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# Structural Health Monitoring of Bridges

Graham Webb[1], Campbell Middleton[1]

[1] Cambridge University Engineering Department, Cambridge, UK

ABSTRACT: Structural Health Monitoring systems are growing in popularity due to their capability to provide infrastructure managers with quantitative data to supplement inspection regimes and aid maintenance decisions. The primary focus of existing research has been on the challenges involved with data collection and transmission in these systems. However, surprisingly little work has yet been published in which readings from such systems are related back to the actual performance of the structure being monitored. Without this crucial step, the majority of data collected are of very little practical use.

The Hammersmith Flyover in London, UK is a 16 span, segmented prestressed concrete bridge, 622m in length. Constructed in the early 1960s, there are now a number of concerns about the health of the bridge due to corrosion of the prestressing tendons and deterioration of the roller bearings. A variety of monitoring equipment has been installed on the flyover in an attempt to provide more information about the state of deterioration.

This paper proposes a number of different ways in which monitoring system data can be interpreted to provide different types of information. These methods are applied to monitoring data from the Hammersmith Flyover. With careful interpretation it is found that useful information can be obtained from some of the monitoring data.

Figure 1. The Hammersmith Flyover.

## 1 INTRODUCTION

Structural Health Monitoring systems are growing in popularity due to their capability to provide infrastructure managers with quantitative data to supplement inspection regimes and aid maintenance decisions. There are many examples of extensive monitoring systems around the world, including the Wind and Structural Health Monitoring System used by the Hong Kong Highways department (Wong 2004), The Humber Bridge in England (Hoult et al. 2008) and the new I-35W Bridge in America (Inaudi et al. 2009). However the primary focus of existing research has been on the challenges involved with data collection and transmission in these systems. Surprisingly little work has yet been published in which readings from such systems are related back to the actual performance of the structure being monitored. Without this crucial step, the majority of data collected are of very little practical use.

## 2 THE HAMMERSMITH FLYOVER

The Hammersmith Flyover in London is a 622m long, 16 span, post-tensioned prestressed concrete segmental bridge carrying a major road into the city (figure 1). Constructed in the early 1960s, it unusually has only a single expansion joint in a span towards the centre, roller bearings at the base of each pier and is restrained against longitudinal movement at each abutment.

There are now a number of concerns about the structural condition of the Hammersmith Flyover. Firstly, it was discovered that many wires in the prestressing tendons had snapped and others were severely corroded. Secondly, there were concerns that expansion of the structure due to temperature changes could be restricted by deterioration of the bridge's roller bearings.

The bridge's owners, Transport for London (TfL), needed to decide whether the bridge was still safe and able to carry the loads being applied to it, or whether it needed maintenance or repair work.

A variety of monitoring equipment was installed on the flyover with the objective of providing the engineers with more information to aid them in their decision making. A large wired monitoring system was installed by a commercial contractor (Watson 2010) and an experimental wireless system was installed by Cambridge University Engineering Department (Hoult et al. 2010). The monitoring equipment included:

- Acoustic Emission sensors installed throughout the bridge to detect and locate wire breaks within the prestressing tendons.
- Displacement gauges located at the base of each pier to measure longitudinal movement of the bearings.
- Strain gauges and inclinometers attached at three different heights on the piers to monitor their movements.
- Temperature sensors at a variety of locations throughout the bridge.

In December 2011 the bridge was closed for three weeks and an extensive programme of strengthening works was started, causing vast traffic disruption.

This paper explores how data from monitoring systems can be used to provide more information about the state of a bridge's deterioration.

## 3 DATA INTERPRETATION

A monitoring system collects data from its various sensors. In most cases it is not possible to measure 'damage' directly, but instead the loading or the bridge's responses are recorded. This data must therefore be interpreted to provide useful information to the monitoring system's operators. Without this step, which is often neglected, the data acquired by the system is meaningless and not beneficial to anyone.

It is proposed that there are a number of different ways in which monitoring system data can be interpreted to provide different types of information (figure 2).

