Interpreting data from bridge performance and health monitoring systems

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ABSTRACT: Structural health monitoring (SHM), particular for highway bridges, is a fertile research area for academics and a potentially very useful tool for bridge management authorities. The academic approach often focuses on sensor technology, data collection, detecting visible and invisible damage and areas that may not be of immediate use to the practical operators who need condensed information for decision making. The steps in the process such as data management, data mining, conversion to knowledge of structural behaviour and integrity are frequently absent, and even the most operationally successful SHM systems may lack the component where deep understanding on the nature of the bridge performance is obtained. This paper presents experience gained in a number of bridge monitoring exercises where static and dynamic response data have been interpreted, with or without the aid of calibrated structural models, in order to characterise the mechanisms at work and the experiences of the structure. Hence, while considerable experience has been gained in pure signal analysis, we are also merging the SHM data with dynamically calibrated FE models in an approach which we believe to be the way forward for future SHM systems.

1 INTRODUCTION

Civil engineers usually view structural health monitoring (SHM) as a global identification process in which the performance of a structure as a whole is considered, preferably holistically, by considering all forms of available performance indicators, including non-destructive testing (NDE). Because of the perceived link between different levels of damage and performance, and because of the history of vibration based damage detection, there has been a bias toward the use of dynamic response data for bridge SHM. While vibration data remain valuable, they need to be integrated with quasi-static response data and conventional observations. The challenges for civil SHM, with bridges representing a major growth area, are being identified as data management and storage, including local embedded systems for data reduction, wireless data transmission, data mining, evaluating performance against structural models, and presentation of minimal and reliable information to bridge managers for decision making.

Bridge monitoring programs have historically been implemented for the purpose of understanding and eventually calibrating models of the load-structure-response chain (Barr et al., 1987, Brownjohn et al., 1994, Cheung et al., 1997, Catbas et al., 2000, Miyata et al., 2002). In the last decade, permanent bridge monitoring programs have evolved into SHM systems which have been implemented in major long span bridge projects in Japan, Hong Kong and latterly North America.

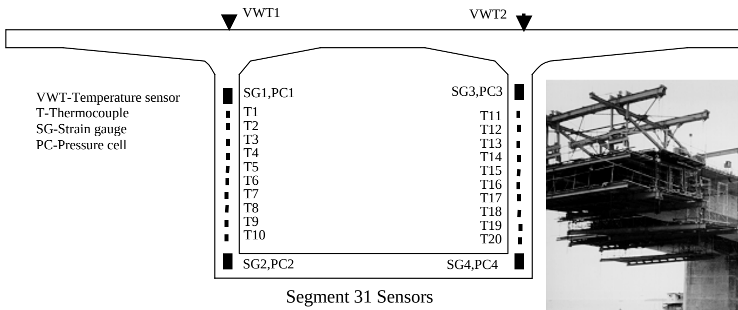


Figure 1 (above) Second link segment instrumentation
Figure 2 (right) Second Link bridge under construction

Less glamorous but possibly ultimately more beneficial developments of SHM have been in optimal monitoring approaches for conventional short span bridges (Bakht & Jaeger, 1990). For smaller bridges global response is more sensitive to defects, visual inspection is less frequent and SHM systems can and do (Alampalli & Fu, 1994) make a real contribution.

Three bridge monitoring exercises are reported here that span the range of monitoring applications and explore applications of SHM technology.

2 TUAS SECOND LINK: LONG TERM PERFORMANCE MONITORING

Based on reported UK experience (Barr et al., 1987) in monitoring glued segmental box-girder bridges a similar instrumentation scheme was installed in the Second Link bridge between Singapore and Malaysia, to validate the design and performance (Brownjohn & Moyo, 2000). The bridge was completed in 1997 and opened to traffic in the same year, has a total length of 1.9km and comprises 27 spans only two of which are in Singapore waters. The 92m main span of this section was studied with an array of instruments installed during the balanced cantilever process of segment casting and post-tensioning.

The instrumentation, shown in Figure 1 in one span during construction (Figure 2) consists in total of four data loggers, twelve vibrating wire strain gauges, forty four thermocouples and one tri-axial accelerometer, distributed in three segments in one half of the span, with networked loggers accessed by modem. In addition, twelve static pressure cells of a type that had previously been used in monitoring of tunnel linings were embedded with the strain gauges.

