

FULL-SCALE PERFORMANCE EVALUATION OF BRIDGES USING DYNAMIC AND STATIC INSTRUMENTATION

James MW Brownjohn
Professor of Structural Dynamics
Vibration.shef.ac.uk
Department of Civil and Structural Engineering
University of Sheffield
Mappin Street
SHEFFIELD S1 3JD

Tel +44 (0)114 2225771

Fax +44 (0)114 2225700

james.brownjohn@sheffield.ac.uk

ABSTRACT

Structural Health Monitoring (SHM) is a popular research topic comprising a range of activities from sensor development to data mining. The essence of SHM is learning about the 'state' of a bridge by measurements of response parameters, along with loads such as temperature and wind. The state of the bridge is defined by a range of structural and response parameters.

The aim of SHM is to check the state of the bridge against acceptance criteria (e.g. overloaded or damaged) and to indicate changes to the state, signaling changes to the structure or the loading.

To do this requires a combination of 'condition assessment', a detailed assessment or snapshot of the structure including analytical modeling, inspection and dynamic testing, followed by long term but less detailed monitoring of performance using permanent instrumentation. Using few sensors and a well developed understanding of the structure from the condition assessment, the long term monitoring serves to check that performance is within bounds, and provides indication of altered state, which can signal more detailed (condition) assessment to fully diagnose the likely fault.

This paper describes condition assessment and long term monitoring of example bridges and how new technology is applied to improve the capability to detect and diagnose anomalous structural performance in real time in order to provide timely alerts for bridge operators to take action.

1 INTRODUCTION

Structural health monitoring (SHM) is a major interdisciplinary research area, with collaboration between civil, mechanical, electrical and computer engineering. Definitions of SHM include an overlap with non-destructive evaluation (NDE) involving examination of the structure at a localized level. However civil engineers usually view 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 NDE. Because of the perceived link between different levels of damage and performance, and because of the history of attempts at vibration based damage detection, there has been a bias toward the use of dynamic response data for bridge SHM.

Vibration data do have value, specifically when applied to evaluate structural condition via comparison of measured modal characteristics with finite element model (FEM) predictions and even systematic FEM updating. This condition assessment can be used to expand a few long term vibration measurements to represent the global performance, in the linear range. Vibration signals should be integrated with 'static' response data which can indicate the trend values of global displacements and internal forces which as important as the dynamic components.

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. Black-box data analysis procedures which are not tied to physical models have their uses (as will be seen in one of the examples in this paper), but ultimately there needs to be understanding of the structural response mechanisms which is best obtained by a combination of observing dynamic and static response and reconciling these with analytical representations of the physical structure.

2 BRIEF REVIEW OF BRIDGE SHM DEVELOPMENTS IN 20TH CENTURY

Bridge monitoring programs have historically been implemented for the purpose of understanding and eventually calibrating models of the load-structure-response chain (e.g. Leitch et al., 1987, Barr et al., 1987, Cheung et al., 1997, Bampton et al., 1986, Lau & Wong, 1997, Macdonald et al., 1997, Miyata et al., 2002). One of the earliest documented systematic bridge monitoring exercises, by Carder (1937), was conducted on the Golden Gate and Bay Bridges in San Francisco to learn about the dynamic behaviour as a consequence of an earthquake.

In the last decade, permanent bridge monitoring programs have evolved into SHM systems which have been implemented in major bridge projects in Japan, Hong Kong and latterly North America. Long-span bridge monitoring systems also provide ideal opportunities to implement and study SHM systems, for example the Wind and Structural Health Monitoring System (WASHMS) (Lau & Wong, 1997) implemented on the Lantau Fixed Crossing has stimulated SHM research in Hong Kong about performance of the bridges themselves as well as SHM methodologies.

Less glamorous but possibly ultimately more beneficial developments of SHM have been in optimal monitoring approaches for conventional short span bridges. There is a history of research in full-scale testing for short-span highway bridge assessment (Salane et al., 1981, Bakht & Jaeger, 1990) where 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. Studies in Australia have focused on the typical very short span highway and railway bridges, in one case leading to a commercial product the 'Bridge Health Monitor' or HMX (Heywood et al., 2000) which is programmed to record selected waveforms of vehicle-induced response while logging statistics of strains.

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

3 HUMBER BRIDGE MONITORING FOR SIMULATION VALIDATION

Several full-scale measurement exercises have been conducted on the Humber suspension Bridge (Brownjohn et al., 1994, Stephen et al., 1993, Ashkenazi & Roberts 1997) which from 1984 to 1998 held the world record for largest span, at 1410m.

