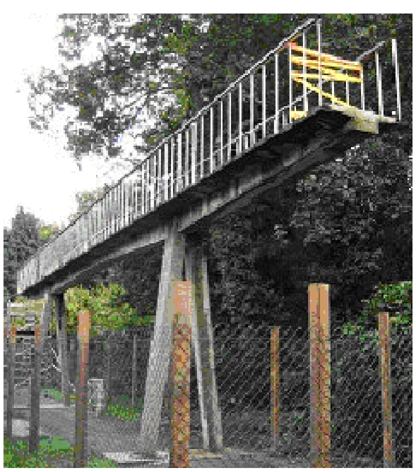

Fig. 1. Concrete footbridge at the National Physical Laboratory (© NPL).

III. Bridge Instrumentation

A. FBG-based Optical Strain Sensors

Before detailing the optical strain sensor system used in this work, a short introduction on Fiber Bragg Gratings (FBG) is provided. A FBG is a periodic modulation of the refractive index of the core of a photosensitive fiber. The modulation of the refractive index was induced by UV light. Different techniques exist to fabricate the type of FBGs used in this work [9]. The periodic modulation acts as a filter reflecting one wavelength. The reflected wavelength, termed the Bragg wavelength, may be expressed by the following formula [9]:

$$\boldsymbol{\lambda}_{\mathbf{B}} = 2\mathbf{n}_{\mathbf{e}}\Lambda \qquad (1)$$

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 induces a shift of the Bragg wavelength. For example, temperature variations that naturally occur on an exposed external structure such as the footbridge under test induce a change of refractive index and grating period, while longitudinal strain (such as that externally imposed during the tests carried out) mainly induces a change in Λ. The temperature and/or strain induced wavelength shift can be modeled by the following equation:

$$\Delta\boldsymbol{\lambda} = \mathbf{S}_{\mathbf{strain}}\Delta\boldsymbol{\varepsilon} + \mathbf{S}_{\mathbf{T}}\Delta\mathbf{T} \qquad (2)$$

where S_{strain} and S_T are the strain sensitivity and temperature sensitivity of the sensor respectively. $\Delta\varepsilon$ and ΔT is the strain variation and temperature variation respectively. The strain variation is composed of two major contributions: the thermally induced strain, $\Delta\varepsilon_{th}$, and the load induced strain, $\Delta\varepsilon_{load}$. The thermally induced strain is related to the concrete expansion, arising from the external temperature changes. This relationship can be modeled using the coefficient of thermal expansion (CTE) of the concrete. Finally the strain variation may be expressed by:

$$\Delta\boldsymbol{\varepsilon} = \Delta\boldsymbol{\varepsilon}_{\mathbf{th}} + \Delta\boldsymbol{\varepsilon}_{\mathbf{load}} = \mathbf{CTE} \times \Delta\mathbf{T} + \Delta\boldsymbol{\varepsilon}_{\mathbf{load}} \qquad (3)$$

It is well known and clear from Eq. (2)-(3) that strain measurement monitored using the FBG-based sensor system can be influenced by external temperature variations. Two contributions can be identified: the temperature effect on the sensor itself modeled through S_T, and the thermally induced strain. In order to estimate the strain, either thermally induced or load induced, it is necessary to have an accurate value of the temperature in the vicinity of the FBG. In the next paragraph, the sensors used in this work and how the temperature is compensated are introduced. Different temperature compensation schemes have been discussed in the literature over the years (and a summary can be found in the work of Majumber [10]).

B. Optical Strain Sensors and Location on the Bridge

Each of the strain sensors installed on the bridge comprises two FBGs: one to measure strain (through monitoring the strain and temperature effects combined) and one to perform temperature compensation (i.e. to measure the temperature effect alone). To achieve a compact packaged sensor for easy use on an external structure such as this, both FBGs were packaged into a single carbon-fiber reinforced polymer (CFRP) patch which can be easily installed at any point of interest on the structure. The FBG used to measure temperature and compensate the thermal effect on the strain FBG is isolated from the patch through the careful design of the sensor casing. A sketch of the sensor illustrating the packaging is presented on fig 2. Packaging the FBGs for this work had been undertaken by a company following a proprietary process, for speed of installation. The strain and temperature sensitivities of the strain FBG sensors patch used are approximately 1.2pm/με and 11pm/ºC respectively. As can be seen from the temperature sensitivity the thermal expansion of the patch is slightly larger than a bare fiber thermal expansion.

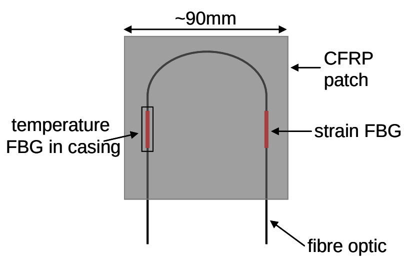

Fig. 2. Sketch of FBG strain sensor packaged into Carbon Fiber Reinforced Polymer patch with a second FBG for temperature compensation. The patch thickness is about a quarter of a millimeter.

