# The Origins of Measurement Uncertainty in SHM—NPL Footbridge Case Study

E. BARTON and T. ESWARD

## ABSTRACT

This paper explores the effects of measurement uncertainty in structural health monitoring (SHM) applications. Uncertainty quantification is an essential part of effective design of next generation SHM systems for smart asset monitoring. Conventional measurement uncertainty analysis which is based on the GUM (Guide to the expression of uncertainty in measurement [1]) cannot straightforwardly be applied to long-duration time series data such as arise in SHM applications. We therefore discuss some alternative approaches and make recommendations for best practice in interpreting SHM datasets. This work is based on experimental data from a well-established monitoring system installed on a concrete reinforced footbridge at the UK's National Physical Laboratory (NPL). Some challenges in the development of a methodology for quantifying measurement uncertainty for civil engineering applications at sensor level and system level are described. The footbridge dates from 1960 but is no longer in use and has undergone deliberate damage and repair cycles over the period of two years, 2010-2011. The data obtained during different stages of progressively increasing damage give a unique opportunity to explore the question of the minimum level of damage that can be reliably detected for a specified degree of accuracy. Our investigation is at the early stages. Therefore only initial findings will be presented.

## INTRODUCTION: OVERVIEW OF EXPERIMENTAL WORK

At NPL we undertook an experimental study by converting a reinforced concrete footbridge to a structural health monitoring demonstrator to provide an independent assessment of sensor capabilities and sensor performance for short and long-term monitoring. The extensive experimental programme was conducted over three years from 2009 to 2011 to investigate the reliability of methods for damage assessment.

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E. Barton, T. Esward
National Physical Laboratory, Hampton Road, Teddington, TW11 0LW.

During the first year of this project a 1960's footbridge was used to create a full-scale test bed designed to investigate the capability of sensing systems for long-term monitoring in outdoor conditions. Sensors necessary for monitoring large civil engineering structures were identified and installed in locations based on the results of modeling and surveying. The performance of wireless and wired sensor and acquisitions systems was evaluated during static loading of the bridge similar to the loading tests used for bridge assessment. The results showed that the sensors were capable of real-time monitoring of the conditions of the structure and have been presented previously [2].

An extensive experimental program of damage / repair cycles was conducted during a second and third year. After detailed discussions with project partners including experts from Sinclair Knight Merz (SKM) and the UK's Highways Agency the various types of damage of civil engineering structures were narrowed down to two key areas: deterioration of reinforced concrete and integrity of repair / strengthening patches. The first stage involved removal of the concrete followed by repairs using the best industrial practices and concrete repair materials. Damage locations and extent of removal reasonably simulated spalling of concrete owing to reinforcement corrosion the deterioration of concrete structures, as is observed in the field. Embedded and surface sensors gave a unique insight in to the load distribution though the cross section of structural members. The second stage started in September 2011 with the cantilever structurally weakened by cutting through the reinforcement, and then strengthened using 4m long carbon fibre reinforced polymer (CFRP) panels installed on the top deck. Various design assumptions are made for current repair and strengthening methods and field data on this topic are scarce. Figure 1a shows the 4m carbon fibre repair panels on top of the cantilever installed to the specifications of the Highway Agency by Concrete Repairs Ltd, a company with 60 years experience in repairs. Fatigue tests used a unique dynamic testing facility, specially designed for this demonstrator by adapting an Instron hydraulic system.

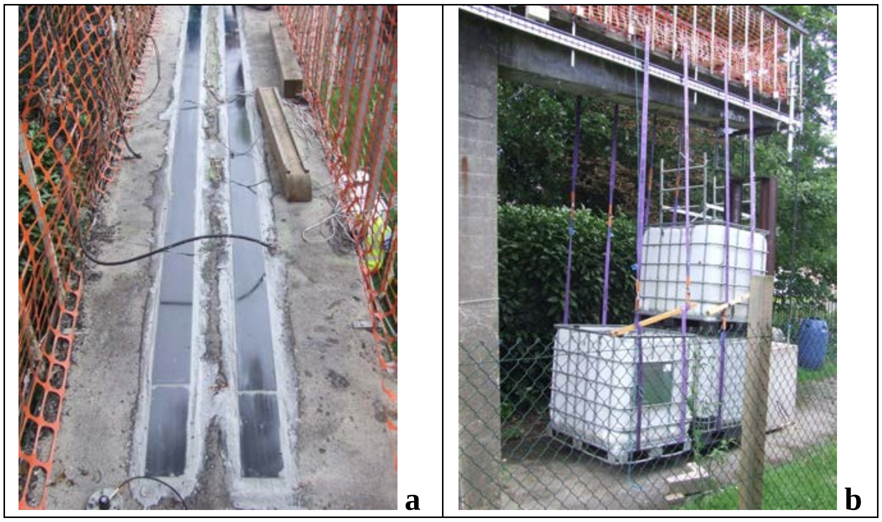

*Figure 1a. Carbon fiber repair patches on top of the cantilever. Figure 1b. Static test set up.*

The static and forced vibration tests were performed regularly to assess the structure and provide useful full-scale experimental data on the design and performance of concrete repair and CFRP strengthening methods. The test set up is shown in Figure 1b. Static loads were applied using water tanks, each tank was about 1200 kg when full.