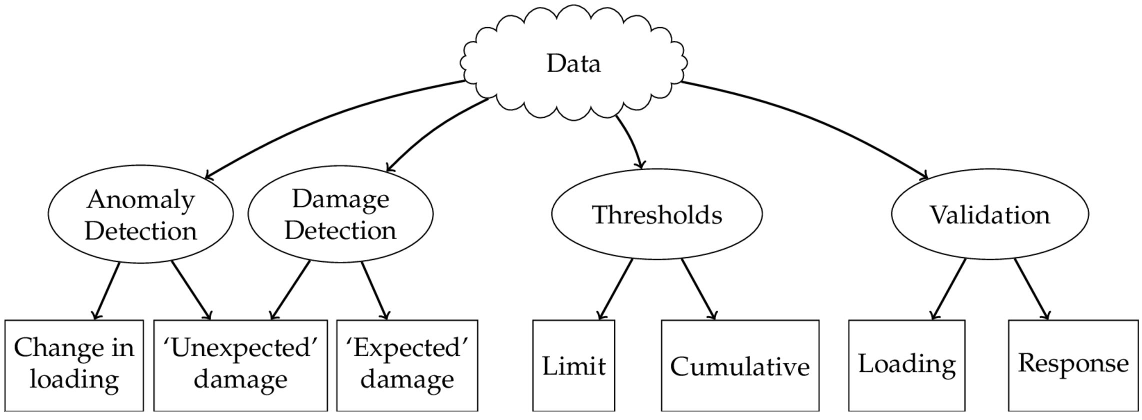


Figure 2. Categories of data interpretation.

### 3.1 *Anomaly Detection*

When data is collected over a period of time it should be possible to identify patterns within it. For example the readings may vary cyclically over a daily or yearly time period, or may always fall between certain limits. If the pattern changes significantly it is an indication that something has changed. It may be that the loading applied to the bridge has changed, or that damage or deterioration has occurred. A monitoring system could be set up to analyse each reading it obtains to decide whether or not it fits the expected pattern. If not the system's operators can be alerted, allowing further investigation to take place.

Determining how different a reading must be to be counted as anomalous is an important consideration. If the threshold is too low then false alarms could be caused by noise in sensor readings. If too high, then damage to the structure may be missed. More detailed discussion can be found in Catbas et al. (2011).

This is a fairly simple way of processing monitoring data although the information obtained is limited; significant further investigations will always be needed to determine the cause of any changes.

### 3.2 *Damage Detection*

The primary objective of many monitoring systems is to detect the occurrence of damage or deterioration. A means of interpreting data to directly provide information about the level of damage or deterioration present would therefore be useful. This can be approached in two different ways. The first approach requires the monitoring system's designer to postulate what sort of damage or deterioration might occur. They can then predict the effects that the damage will have on the structure with the aim of identifying measureable parameters which change. These parameters can then be used as an indication of whether the damage or deterioration has occurred. This will not always work as some damage or deterioration has very little effect on the structure's response. This method will also obviously only detect damage which the designer has foreseen and so is highly dependent on their experience with similar structures.

The second approach does not require any input from the designer as to what damage is expected to occur. Instead the monitoring system is used to calculate various properties of the vibrational response of the structure, such as natural frequencies and mode shapes. As in anomaly detection the system can then detect changes in these properties. It is hoped that by analysing the changes it is possible to locate and quantify the damage on the structure. Unfortunately, whilst such a capability would be extremely useful in a monitoring system, it has not proved successful in any real structures. The changes in vibrational properties caused by moderate damage and deterioration are so small that they cannot be distinguished from changes due to temperature or noise in the measurements. Farrar and Jauregui (1998) introduced damage to a steel girder bridge by introducing torch cuts. Even after cutting through more than half of the section, the first natural frequency of the structure only changed by 7.6%. Xia et al. (2012) highlight that daily temperature variations can cause comparable changes in natural frequency.

### 3.3 *Thresholds*

A further way of interpreting sensor data is to set a threshold, which if exceeded indicates that there is a problem. In some cases these thresholds can be set without the requirement to predict exactly what damage or deterioration may occur. For example, a bridge over a railway may be required to have a certain vertical clearance above the tracks. By monitoring vertical deflection of the deck it would be possible to determine if the required vertical clearance is present. If not, further action can be taken. The cause of the problem may not be known, but the owners of the structure will have been alerted to a problem, allowing them to take further action.