Strain, stress and temperature data have been recorded over long periods at hourly intervals between 1997 and 2004 and used (Moyo & Brownjohn, 2002a, b) for developing procedures for anomaly detection. In particular, data from the construction process provided valuable information on early-life strain development for characteristics construction events that may have analogs in post-construction activity, hence providing a learning process for future performance diagnosis.

A fundamental issue in SHM is data normalization, which is compensation of 'noise' due to environmental or ambient loads to reveal the useful 'signal' (Alampalli 1998, Sohn et al., 1999) whose non-stationarity or deviation from the established pattern of response may indicate an altered structural state or damage. For example, Figure 3 shows strain signals of one segment during construction in which some abnormal, abrupt events, notably segment casting, can easily be identified by visual inspection of strains from gauges near the bottom of the beam. Other events such as tensioning and form shifting, or even casting in remote segments, are not detected by simple visual examination against apparent diurnal variations. Elimination of ambient noise may be possible via some form of validated structural model relating loads to their effects, but as in the case of Second Link, such a model may not be available and 'output-only' type models are used to detect anomalous events. Two different analytical procedures were used for Second Link.

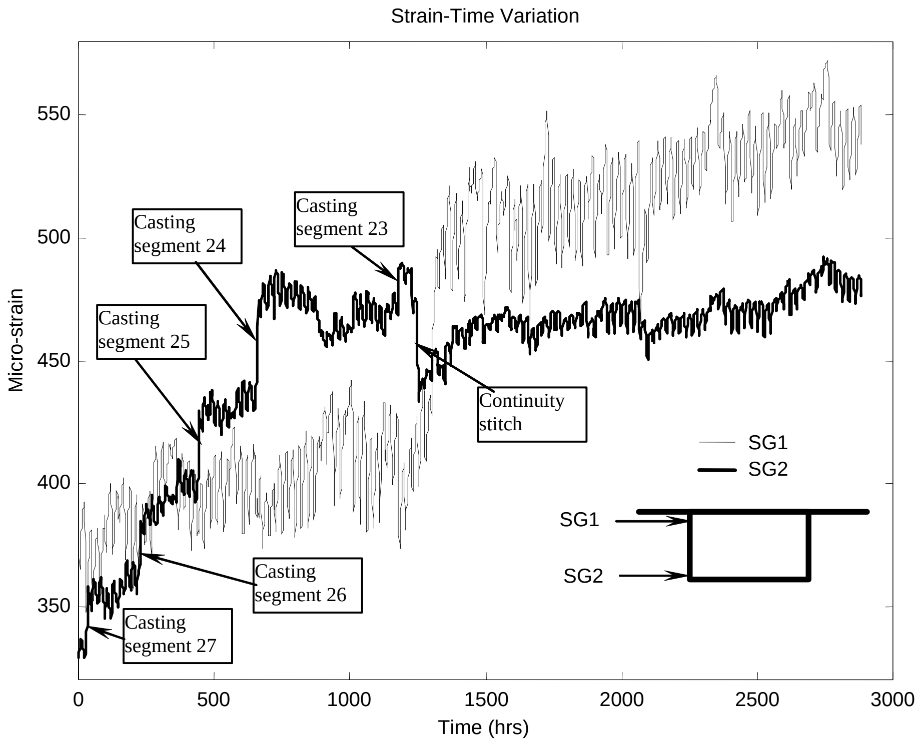


Figure 3 Strain variation in segment 31 during construction

In the first method (Omenzetter at al., 2004) raw strain data are filtered into high and low frequency components using the Daubechies discrete wavelet transform. The highest frequency component, or wavelet details, is retained as a series of time varying coefficients and conveniently indicates discontinuities in the original time series, as shown in Figure 4. It can clearly be seen that the previously hidden events now stand out from the bulk of data. For automatic detection of unusual values of wavelet coefficients their time series can be further processed by forming a vector autoregressive moving average (ARMA) model of multiple channels and identifying outliers from the best fit to the data with some degree of consistency among the channels. Having identified anomalies, intervention analysis (Moyo & Brownjohn, 2002b) uses the Box-Jenkins models on original strain time series in the region of the identified anomaly to qualify and quantify the change in the strain signal. Figure 5 shows an example of intervention analysis of one of the cable tensioning events revealing a permanent set of 12 microstrains (Fig. 5b).