In the 1980s research was being conducted to establish the performance of long span suspension bridges in seismic areas subject to different ground vibration at the widely separated supports. The Bosphorus (Istanbul) and Humber (UK) bridges have a common design and feature aerodynamic closed steel box decks and inclined hangers. Due to the similar design, faith was put in finite element simulations of the Bosphorus Bridge (Dumanoglu & Severn, 1988) via validation of a similar model of the more accessible Humber Bridge by ambient vibration survey (Brownjohn et al., 1987). Humber was subsequently used for validating modeling procedures for simulating wind induced response of the performance of proposed 3300m span Stretto di Messina (Messina Straits) suspension bridge (Branceleoni & Diana, 1993). To this end, an instrumentation project was sponsored by Stretto di Messina Spa, organised by Politecnico di Milano and assisted by University of Bristol, ISMES Bergamo and Humber Bridge Board (Brownjohn et al., 1994). Figure 1 shows the bridge during the monitoring with optical displacement tracking system targets visible on the gantries.

Safe (high) flutter speeds achieved through design of the deck girder shape require good understanding of the wind-structure interaction; even with reasonably accurate modeling of the structure there is still great uncertainty in the loading mechanisms. In the Humber monitoring exercise, wind,

displacement and acceleration signals were recorded for a range of wind conditions, allowing for system identification of the aero-elastic components of stiffness and damping, for comparison with wind tunnel estimates. More importantly, predictions of response based on knowledge of the structure, wind conditions and structural and aerodynamic system were validated, allowing for the same modeling procedures to be used to predict the response of the Messina bridge based on local climate, structural design of the bridge and aerodynamic parameters determined from wind-tunnel test.

The monitoring exercise also provided data to establish relationships between loading effects and responses e.g. Figure 2 shows variations of modal parameters wind characteristics for the first torsional mode, critical for aero-elastic stability, derived from analysis of wind and response data over the entire monitoring period. Significant changes were observed in the modal parameters due to wind, but additionally from the static data it was surprising to learn that slowly varying deck deflections due to temperature changes were greater than static deflections due to wind.

Inspection and maintenance programs for Humber follow UK guidelines with structural components checked every two years, principal inspections every six years and special inspections. Numerical simulations showed that observation of global response e.g. deck accelerations is highly unlikely to indicate structural deterioration to the major components of the superstructure. The components that do need occasional attention or even replacement are hangers (suspenders) and bearings, for which a range of short term assessment procedures can be applied and this could be an ideal application for low cost autonomous wireless vibration sensors (Lynch et al., 2003).

One observation from the Humber monitoring and from dynamic tests on two Turkish suspension bridges is that the character of deck fundamental vertical vibration modes is very sensitive to the condition of the bearings at the piers or anchorages. Hence a simple system to track fundamental vertical mode characteristics can help assess the bearing condition.

4 SECOND LINK: LONG TERM PERFORMANCE MONITORING

A monitoring program to study performance of glued segmental box-girder bridges was conducted in the UK in the 1980s (Barr et al., 1987) with the primary aim of establishing the structural effects of temperature variation along with the long term strain history, and using embedded vibrating wire strain gauges. Based on the UK program, a similar instrumentation scheme was installed in the Second Link Bridge between Singapore and Malaysia, shown in Figure 3, to validate the design and performance (Brownjohn & Moyo, 2000). The bridge was opened in 1997, has a total length of about 1.9km and comprises 27 spans; the Singapore side (to the right of the picture) is about 170m long and the main span of this section is 92m long. The bridge was cast in-situ as a continuous box girder using the post-tensioned balanced cantilever method.

Instruments were installed in the bridge in order to monitor its short- and long-term performance under environmental and traffic loads. The instrumentation consisted of four data loggers, twelve vibrating wire strain gauges, 44 thermocouples and one tri-axial accelerometer, distributed in three segments of the main span. In addition, 12 static pressure cells of a type that had previously been used in monitoring of tunnel linings. The arrangement of installed instruments in one of the three instrumented segments is shown in Figure 4.

Strain, stress and temperature data were recorded at hourly intervals in periods from 1997 to 2004, and used (Moyo & Brownjohn, 2002a,b) to develop procedures for anomaly detection. In particular, data from the construction process provided valuable information on early-life strain development and reference characteristics for events such as post-tensioning and concrete pouring. These events may have analogs in post-construction activity, and the lessons learnt from the construction monitoring can be used for understanding subsequent bridge behavior, including damage detection.

One fundamental problem in SHM is data normalization (Alampalli, 1998; Cornwell et al., 1999; Sohn et al., 1999). Often the signal non-stationarity or deviation from the established pattern of response may indicate an altered structural state or damage. However, such changes in the monitored signal are often obscured by ambient inputs or noise, and it is necessary to compensate for or filter out these effects. For example, Figure 5 shows strain signals of one segment during construc-

tion. It can be seen that some abnormal, abrupt events, notably segment casting, can easily be identified by visual inspection of strains recorded by some sensors, in this case those placed near the bottom of the beam. However, identification of more subtle events, e.g. tensioning and concreting form shifting, or even identification of casting events from the data from other sensors by simple visual examination of the time series is very difficult. Eliminating the ambient noise may be possible using some form of structural model relating loads to their effects. In the case of Second Link, access for dynamic testing was practically impossible, so no such model was available. ‘Output-only’ type models were thus used to detect anomalous events without any knowledge of the structure.