For a study of this type, the advice of structural engineers has been sought on the optimum placement positions of the sensors. Thus the positions of the ten strain sensor (sets) used has been determined by a close analysis of the outputs of the finite element simulations carried out in another study and provided to the authors by the managers of the bridge. The simulations were designed to identify the areas of the bridge which were subjected to the highest strain when the bridge was loaded and thus the points where the most significant measurements on the structure could be made.

Fig. 3 presents the location of the sensors on a sketch of the structure. In order to achieve the objectives of the greatest understanding of the structure that could be achieved using the different sets of sensors, sensors 1 and 2 are mounted on the outside of each leg of the left pier using the view of fig 2. Five sensors are located on the top of the deck: two on each side of each pier (sensors 3 and 4 and 6 and 7) and one in the middle of the deck (sensor 5). Sensors 8 and 9 are located on each side of one leg of the right pier. Finally, sensor 10 is attached in the middle underneath the deck. During the loading test (details of which are presented in section IV), the cantilever on the right hand side of the bridge (with respect to the picture in fig. 3) was subjected to the load. Therefore, the majority of the results presented in this paper were focused on sensors 6 to 9, as they were expected (from the prior finite element analysis) to experience the highest level of strain and to give the best insight into the strain experienced by the whole structure.

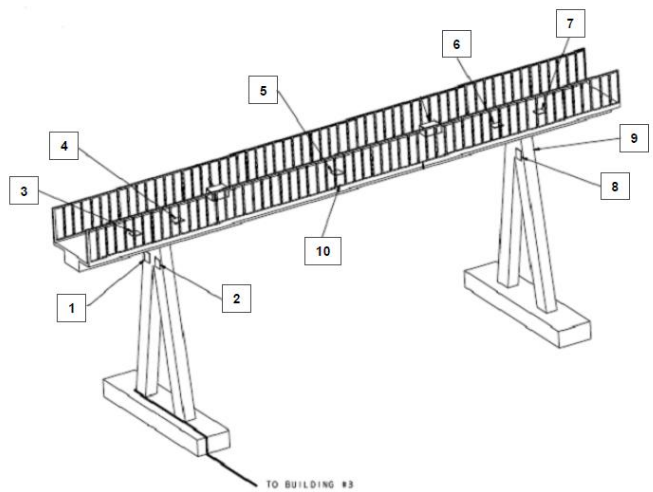

Fig. 3. Position of the ten fiber optic strain sensors on the footbridge (© NPL).

C. Instrumentation

The wavelengths of the twenty (two sets of ten) FBGs were monitored using a MicronOptics sm125 4-channel interrogator. The maximum data acquisition rate is 5Hz which was adequate for the slow rates of loading of the structure. Thus during the loading test presented in section IV, the data rate used gave one sample every 200ms. For environmental monitoring (where relatively slow changes are experienced), a data rate of 0.05Hz, i.e. one sample every 20s, is adequate and was used (thus avoiding a superfluity of data being created over the very long monitoring periods of the bridge structure). The wavelength precision from the interrogation instrument was 2.5pm, which is equivalent to less than 2με. The interrogation box was placed a convenient distance of 15 meters away from the bridge for ease of downloading the data. The sensors were connected to this box using single-mode optical fibers and sensors 1 to 5 were connected to channel 1, while sensors 6 to 10 were connected to channel 2.

D. Installation and Preliminary Test

The sensor patches used in this work were attached to the concrete using commercial cyanoacrylate glue. Following installation, after a period of time to let the sensors settle, the wavelengths corresponding to the strain and temperature measurements were monitored on a continuous basis. On analysis, the results obtained from sensor 4 show that the strain profile from the FBG presents a double peak profile. The spectrum of the bare FBG had been checked before packaging and mounting and no significant side lobe was visible at that stage. Therefore, the most likely explanation for this unusual and anomalous performance is a geometrical modification of the fiber either during the packaging process or the mounting on the bridge leading to birefringence. As a consequence of this double peak, the output from sensor 4 has been discarded but that has had no significant deleterious effect on the overall analysis carried out on the structure. Fortunately, no other problems had been detected with the other nine remaining sensors and data from them could be used as obtained.

IV. Loading Tests

Over the two year period of the study, a number of loading tests had been undertaken, at regular intervals during the first year of study of the bridge. The paper presents the results of several such representative tests during that time. The first loading undertaken, which lasted two days, had been performed at the start of the project. The results are presented in section IV.A and IV.B. In order to provide quantitative information on the actual load applied and thus achieve control of the effect on the structure, two water tanks, each yielding a load of one tonne load when the tanks were filled and had been suspended on the right hand side cantilever of the bridge (when using the view seen in fig. 3). The first tank to be filled, in this study named tank 1, was the closest to the pier of the bridge.