The second analytical procedure operates directly on the strain time series (Omenzetter et al., 2003) and was inspired by the studies of Sohn et al. (2001), who modeled dynamic signals using autoregressive (AR) time series models, and through examination of the changes in AR model parameters were able to detect damage. In the case of the long term monitoring of Second Link, a vector seasonal autoregressive integrated moving average (ARIMA) model is established for the recorded strains with a seasonal part accounting for strain variations due to ambient temperature cycles. The parameters of the ARIMA model are allowed to vary with time and are identified on-line using a Kalman filter. Changes in the model parameters reveal unusual events as well as structural changes, e.g. Figure 6 shows ARIMA coefficient changes due to cable tensioning events. These changes are either step-like jumps and drops in the coefficient value which then seem to stabilize for some time at the new levels, or spiky transient oscillations without any apparent level shifts.

The Second Link monitoring exercise is an ongoing research program constantly seeking improvements in the developed analytical procedures and the optimal approach which may be a hybrid of the two forms, involve other signals and ultimately physical structural modelling. There are flaws and limitations in the procedures, but overcoming them successfully is critical for making them potentially useful to the bridge operators.

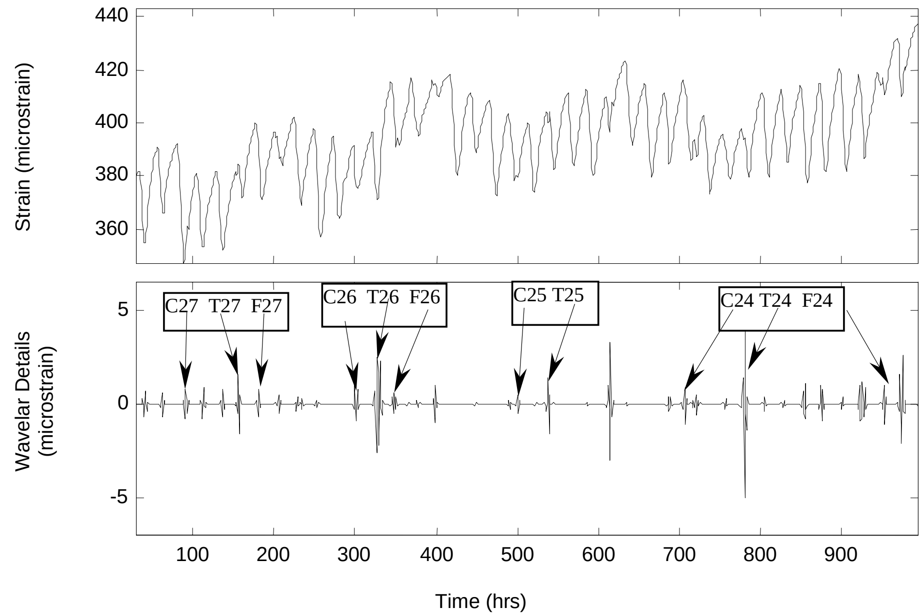


Figure 4 Wavelet decomposition of strain data (Abbreviations: C – concreting, T – cable tensioning)

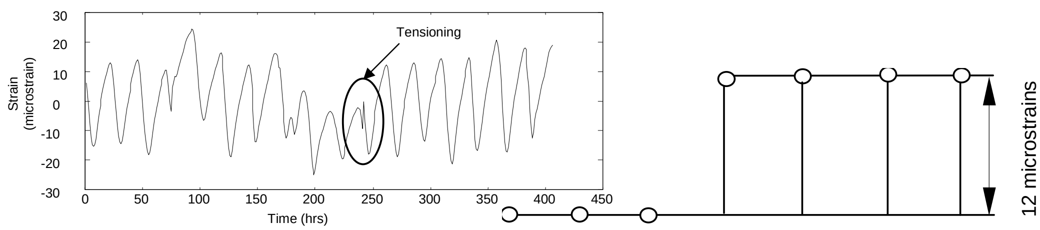


Figure 5 Intervention analysis of a cable tensioning event: strain time series and impact of tensioning.