## INTERPRETATION OF THE RESULTS

Although the analysis and interpretation is at its initial stage, the results obtained during assessment tests under favorable conditions were of sufficiently high quality to be suitable for experimental validation of the assumptions used in bridge design codes. For example, Figure 2 shows the strain along the repair patch measured using optical Fiber Bragg Grating (FBG) sensors during the static loading and unloading test which followed 400000 fatigue cycles.

Time is on the abscissa and the ordinate represents strain along the patch where FBG 1 and 2 are installed at the end of the cantilever and 7 and 8 near the column. The low noise strain data clearly shows the three loading steps, each taking about one hour (the time taken to fill each water tank) and three unloading steps of about 10 min each, separated by 15 min intervals.

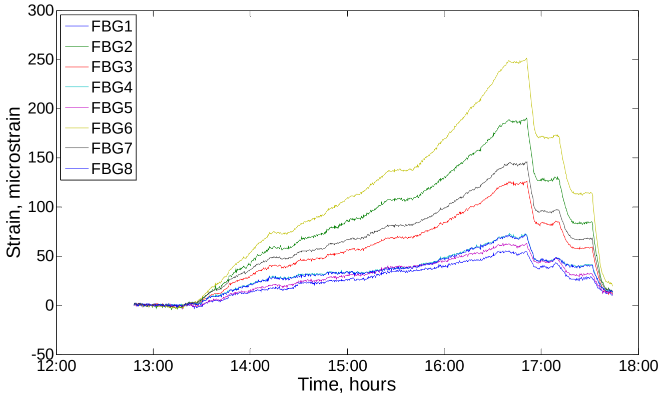

*Figure 2. Strain along the CFRP repair patch.*

However, comparison of results obtained under different environmental conditions posed significant challenges. In metrology, the dispersion of the values attributed to a measured quantity is described in terms of uncertainty. The first step in calculating the combined uncertainty from a collection of sensors that are observing the same physical quantity is to calculate the uncertainties for individual sensors. Traditional sources of uncertainty including calibration factors, noise, zero set, zero drift were considered. Several other factors that influence the results such as temperature sensitivity, variability of material parameters and non-linear behaviour were also identified. Temperature sensitivity was ranked as the most significant factor. Therefore here we will concentrate on temperature effects including sensor temperature compensation. The majority of sensors are sensitive to temperature and well-established methods for temperature compensation have been developed. For illustration purposes only FBG sensors provided by Smart Fibres and Epsilon Optics will be used in this paper.

## CHALLENGES

This section will describe challenges encountered at different levels. First we analyse temperature sensitivity at the sensor level before and after installation, followed by thermal behaviour of a system itself i.e. a structure during the testing campaign.

## Temperature compensation for a free FBG sensor

Each sensor patch consists of two Fibre Bragg Gratings. One is used to sense strain and temperature (FBGa) simultaneously and the other senses only temperature (FBGb) because it is not attached but is only enclosed in the patch. The two FBGs are close enough to allow their temperatures to be considered the same. The technique for dual FBGs temperature compensation is as follows: the wavelength shift of the FBGa which senses both temperature and strain, can be given as

$$\Delta\lambda_{F\,BGa} = k_{\varepsilon}\varepsilon + k_{a}\Delta T \qquad (1)$$

FBGb is sensitive only to temperature and its wavelength shift is

$$\Delta\lambda_{F\,BGb} = k_{Tb}\Delta T \qquad (2)$$

where $\Delta\lambda$ is the wavelength shift for FBGa and FBGb respectively, $k_{\varepsilon}$ is strain coefficient and $k_{Ta}$ and $k_{Tb}$ are coefficients of thermal expansion which were determined experimentally in the laboratory or taken from a datasheet provided by the sensor manufacturer. Temperature compensated strain was calculated by substituting $\Delta T$ from Eq.2 into Eq.1.

In this work we calibrated sensors in the laboratory. Temperature coefficients were obtained experimentally by heating and cooling the specimen in the oven. A typical free patch was first measured on its own and then attached to the concrete block from the bridge step using the same procedure as during installation on the main bridge. A thermal coefficient for a free patch is 11+/-2.5 picometer/degree and for a patch attached to the concrete block is 33+/-4 picometer/degree. It is important to note that the sensitivity to strain is estimated to be of 1.2+/-0.5 picometer/microstrain. A difference of an order of magnitude is not uncommon for many sensors.