Thresholds can also be defined on a cumulative basis. For example many bridge bearings have a lifetime specified by the manufacturer in terms of the total distance travelled. By continuously monitoring displacement of the bearing the total distance travelled can be recorded, allowing the remaining life time to be estimated.

### *3.4 Validation*

Sensor data can also be used to validate assumptions made during the design of bridges. This information may not be of interest to the bridge's owners, but could be used by bridge designers to help improve the design of similar bridges in the future. Information about the loading being applied to the bridge can be compared to design load cases to determine whether they are appropriate. The expected responses of the structure can also be compared to measurements to help validate any modelling assumptions made during the design process.

## 4 HAMMERSMITH FLYOVER DATA INTERPRETATION

A number of the data interpretation strategies introduced above can be applied to the monitoring data collected at the Hammersmith Flyover.

### *4.1 Validation*

Temperature can often be an important load case for bridges. During the design of a bridge a maximum temperature range is assumed and analyses are performed to ensure that these temperatures do not cause any design limits to be exceeded. The Hammersmith Flyover's monitoring systems include a number of temperature sensors. Data from these can be collected and used to investigate whether the original design temperature assumptions were valid. It can also provide more information about how the temperature in the structure is varying, which may be useful for a more detailed understanding of the structure's behaviour.

Figure 3 shows the location of some of the temperature sensors throughout a cross section of the Hammersmith Flyover. It is often assumed that the top surface of a bridge is 10-15°C warmer than the underside due to solar radiation effects. Figure 4 shows how the temperature at the four different locations varied over a month. It can clearly be seen that this assumption is not valid in this case. The top surface of the bridge has a much larger daily variation in temperature than the underside, but is not always warmer. If differential temperature gradients through the deck are found to be important then this information could be very useful.

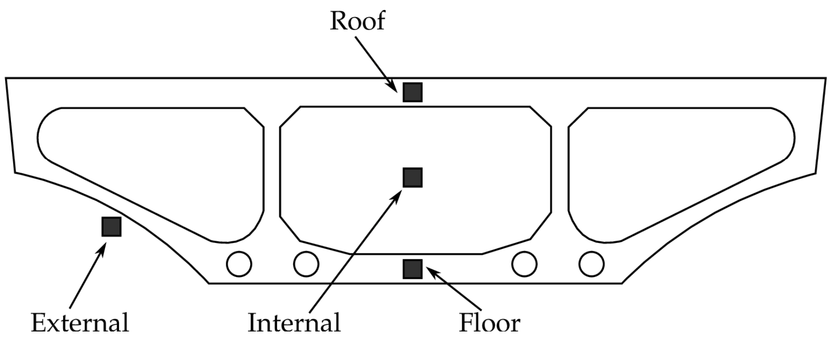


Figure 3. Temperature sensor locations.