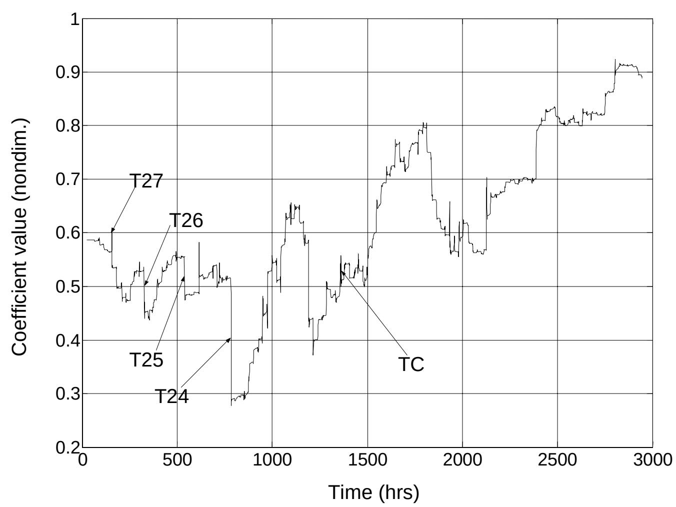


Figure 6 Identified values of an ARIMA model coefficient showing changes due to cable tensioning (Abbreviations: e.g. T26 – tensioning of cables in segment 26, TC – tensioning of closure strip).

3 PIONEER BRIDGE: SHORT TERM MONITORING FOR BRIDGE RETROFIT

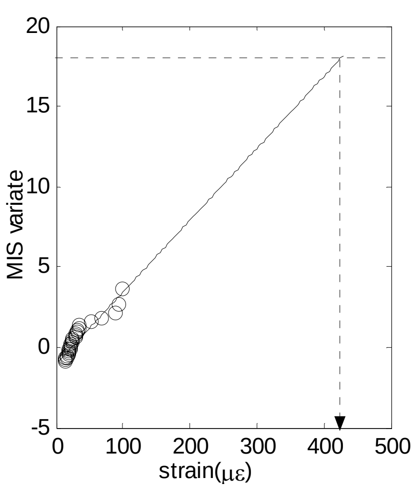
Almost all the highway bridges in Singapore are reinforced or post-tensioned concrete and at the time of writing, the Land Transport Authority of Singapore (LTA) was in the midst of a major program of upgrades on existing bridges to sustain higher axle loads with contractors now obliged to provide evidence of improved performance, e.g. through monitoring.

Figure 7 Pioneer Bridge

The specifications for monitoring instrumentation are evolving, and research (Moyo at al., 2003) has been conducted to identify a rational procedure for assessing the success of the upgrade, based on Heywood et al. (2000).

The approach has been demonstrated on Pioneer Bridge (Figure 7), an 18m span bridge comprising parallel pre-stressed inverted T-beams tied together by tendons and deck slab and supported on nominally pinned bearings. The major structural change in the bridge upgrade program involved fixing the deck end bearings via massive reinforcement resulting in an integral bridge.

A multi-stage approach was used to assess the upgrade. First, a bridge health monitor (Heywood et al., 2000) was installed to log traffic-induced vertical accelerations and longitudinal strains on the soffit of sample T-beams. The monitoring system comprised four demountable strain gauges, four accelerometers and a battery powered data acquisition box with sensors mounted at mid-span of selected girders for one month before and after strengthening works and recording peak levels of strain and acceleration from waveforms captured on trigger by the passage of heavy vehicles and then used to develop a statistical model of live loading which was assumed to be Type 1 Extreme value distribution. Two forms of the extreme type 1 distributions were used to estimate live load strains for a 200,000 year return period or 0.06% chance in 120 years. Standard Gumbel distribution, which is generally accepted as the appropriate distribution for bridge live loading (Das, 2001) was used, as well as the method of independent storms or MIS (Cook, 1989) which is not limited to a single peak value in the sample period (e.g. one day). Both methods indicate 20% higher levels of peak strain before the upgrade, even with an distribution that is probably not limited to a single population of event types. Figure 8 shows the Gumbel plot using MIS.