Following this loading, a series of controlled damage events was applied to the reinforcement bars in the bridge, in order to simulate the effect of a serious damage event to a working bridge e.g. through it sustaining an impact. The exact damage mechanism is explained in section IV.C Following this carefully applied damage event, a further loading test was performed using the same set-up, the work being carried out over a period of two days. The results thus obtained are presented in section IV.C and IV.D.

A. *Loading Test 1: 'The Afternoon Test'*

The first test was performed during one afternoon taking note of the prevailing meteorological conditions. On that day, the weather had been constantly cloudy but with limited variation in the solar radiation falling on the structure. Fig. 4(a) presents the loading scheme for this first test which commenced with the filling of tank 1. A five minutes pause was observed after filling half of the tank and after fully filling it to limit the shock of the weight applied. After this second pause, filling was begun for tank 2 until it was then half filled. After a few minutes pause, additional water (load) was added to the tank until the total load was 1.7 tonnes. The reason for stopping the loading was due to the acoustic emission monitoring system installed on the bridge (as part of another experiment) picking up signs of cracking. The two tanks were then immediately emptied to reduce the effect on the bridge after this extreme loading test.

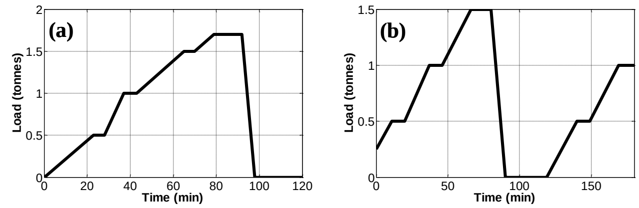

Fig. 4. Loading schedules for (a) Test 1, 'The Afternoon Test' and (b) Test 2, 'The Morning Test'.

Figure 5 presents the temperature variation measured by sensors 6 to 9. It should be noted that the variation was limited to, at maximum two degrees, as noted by the end of the test.

Fig. 6(a) and (b) present the recorded strain variations obtained from sensors 6 to 9. The data have been filtered in the post-processing to reduce the noise originally detected the system. Sensors 6 and 7 each experience a similar level of tensile strain. It should be noted that the rate of increase of the strain is larger when tank 2 is filled (starting at the 45min time point on the abscissa) than when tank 1 is filled and this observation is consistent with the position of tank 2 being closer to the end of cantilever. From fig 6(b), it can be seen that the strain measured by sensor 8 is tensile and sensor 9 is compressive. Furthermore, sensor 9 experiences a larger strain than does sensor 8, which is not an unexpected conclusion.

By using the strains measured by these four sensors, it was possible for structural engineers to reconstruct the movement of the bridge when the cantilever is loaded. Under the load, the pier bends toward the cantilever and the deck is bending on both side of the pier.

After the load was removed, sensors 6, 7 and 8 were seen to exhibit a 'residual' strain reading. Only sensor 9 comes back to the zero strain measurement before the load was applied originally. This residual strain effect – representing a resetting of the 'zero position' when the load was removed – can be explained by either a change in the sensor attachment to the concrete to the loading or by the effect of the cracking, which the acoustic emission monitoring system picked up.

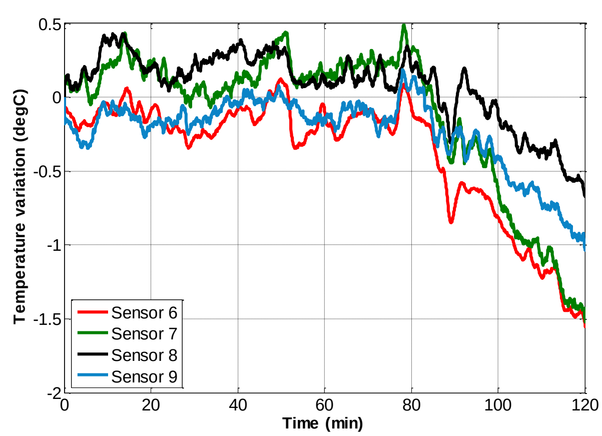

Fig. 5. Temperature variations for sensors 6 to 9 during the first loading test. Interrogator data acquisition rate is 5Hz.

B. Loading Test 2: 'The Morning Test'

A similar test to that previously recorded was performed the following morning. In this instance, the weather was sunny with scattered clouds. Fig. 4(b) shows the loading schedule for the test, labeled Test 2. Tank 1 is loaded first. A pause is observed when tank 1 was half filled and when it was fully filled. Following that tank 2 was half filled, thus to reach a maximum load of 1.5 tonnes (ensuring a total load that does not exceed that reached during Test 1 that lead to the acoustically-observed cracking). Following the application of the load, both tanks were then emptied and finally, tank 1 was filled again to create an additional load.