Two different analytical procedures were used for detection of anomalous behavior. The first one [28] employed wavelet transform. Raw strain data are filtered into high and low frequency components using the Daubechies discrete wavelet transform. The highest frequency components, or wavelet details, are retained as a series of time varying coefficients and conveniently indicated discontinuities in the original time series, as shown in Figure 6. 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. A best fit ARMA model is obtained and the various outliers to this model can be detected and examined. As the data are multi-channel, it is possible to highlight outliers consistent among the channels and differentiate effects on different parts of the structure. 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. This procedure proved to be very successful at characterizing the structural state changes. In the absence of an analytical model to interpret the changes, we noted the construction operations causing the changes.

The second analytical procedure operates directly on the strain time series and does not involve wavelet transform (Omenzetter et al., 2003). It was inspired by the studies of Sohn et al. (2000, 2001), who used a combination of autoregressive (AR) and autoregressive-with-exogenous-input (ARX) time series models to detect altered structural states.

In the case of continuous monitoring of Second Link, a ‘vector seasonal autoregressive integrated moving average’ (ARIMA) model was established for the recorded strains. Through its seasonal part the model accounts for strain variations due to ambient temperature cycles. The parameters of the ARIMA model are allowed to vary with time and can be identified on-line using a Kalman filter. By observing various changes in the model parameters, unusual events as well as structural changes can be revealed. Figure 7 shows an example of changes in an ARIMA coefficient due to cable tensioning events during construction. 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 two methods indicate the type of signal processing now available for investigating data characteristics and discriminating changes in performance patterns. Tools like neural networks, vector support machines and principal component analysis together show great promise in achieving reliable ‘level 1’ SHM, which is an indication that there has been a structural change (which could be damage). It is then up to detailed condition assessment to diagnose the observed changes.

5 PIONEER BRIDGE: SHORT TERM MONITORING FOR BRIDGE RETROFIT

All but a handful of highway bridges in Singapore are reinforced or post-tensioned concrete and the Land Transport Authority of Singapore (LTA) has recently been engaged in a major program of upgrades on its stock of almost 2000 highway bridges to sustain higher axle loads.

LTA now includes a provision for structural monitoring in tender specifications for most of its bridge upgrades (and even for some of its new bridges), making the upgrade contractor responsible for producing evidence of satisfactory improvement in performance. The specifications for instrumentation and proof of structural improvement are evolving, and research (Moyo et al., 2003) has

been conducted to identify a rational procedure for assessing the success of the upgrade, based on work by Heywood et al. (2000).

The approach was demonstrated by application to Pioneer Bridge (Figure 8), an 18m span bridge comprising parallel pre-stressed inverted T-beams tied together by tendons and deck slab and supported on pinned bearings. The major structural change in the bridge upgrade program involved fixing the deck end bearings via massive reinforcement.

A multi-stage approach was used to assess the upgrade. First, a HMX bridge health monitor (Heywood et al., 2003) was installed to log traffic-induced vertical accelerations and longitudinal strains on the soffit of sample T-beams. Sample waveforms were logged while statistics of strain excursions during passage of heavy vehicles were obtained over a one-month monitoring period. Second a modal survey of the bridge was conducted to establish a validated finite element model of the bridge. Third and fourth, after the structural upgrade the modal survey and short-term monitoring were repeated.

Figure 9 shows strain instrumentation and a representative strain time series due to a passing truck. Statistical analysis of peak strain values from the monitoring provided live strain values for design return periods; Figure 10 shows Gumbel plots of live strains extrapolated to indicate 120-year return period values and indicating improvement in performance due to the upgrade.

Figure 11 shows the frequency response function (FRF) before and after the upgrade, indicating a considerable increase in stiffness and damping capacity due to the upgrade. The mode shape plots serve to identify which FRF peaks correspond, and also show (on close examination) the change in curvature at the abutments due to the change in fixity. The dynamic test data were used to update a finite element model which was then 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.

While the more elaborate modal survey and model updating procedures are not likely to be used in all upgrade exercises, simplified forms of dynamic testing that can show an improvement in fundamental frequency could be used to show improvements in stiffness.