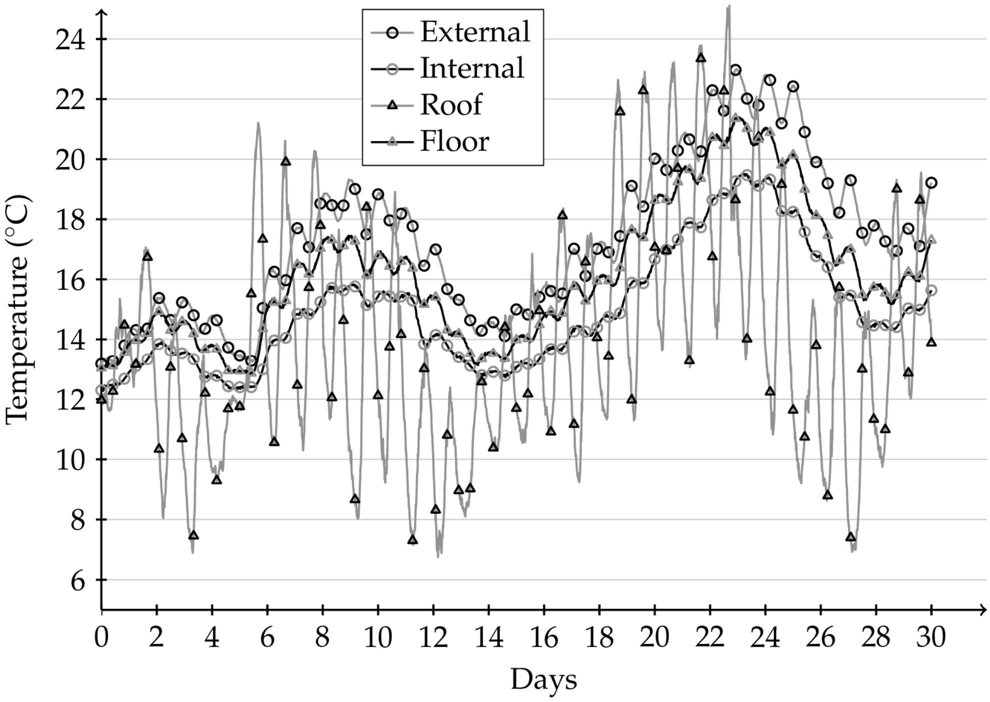


Figure 4. Plot of temperature data from April 2011.

### *4.2 Thresholds*

The Acoustic Emission monitoring system is able to detect wire breaks within the bridge's prestressing tendons. It is also able to locate each break to within 500mm. Since the system was installed many years after the bridge was constructed it is not possible to derive the total number of broken wires at any location. Instead the system only provides the number of additional wire breaks detected since it was installed and also the rate at which breaks are occurring. Predicting the effect that these wire breaks have on the structure is difficult as there are a large number of unknown parameters. However thresholds can be set; once the number of additional wire breaks, or the rate of new wire breaks, exceeds a certain value the bridge should be closed pending further investigations. Figure 5 shows a plot of cumulative wire breaks detected by the monitoring system. The increasing number and rate of wire breaks was a key factor influencing the owner's decision to close the bridge for emergency repairs on 23rd December 2011.

### *4.3 Damage Detection*

One of the concerns with the Hammersmith Flyover was that the bridge's roller bearings may have corroded and seized. If true, this would mean that the bases of the piers could not move horizontally, so the piers would bend as the deck spans expand and contract due to temperature changes. This would induce strains in the sides of the columns and it is important to know if these could approach the concrete failure strain. A simple plane frame beam model of the flyover was constructed and various load cases were applied to it. Further details of this analysis can be found in Webb and Middleton (2013). It was found that pier displacement is predominantly caused by temperature increases, with live loading having only a very small effect. Since both temperature and pier displacement are measured by the monitoring system, a graph of pier displacement against temperature can be plotted. If the bridge's bearings are

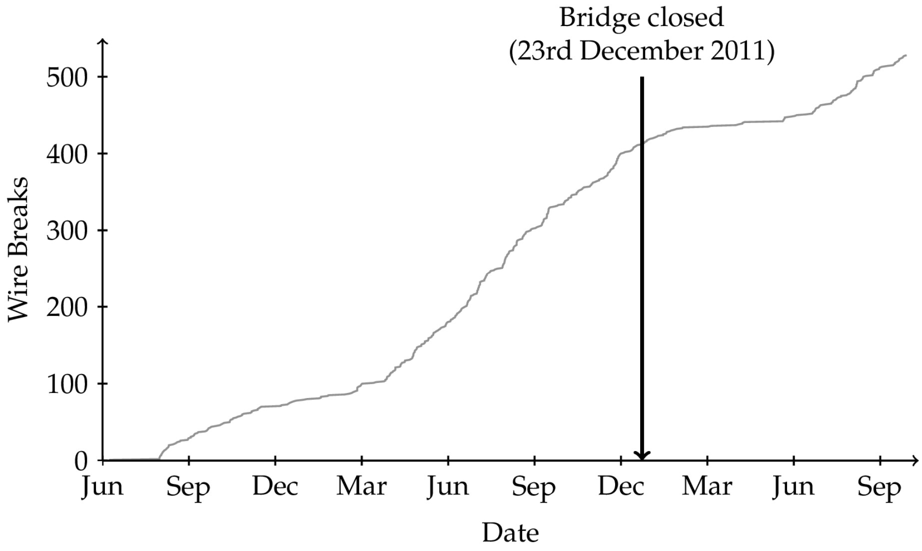


Figure 5. Cumulative wire breaks in all spans (2010 – 2012).

allowing free movement as designed, these plots should show a good correlation. Any deviation from this will be a good indication of the state of the bearings.