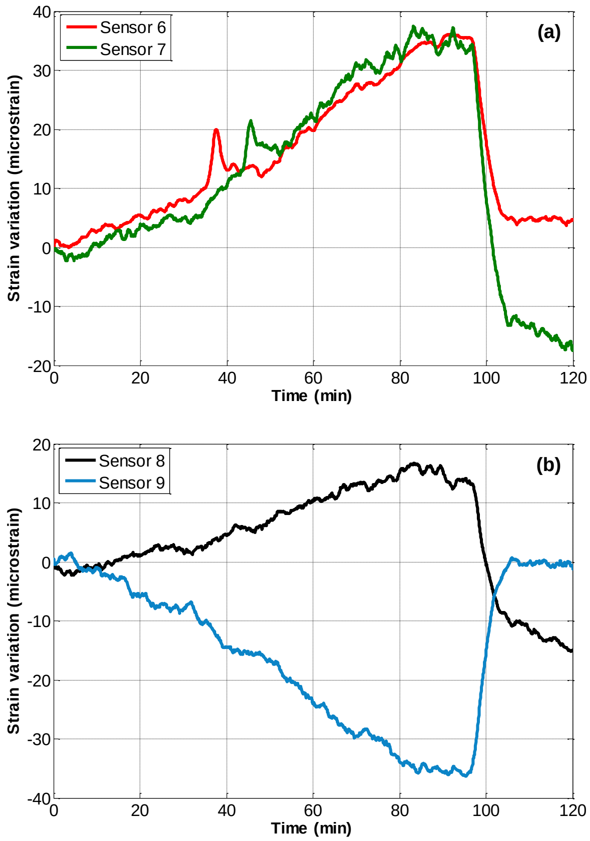

Fig. 6. Strain variations for (a) sensors 6 and 7 and (b) sensors 8 and 9. Interrogator data acquisition rate 5Hz.

Figures 7 (a) and (b) present temperature variations and strain variations recorded from sensors 6 and 7 respectively. It can be noted that the variation of temperature measured by the sensors is greater than was observed during the first test, emphasizing the value of recording and thus correcting for ambient temperature variations – the temperature measured by the FBGs was influenced by both the ambient temperature and the presence of solar radiation. Due to the variable cloud cover, the temperature could vary by up to 10 degrees in a short period of time. The strain variation for sensors 6 and 7, observed after removing the temperature sensitivity of the packaged FBG, was highly influenced by the external temperature variation and the concrete reacting to this. The strain observed due to the bridge loading cannot be seen clearly as the thermally induced effect on the sensors is significantly larger than the strain change. This point, regarding the influence of the CTE of the concrete used, is considered further in section 5.2.b.

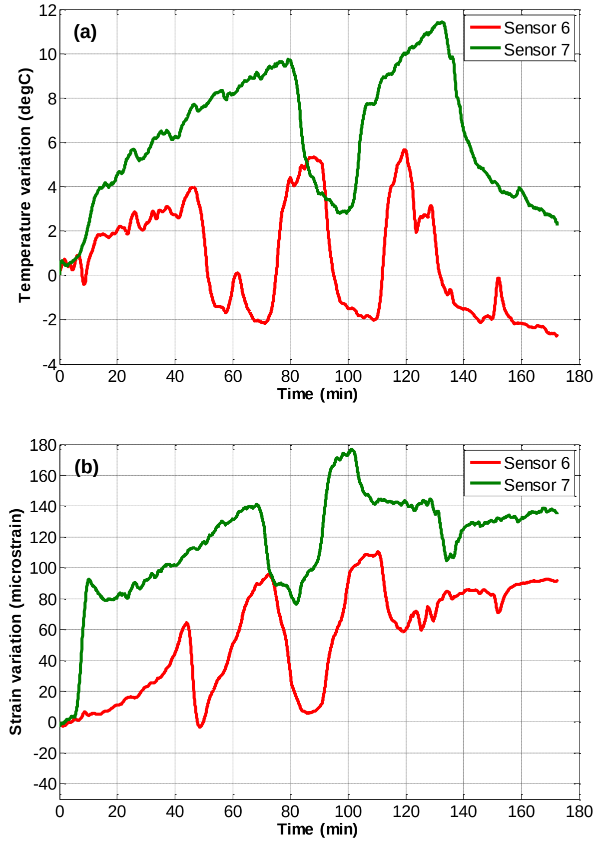

Fig. 7. (a) Temperature variation and (b) strain variation for sensors 6 and 7 for Test 2. Interrogator data acquisition rate is 5Hz.

C. Test 3: Afternoon test after controlled damage to the reinforcement bars

Following the first two loading tests presented earlier in Sections A and B, the footbridge was damaged in a controlled manner to represent the effect of an impact. The concrete cover of the reinforcement bars on the deck immediately above the pier was removed and a quarter of the diameter of the reinforcement bars was milled out, resulting in a damage area of the rebar of about 10 mm.

Following this carefully controlled damage regime, two loading tests were carried out on two consecutive days (approximately five weeks after the first tests were performed). The results of the first loading test are presented in fig. 8 in which two loading cycles were performed. In this sequence, Tank 1 was filled first (with a pause being observed in the filling after half the tank filled) and then the tank is filled to capacity. Following this, tank 2 is filled (with also a pause after the tank being half and fully filled, as before).