## Thermal loading of a footbridge

The strains and deflections due to thermal loading of the structure observed during the tests were unexpectedly large and complex. For example, Figure 3 shows strain in the carbon repair patch during a day of a static loading test. The first and peaks around 12 and 1pm are due to temperature change and the third one is due to loading of about 2 tonnes that exceed the serviceability load for that type of structure.

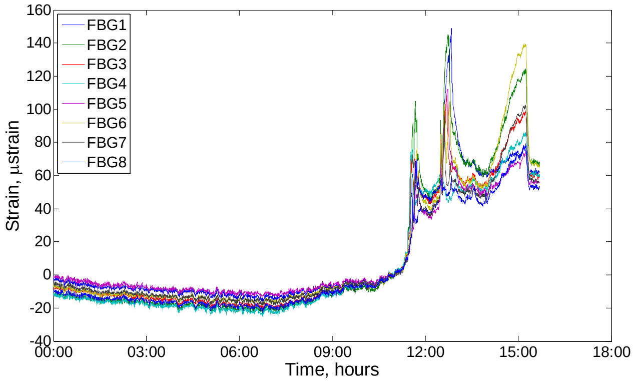

*Figure 3. Strain along the CFRP patch during a day of a static test.*

## Variable time lag

Traditionally temperature compensation is done at the same moment in time and sometimes automatically. However, raw wavelength data presented in Figure 4 below illustrate a significant time lag between strain and temperature sensors. Each graph represents a sensor in a different location along the bridge. We investigated the origin of the time lag with limited success. The correlation between FBG sensors and solar radiation sensors measuring the thermal component corresponding to sunny side and shady side was examined previously [3]. It led to additional features appearing in the data. It was also shown that if the traditional method for temperature compensation is used strain variation of up to 300 με (peak to peak) were inferred where no strain was present.

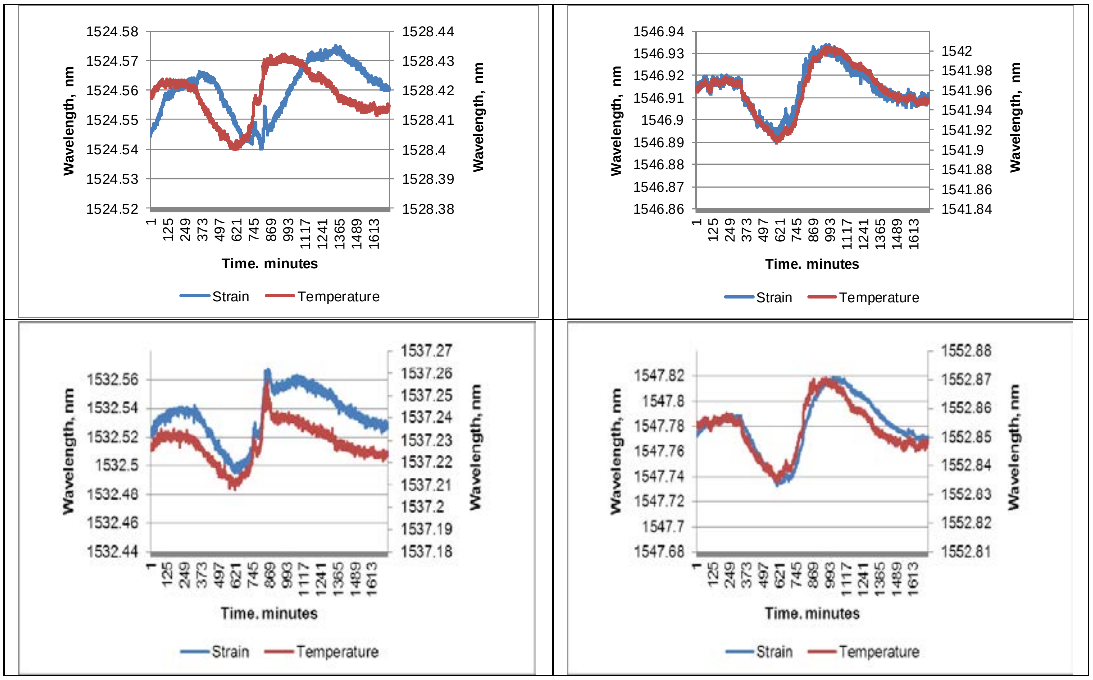

*Figure 4. Strain is shown in blue and temperature in red from four FBG sensor in different locations for period of 2 days.*

In general the time lag is variable and relationship between different contributing factors including temperature gradient, humidity, thermal mass of sensors and type of installation is complex, appearing to be pseudo random. Based on our observations so far, the FBG monitoring systems under discussion performed very well within specified parameters for over 80% of the monitoring campaign. However, data from a single sensor could be insufficient to determine the cause of an individual feature in the output and reliability of a system can be questionable.