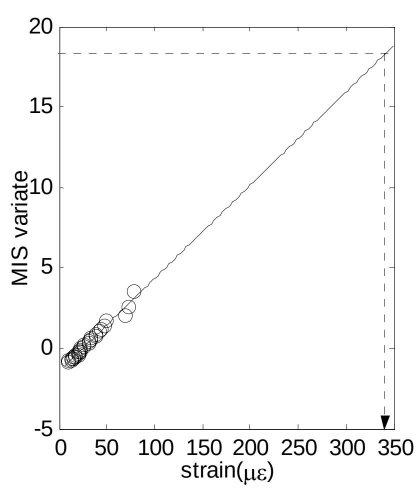


Figure 8 Method of independent storm Gumbel plot before and after retrofit with 120,000 year strains

Second, modal surveys of the bridge were conducted to establish a validated finite element model of the bridge before and after upgrading. The material properties used to develop the finite element model of the bridge were obtained from samples cored from the bridge. Frequency response functions (FRFs) before and after the upgrade indicate a considerable increase in stiffness and damping capacity due to the upgrade, with the first natural frequency increasing by almost 40%.

The validated finite element models were used to estimate the dead load strains in the concrete. The sum of factored dead and live strains was compared before and after upgrading to show an improvement in the proportion of ultimate capacity for the same return period. The overall change in strain, including dead load strains, was about 21% which is in close agreement with change in natural frequency.

4 PASIR PANJANG SEMI-EXPRESSWAY (PPSE)

Based on the Second Link experience a program was developed for PPSE (Figure 9), a major elevated expressway under construction in southern Singapore and comprising a viaduct of twin box decks of precast segments supported on single central pylons above an existing main road. The viaduct will carry goods traffic between two major container terminals and is arranged in ‘bridges’ of five spans of 20m-46m between expansion joints.

Figure 9 PPSE under construction

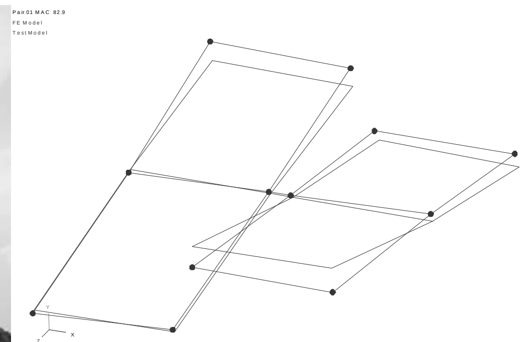
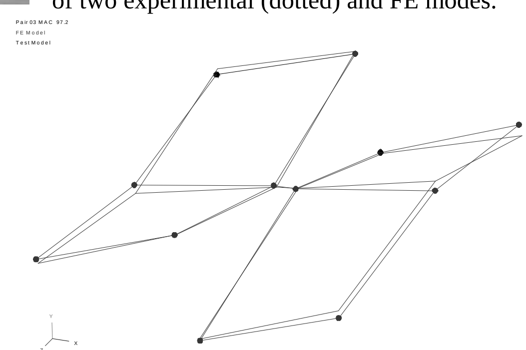


Figure 10 (above and below) correspondence of two experimental (dotted) and FE modes.



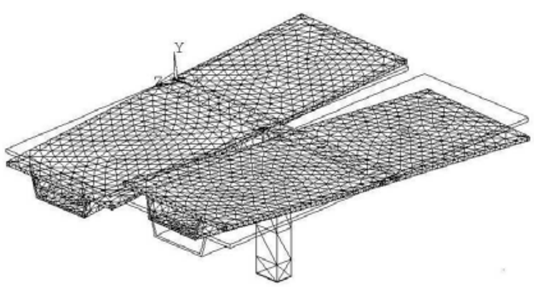


Figure 11 Detailed FE mesh

The aim of the monitoring program has been to develop a system that will track the performance of a complete section of the expressway comprising as many as five bridges. In each bridge one span is instrumented at two segments together with the adjacent pier. Ten segments have been instrumented in this way. Instrument cables from two segments and a pier are routed to a logger equipped with GSM or GPRS wireless communication system. At present, three spans are online and stress and strain data, recorded every half hour are sent by e-mail as a daily summary from an e-monitoring server operated by the contractor. In order to interpret the variations of signals during and after construction, one bridge is being modeled, and as a calibration of the

FE modeling, free-standing balanced cantilever sections centred on each of the instrumented piers have been tested dynamically (e.g. by jumping) to obtain free vibration properties; Figures 10 shows comparison of two modes obtained by testing (dots) and analysis using a fine-meshed cantilever model. The comparison shows that assumptions of material properties and boundary conditions re reasonable and the extrapolated 'bridge' (Figure 11) predicts modes that have been shown to agree reasonably with modes identified in ambient vibration measurements.