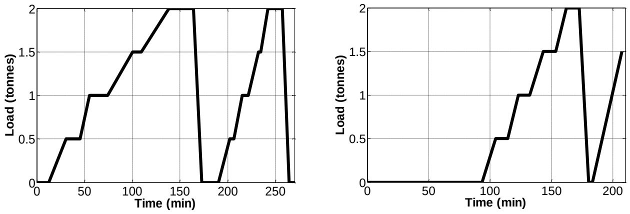

Fig. 8. Loading schedules for (a) Test 3, The Afternoon Test and (b) Test 4, The Morning Test.

Figs. 9 (a) and (b) present the strain variation measured using sensor 6 to 9. As was observed during Test 1, sensors 6 and 7 experience and record a tensile strain. However, unlike the previous test, the strain experienced by sensor 7 is larger (by about 10µstrain) when compared to that seen by sensor 6.

Sensors 8 and 9, on the other hand, experience different strains. Sensor 8 measures a tensile strain and sensor 9 a compressive one. This is similar to the results obtained during Test 1. The level of strain is larger than for Test 1, mainly due to the larger load being applied. It is interesting to note that unlike in Test 1, the acoustic emission monitoring system does not record significant cracking even for a load of 2 tonnes being applied.

However, after the first cycle, the measured strain does not come back to the original level, this being due to the thermally induced variation of concrete. Even if the temperature is essentially constant, a small change in temperature was measured during the test.

After this period of testing, the results suggest that damaging the rebars has modified significantly the behavior of the bridge as would be expected. Sensors 6 and 7 are thus experiencing different levels of strain as a result of this damage to the rebars, even if they are still subject to a tensile strain. Furthermore, it is now possible to load the bridge to a higher level without inducing significant (acoustically monitored) cracking.

D. Test 4: Morning test after controlled damage to the reinforcement bars

Following the conclusions observed from Test 3, another test was performed to confirm the behavior of the bridge. The loading scheme used is presented on fig. 8(b) and consists in one load cycle up to 2 tonnes, and then the emptying of both tanks, followed with a one tonne loading (i.e. only tank 1 is filled).

As for Tests 1 and 3, the temperature and solar irradiance were essentially constant during the length of the test, and therefore, only the load induced strain is measured by the sensors. Fig. 10(a) shows the strain variations for sensors 6 and 7. As for Test 3, a strain difference observed in the results seen from sensors 6 and 7 is clearly present, confirming the results obtained in Test 3. Fig. 10(b) presents the strain variations measured by sensors 8 and 9. The same pattern as was seen in Test 3 appears but the level of strain is larger than observed during Test 3. The most likely explanation of the results is that, compared to Test 3, there was almost no temperature variation during Test 4 giving the different results.

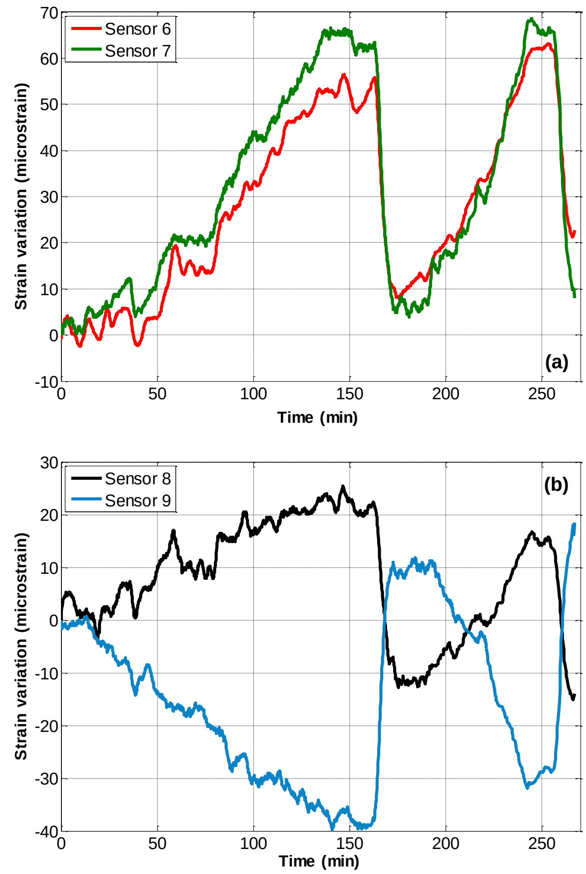

Fig. 9. Strain variations for (a) sensors 6 and 7 and (b) sensors 8 and 9 during Test 3. Interrogator data acquisition rate 5Hz.

E. Conclusions of the loading tests

The four loading tests performed on the bridge have highlighted the value of a fiber optic-based monitoring system and also some the serious issues involved in installing such a system outdoors on a test bridge. The system installed has been able to record the strain variations induced by the loading and, furthermore, has been able to show the effect of damage on the outputs when this has been done on the bridge. Thus coupled with the finite element modeling that underpinned this work, the results seen could be used to indicate where the reinforcement bars have been damaged even though this is not visible to inspection.. The work shows the value of obtaining accurate temperature data for an exposed structure such as this and it may be useful to make temperature measurements outside the packaged sensor sets as well to obtain a full picture. Dealing with this problem could be more problematic when the CTE of the concrete used is not known.