## NOVEL APPROACHES

The main question was the extent to which the significant number of sensors within an area of interest can be used advantageously to improve the reliability of the monitoring system. A data fusion method was chosen as one of the first approaches.

### Data fusion and uncertainty evaluation

There are many situations in which it is necessary to aggregate measured values of a single measurand. For example, the values may be repeated indication values from a single sensor or provided by different sensors. For the aggregated value to be meaningful and its associated uncertainty reliable, it is necessary that the measured data (comprising measured values and associated uncertainties) are consistent.

Data fusion of this kind requires that the sensors whose results are being fused provide estimates of the same physical quantity. In addition, it is assumed that when using the sensor output to obtain an estimate of the measurand and the associated uncertainty, the only available knowledge about the measurand is that determined from the outputs of the sensors themselves.

NPL has developed software that can be used to evaluate uncertainties when sensor output data are aggregated, to identify sensors that are not performing consistently with other sensors, and to assist network designers in specifying sensors and networks to meet their measurement performance aims. The methods we have developed are capable of generalisation to wide classes of time-series problems, and the software is extensible to many different application domains. The methods are described in (4,5,6,7).

The models we employ include several stages or sub-models to represent the complete measurement, covering specifically (i) the manner in which the values of the sensor output are related to the sensor input, (ii) how sensor noise is included in the measurement, (iii) sampling and quantisation of the sensor output, and (iv) how an estimate of the measurand is recovered from the sampled and quantised sensor output. In this paper we have applied out methods to tilt data from the NPL bridge.

We include three data fusion methods in the software. Two of these are based on work reported previously by the National Physical Laboratory (the chi-squared method of determining the largest consistent sub-set) [4,5,6] and the Department of Engineering Science, Oxford University (the maximum clique method for determining sensor consistency) [7]. The third method based on a Kalman filter.

### Example

The software was developed to simulate the performance of the sensors that measure the same quantity. In the SHM sensors are installed in different locations and therefore measure spatially distributed measurand. Seven heterogeneous sensors installed along the deck to measure displacement and tilt were chosen for this example. Their output was normalised using an FE model to simulate their performance as if they were measuring displacement in the same location. Each sensor output was described using a linear calibration function and uncertainty was also calculated for each sensor. Figure 5 shows the estimate of the measurand that arise from aggregating the estimates of the measurand provided by the individual sensors shown in the previous figure. In this case the figure shows the estimates and coverage intervals corresponding to (approximately) a 95 % coverage probability.

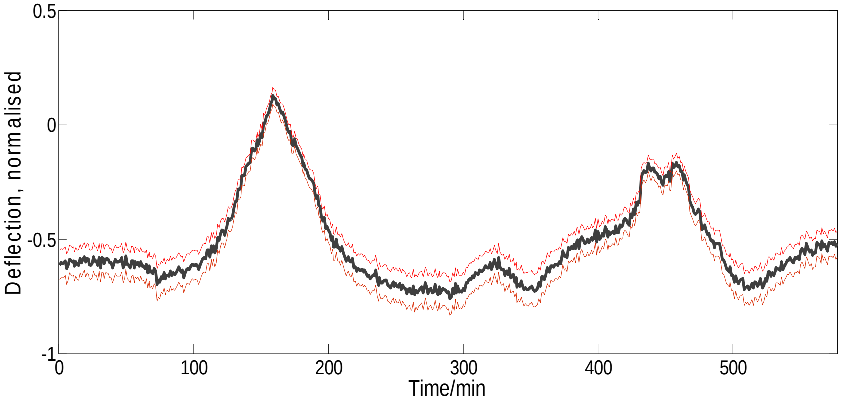

*Figure 5. Estimated deflection and uncertainty.*

This example illustrated that if the relationship between sensors was known the output could be normalized. The results appeared to be consistent and data fusion has improved upon the uncertainties associated with individual sensors. These results are encouraging and indicate that data fusion approach may be used for different sensors installed on the bridge. Moreover, data from seven sensors can be combined to produce a ‘master curve’. More work needs to be done to validate these results for other type of sensors and investigate a possibility of using ‘master curve’ as a performance indicator of a whole structure.

## CONCLUDING REMARKS AND FURTHER WORK

There is a lack of consensus on evaluation of uncertainty for measurements in SHM area and at this stage GUM does not provide practical guidance. New approaches are required to address the uncertainty of a whole system including sensor calibration in real environments and assessment of multiple heterogeneous sensors. It is also clear that for a medium / long term monitoring uncertainty should be specified as a time variable parameter.

As number of sensors increases the calibration of individual sensors becomes impractical and new methodologies are needed to characterize the quality of the data to make sure that the results are understood and properly interpreted.

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