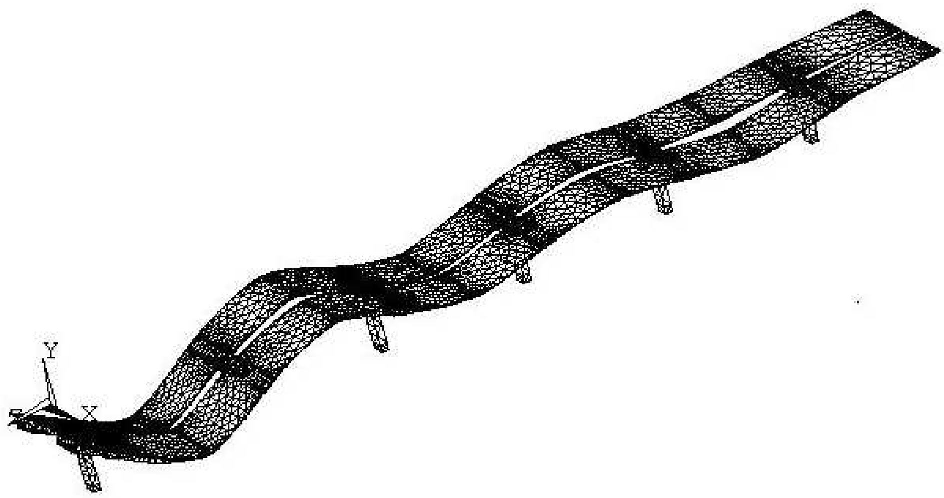


Figure 11 Full 'bridge' model extrapolated from validated single-cantilever model.

Model updating is being used to identify the correct boundary conditions for the pier as well as the relevant concrete properties. In the final updated model, effects of differential temperature loading, settlement, loss of post-tensioning and other ambient (but not dynamic) effects will be simulated to aid pattern recognition in the collected data.

While quasi-static response data are manageable directly and arrays of accelerometers are unnecessary if modal properties are known, tracking dynamic performance is useful for two reasons. First, there is a the possibility that variations in modal frequency and damping can indicate certain forms of structural change. Second, they are useful for tracking live loads. In fact dynamic strain data will provide more directly useful information, suggesting an implementation of the HMX bridge monitor (Heywood et al., 2000) as used at Pioneer. The strain sensors in such a system are necessarily discrete, and as SHM research is moving toward wider applications of fibre optic systems, PPSE is being used to test field operation of fibre Bragg grating (FBG) strain sensors. In this instance two arrays of 11 FBG sensors have been attached to the inside box soffit connected to a ruggedised portable logger which will capture the light spectrum around the FBG frequencies, as shown in Figure 12. A local processor communicating via USB will identify the peaks in the reflected light spectrum to track strain changes dynamically.

5 DISCUSSION

SHM is developing towards an integrated approach to structural performance diagnosis through a combination of advanced sensors, data storage and transmission followed by data mining for extracting information about the structural and loading conditions. Up to a point it is possible to learn about structural condition by measuring response only, e.g. by recognizing patterns distilled from signals buried in various forms of 'noise'. Vibration based diagnosis has always played a major part in SHM and we believe that a major application is to validate and calibrate structural models which can be used to identify altered structural states through direct on-line system identification or by combination with live load response, as in the case of aeroelastic parameter identification suspension bridges (Cheli et al., 1992) or in the Pioneer exercise for load capacity assessment.

6 ACKNOWLEDGEMENTS

The authors wish to acknowledge funding by Building and Construction Authority, Singapore and the wholehearted support of Land Transport Authority, Singapore and SysEng (Pte) Ltd as well as contributions by students and former colleagues from NTU, Singapore.

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