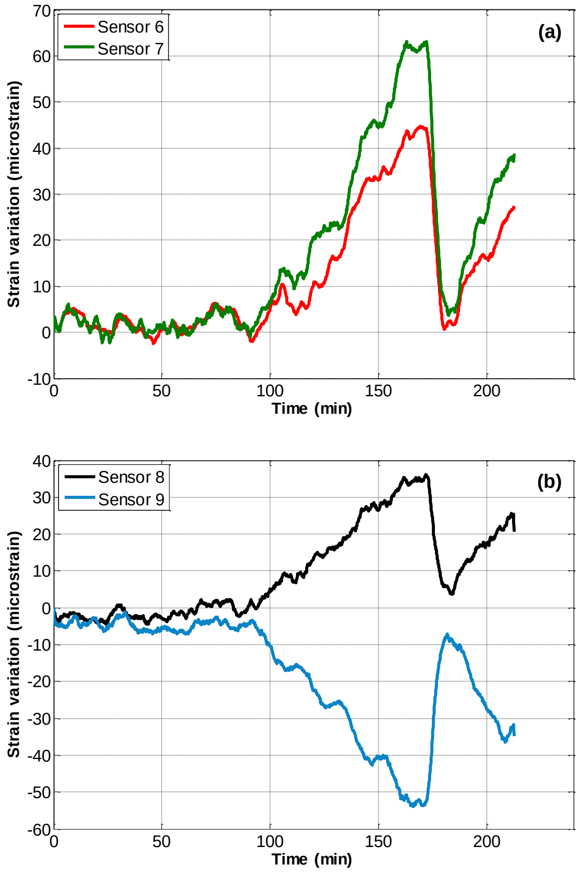

Fig. 10. Strain variations for (a) sensors 6 and 7 and (b) sensors 8 and 9 during Test 3. Interrogator data acquisition rate 5Hz.

V. Environmental Testing

The major part of the monitoring of the bridge and the performances of the FOS system is environmental monitoring that has been performed for the past two years. During that time, it has been possible to identify a series of key issues from tests that are summarized in the following paragraphs.

A. Temperature Compensation

As highlighted by eq.(2)-(3), any FBG-based sensor is also sensitive to temperature variations. Thus an accurate knowledge of the temperature in the vicinity of the FBG is critical to allow an accurate estimation of the strain of the bridge. Thus a carefully packaged sensor set is required with tests required to ensure that both sensors respond in a similar way to temperature changes to avoid errors in compensation.. The use of FOS strain sensor sets on an existing outdoor bridge creates two major challenges which need to be addressed: a possible time-lag between temperature and strain FBGs and the knowledge of the CTE of concrete.

1) Time-lag between temperature and strain sensors

It is clear from the data collected that close attention needs to be paid to achieving the required temperature compensation. Under unfavorable circumstances, a temperature change can be experienced by one FBG earlier than on the other FBG, create a time lag issue. As an example, for sensor 7, the time lag between the responses of each of the FBGs used can be seen in fig 11. In the work reported, a clear lag of about 15 minutes was seen to exist around 11.30am. However, shortly before 12.30pm that day, both wavelength shifts were seen at the same time. This observed time lag could be explained by taking into account the location of the sensor on the bridge, the time of the day and the environment of the bridge. The sensor was located on the deck of the bridge, which was partially covered by the shade of trees in the vicinity. If the time of the day (around noon) was taken into account, one explanation is that both FBGs are not experiencing the same environmental conditions. For example, the temperature sensor may be covered by the shade of a tree, which would then create a temperature difference across both FBGs due to the difference in solar radiation received. Such a situation would arise during the day, depending on the position of the sun and the cloud cover. It should be noted that sensor 10, which is located in a position with no direct sun exposure has not shown this time lag in the outputs of the sensors during its use for two years of monitoring and similarly to support this explanation, no time lag is observed when the system is monitored during the hours of darkness.

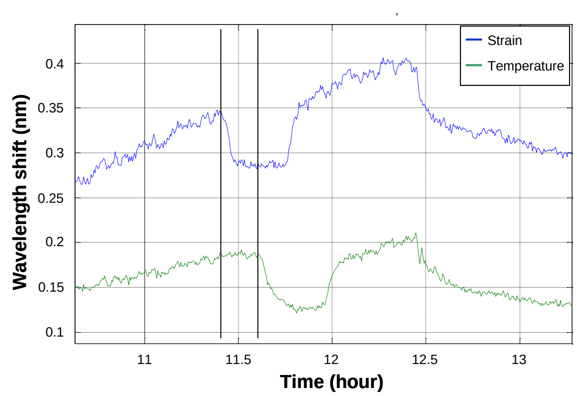

Fig. 11. Example of time lag between strain and temperature sensors.