Figure 6 shows plots of displacement against temperature for the bases of five piers in the eastern half of the bridge, both predicted and measured values. The piers have been numbered, starting from the abutment. It can be seen that there is a good linear relationship between temperature and displacement for each pier. This confirms the expectation that displacements are predominantly caused by temperature variations. It can also clearly be seen that the movements of three of the piers compare very well with the predictions. In contrast piers 1 and 3 stand out. These piers are moving to a much smaller extent than expected, suggesting that their bearings could be restricting free movement. The cause of this restriction can clearly be

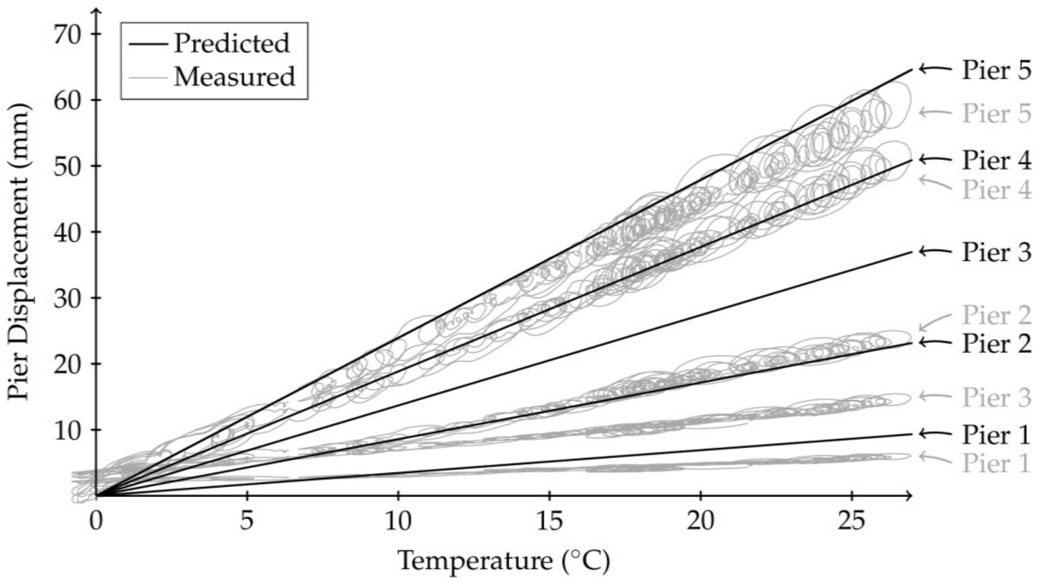


Figure 6. Predicted and measured pier displacements versus temperature for five piers (Webb and Middleton, 2013)

seen at pier 3. In each bearing pit, in addition to the bearings supporting the pier, there are also four emergency plinths. These were designed to prevent the pier dropping by more than a few centimetres should the bearing collapse. During construction metal shim plates were temporarily inserted between the emergency plinths and the base of the pier (Rawlinson and Stott 1963). At pier 3 it appears that the shims are still in place, they have corroded over the last 50 years and become wedged between the pier and the plinth.

## 5 CONCLUSIONS

It is often not clear how data from Structural Health Monitoring systems will be used to benefit the system's operators. This paper has proposed that there are a number of different ways in which monitoring data can be interpreted to provide different types of information. Which of these techniques is appropriate for any particular situation will depend on the objectives of the monitoring system being considered. Some of these interpretation strategies have been applied to data from monitoring undertaken at the Hammersmith Flyover in London, to demonstrate how useful information can be obtained. It was found that temperature distributions through the structure differed from standard assumptions. Acoustic Emission monitoring provided further evidence to engineers that the structure required repair works. Additionally, displacement and temperature data indicated that some of the bridge's roller bearings were not allowing free movement as they were designed to.

It is hoped that this 'toolkit' of interpretation strategies can be of use during the design of monitoring systems. It will help designers decide what information can be obtained from a Structural Health Monitoring system, and what sensor data is therefore required.

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