The extent of this problem will also be dependent on the type of packaging used. In the present case, the temperature FBG is situated about 8cm from the strain FBG making the FBGs susceptible to different solar radiation levels. From this study, it seems logical that both FBGs should be as close as possible in order to limit the inaccuracy that could arise due to this problem. However a study of this type highlights that the problem can exist even if the sensor packaging is carefully planned, thus to emphasize the critical importance of the correct mounting of the sensor package and inclusion of stand alone temperature sensors as required to take account of the prevailing environmental conditions.

2) CTE of the Concrete under Test

Figure 7 shows that the thermally induced strain is the largest contribution to the strain experienced by the exposed exterior bridge. The coefficient of thermal expansion has expressed the link between the temperature variation and the strain variation. In the case of environmental monitoring under conditions where there is no load applied to the bridge, knowledge of the value of CTE is not critical as only the thermally induced strain is experienced by the bridge. However, if the bridge is loaded either by traffic in normal use (or by a defined load for this monitoring purpose) an accurate knowledge of the CTE is vital to allow an accurate estimate of the strain added by the load and to compare strain variations under different loading conditions to help evaluate the safety of the structure, as demonstrated in Section IV. On bridges already constructed and especially those which have been built for some time or have experienced environmental damage (where original data were not kept or have been lost), a knowledge of the CTE is not readily available and, as a consequence, it may be difficult to distinguish the load induced from the thermally induced strain. However the monitoring system gives a clear indication of the *total strain* to which the structure is exposed, which is valuable information in order to estimate the condition of the concrete structure.

B. *Sensor Reliability*

Over the course of the two years of this set of tests, as would be expected several issues with the reliability of the sensors became evident. The first major issue was the optical fiber linking sensors 6 to 10 to the interrogation unit being damaged leading to the loss of data from these sensors. The cause of the damage is unknown, but with the bridge being used as a test-bed by different research groups and companies, the risk of such an accident is higher than in normal bridge monitoring. Thus it is important in long term tests to take care to protect the cabling connecting the sensors to the interrogation system.

The second problem has been the observation of a diminution of the signal quality in sensor 1, most likely due to the changes occurring over the 2 year period in the mounting of the sensor set itself. It is clear that after more than one year, the quality of the strain transfer had decreased to the point where it was impossible to detect any change in the signal from that device. Thus sensor 1 presents an example of a dramatic change in strain transfer observed during the period of the tests over the 2 years and a more limited change may have appeared in some other sensors. Fig. 12 presents the strain variation as a function of temperature variation for sensor 7 at three different periods of the year: late June, early August and early May the following year. The June measurements have been taken before Tests 1 and 2. The August measurements have been taken after Test 3 and 4, and therefore after the rebars being damaged. Finally, the third set of data was measured after the bridge had been exposed to conditions during a winter that was one of the coldest in UK history. From Fig. 12, it can be noted that three set of data exhibit a linear relationship, but, however, their slopes are different. The June data have a slope of 10.2 μstrain/^{o}C; the August data have a slope of 9.5 μstrain/^{o}C; finally the May data has a slope of 15.3 μstrain/^{o}C. These data seem to point towards a change in the strain transfer between the bridge and the sensor. Another possible explanation is a change in strain transfer between the CFRP patch and the strain FBG. More work is being done to understand more fully the origin of the degradation of the sensors.

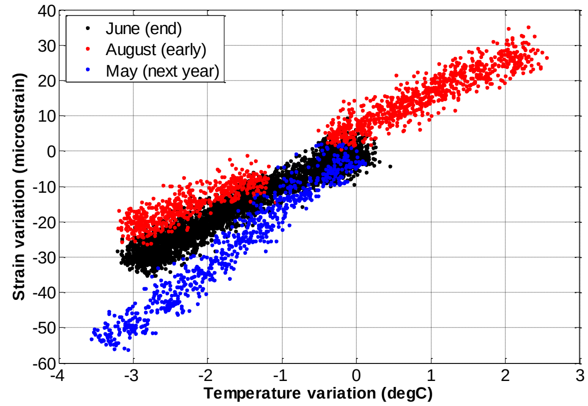

Fig. 12. Strain-Temperature curve for sensor 7 for three different periods: black dots correspond to measurement taken in late June; red dots to measurement in early August and the blue dots in early May the following year.

VI. CONCLUSION

In this paper, data from an extended set of tests on a concrete footbridge have been presented illustrating that an optical fiber sensor system that can be installed and used to give reliable and informative data for structural health monitoring of an existing bridge or a similar concrete structure. The work has evaluated a typical sample platform – tested for more than two years, as a 50 years old bridge at the National Physical Laboratory, UK. The loading and environmental tests that had been performed have both demonstrated the potential of the system developed and implemented and through the tests a number of issues related to long term monitoring of outdoor concrete structures have been revealed. The tests have included an environmental monitoring program which has highlighted several key issues about using temperature compensated sensors outdoors. Recommendations on the design of packaged sensors have been proposed and as the test site is still 'live', work is still underway to gather more data and to continue to evaluate such fiber optic test systems in the field.

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Frederic Surre (S'00-M'03) received the B.Eng in Electronic Engineering and the M.Eng in Microwave and Optical Communications from Ecole Nationale Supérieure d'Electrotechnique, d'Electronique, d'Informatique, d'Hydraulique in Toulouse, France in 1998. He received the Ph.D. in Electronic Engineering from the Institut Polytechnique de Toulouse in 2003. His doctoral work involved modeling and design of multiscale circuits for microwave applications. During his PhD, he co-created and chaired the IEEE Student branch at ENSEEIHT in 1999 and 2000 respectively.
Between 1998 and 1999, he was a Research Engineer with the Physics Laboratory, École Nationale Superieure d'Aeronautique et de l'Espace, France, where he was responsible for opto/microwave measurements. After spending one year working on quasi-optical systems at Queen Mary College, University of London, U.K., he joined both Trinity College's School of Physics, Dublin, Ireland, and Dublin City University's Research Institute for Networks and Communications Engineering, Dublin, Ireland. His research interests included polarization dependence of ultrafast dynamics in semiconductor optical amplifiers (SOAs), noise in SOAs, and generation and guiding of Terahertz waves. He co-patented two new Semiconductor Optical Amplifiers and he co-pioneered the generation of TeraHertz wave using passively mode-locked semiconductor lasers. In 2008, he joined City University London, UK to work on optical sensors for structural health monitoring and TeraHertz generation using Bragg gratings. He has authored more than 50 papers in peer-reviewed journals and international conferences and currently holds 1 patent.
Dr Surre is chairman of the IEEE Instrumentation and Measurement Technical Committee 16. He was chair of the topic "Advances in Terahertz Devices and Applications" in IEEE Photonics Winter Topicals Meeting 2010 and organized a special session on "Optical Metrology for Structural Health Monitoring" during IEEE Sensors Conference 2011. He is counselor of the City University London IEEE Student branch.

T. Sun received the Bachelor of Engineering, Master of Engineering, and Doctor of Engineering degrees in mechanical engineering from the Department of Precision Instrumentation, Harbin Institute of Technology, Harbin, China, in 1990, 1993, and 1998 respectively, and received the Doctor of Philosophy degree in applied physics from City University, London, U.K., in 1999.
She was an Assistant Professor at Nanyang Technological University, Singapore, from 2000 to 2001, before rejoining City University in 2001 as a Lecturer. Subsequently, she was promoted to a Senior Lecturer in 2003, a Reader in 2006, and a Professor in 2008 at City University. She has been leading a research team focused on developing a range of optical fiber sensors for a variety of industrial applications, including structural health monitoring, early fire detection, homeland security, process monitoring, food quality and automotive emission monitoring. She has been working closely with partners across disciplines from academia and industry, both in the U.K. and overseas. She has authored or coauthored some 170 scientific and technical papers.
Prof. Sun is a member of the Institute of Physics, the Institution of Engineering and Technology, and a Chartered Physicist and Chartered Engineer in the U.K.

Kenneth T. V Grattan graduated in physics from Queen's University Belfast, Northern Ireland, U.K., with a B.Sc. degree (first class honours) in 1974 and a Ph.D. degree in laser physics. His research involved the use of laser-probe techniques for measurements on potential new laser systems. He received the D.Sc. degree from City University London, London, U.K., in 1992 for his sensor work. In 1978, he became a Research Fellow at the Imperial College of Science and Technology, sponsored by the Rutherford Laboratory to work on advanced photolytic drivers for novel laser systems. This involved detailed measurements of the characteristics and properties of novel laser species and a range of materials involved in systems calibration. In 1983, he joined City University as a "new blood" Lecturer in Physics, being appointed Professor of Measurement and Instrumentation in 1991 and Head of the Department of Electrical, Electronic and Information Engineering, and in 2008, Dean of the Schools of Engineering and Mathematical Sciences and Informatics. His research interests have expanded to include the use of fiber-optic and optical systems in the measurement of a range of physical and chemical parameters. The work has been sponsored by a number of organizations including EPSRC, the EU, TSB, private industry and BTG, with a number of patents for systems for monitoring in industry. He is the author and coauthor of nearly 700 publications in major international journals and at conferences and is the coeditor (with Prof. B. T. Meggitt) of a five volume topical series on Optical Fiber Sensor Technology. He is Dean of the School of Engineering and Mathematical Sciences and Dean of the School of Informatics at City University London. He is extensively involved with the work of the professional bodies in the U.K. and was President of the Institute of Measurement and Control during the year 2000.
Prof. Grattan was awarded the Callendar Medal of the Institute of Measurement and Control in 1992, and their Honeywell and ICI Prizes for published work as well as the Applied Optics Divisional Prize of the Institute of Physics in 2010. In 2008, he was elected a Fellow of the Royal Academy of Engineering, the U.K.'s National Academy for the engineering field.