6 TAMAR BRIDGE

The final example described here is a work in progress. Suspension bridges were not built in the UK between the late 19th century and 1958 when construction began on the Forth road Bridge. A year later construction began on Tamar Bridge (Figure 12) in south west England, and the bridge was opened in 1961, three years before Forth Road Bridge. Increased traffic and greater axle loads for heavy goods vehicles led to a requirement for Tamar to be strengthened and widened (List, 2004). Between 1999 and 2001, the concrete deck slabs were replaced with an orthotropic steel deck, 16 additional stay cables were added and additional lanes cantilevered either side of the main deck. Among other less obvious changes were modifications to the deck bearings. The original system shown in Figure 13 linked main and sidespans at the Plymouth (east) tower while allowing relative movement at the Saltash (west) tower. The restraint at the Plymouth end was removed during the upgrade and the fixity is now provided by the continuation of the cantilevers around the towers.

The bridge performance is generally satisfactory but there is a little concern over two observations on the performance. First, the deck has notably shifted in the longitudinal direction putting strain on shorter suspenders, and second some of the additional stays have experienced significant oscillations during conditions of strong wind and rain. To combat this, some of the stays have been equipped with simple fluid dampers (Figure 14 left). Forced vibration testing demonstrated the effectiveness of these simple devices.

As part of the ongoing maintenance and bridge inspection program, the operators are interested to expand a monitoring system installed by Fugro to check performance, principally vertical deck deflections, during construction. Hence a monitoring program is being designed with the following objectives:

- Monitor selected stay cable vibration levels (using accelerometers)
- Monitor deck deformation at bearings (using linear potentiometers)
- Measure deck accelerations (using accelerometers)
- Track tower and deck midspan deflections (using GPS or total stations)

Weather data from the existing monitoring system as well as limited cable load data will be extracted and merged with the above data. The combined data set will be tracked to flag immediate performance anomalies (e.g. excessive cable vibration) and look for changes in daily performance patterns. Some of the procedures developed for Second Link will be used, and an ambient vibration survey using state of the art output only system identification will be used to updated finite element models being developed for performance diagnosis.

CONCLUSIONS

Experience with a number of instrumented bridges has shown that calibration of a finite element model using dynamic test data followed by a period of performance monitoring is a very useful tool for cost-effective performance tracking. Monitoring performance through key response parameters and use of powerful signal processing procedures allows for identification in changes in structural condition. The technology is available at different levels of sophistication; there is always a lot to be learned from tracking the performance of structures at full-scale, and as Bakht says (1990) there is a surprise every time.

REFERENCES

- Alampalli S, 1998, *Influence of in-service environment on modal parameters*. Proceedings, IMAC16 vol. 1, Santa Barbara, CA. 111-116.
- Alampalli S, Fu G, 1994, *Instrumentation for remote and continuous monitoring of structure conditions*. Transportation Research Record 1432, 59-67.
- Ashkenazi V, Roberts GW, 1997 *Experimental monitoring of the Humber Bridge using GPS*. Civil Engineering, Proc ICE 120 177-182
- Bakht B, Jaeger JG, 1990, *Bridge testing: a surprise every time*. ASCE ST 116 no. 5, 1370-1383.
- Bampton MCC, Ramsdell JV, Graves RE, Strobe LA, 1986. *Deer Isle-Sedgwick suspension bridge. wind and motion analysis* Report FHWA/RD-86/183
- Barr I G, Waldron P, Evans H R, 1987 *Instrumentation of glued segmental box girder bridges*. Monitoring of Large Structures and Assessment of their Safety. IABSE Colloquium Bergamo 1987
- Branceleoni F, Diana G, 1993, *The aerodynamic design of the Messina Straits Bridge*. Journal of Wind Engineering and Industrial Aerodynamics 48, 395-409.
- Brownjohn JMW, Boccione M, Curami A, Falco M, Zasso A, 1994, *Humber Bridge full-scale measurement campaigns 1990-1991*. JWEIA 52 185-218.
- Brownjohn JMW, Moyo P 2001, *Monitoring of Malaysia-Singapore Second Link during construction*, Proc SPIE, 4317, 528-533
- Brownjohn JMW, Dumanoglu AA, Severn RT, Taylor CA, 1987, *Ambient vibration measurements of the Humber suspension bridge and comparison with calculated characteristics*. Proc ICE, pt 2, vol. 83, 561-600.
- Carder DS, 1937. *Observed vibrations of bridges*. Bulletin, Seismological Society of America, vol. 27, 267-303.
- Cheung MS, Tadros GS, Brown J, Dilger WH, Ghali A, Lau DT, 1997, *Field monitoring and research on performance of the Confederation Bridge*. Canadian Journal of Civil Engineering Vol. 24, 951-962.
- Cornwell P, Farrar CR, Doebling SW, Sohn H, 1999, *Environmental variability of modal properties*. Experimental Techniques vol. 23 no. 6, 45-48.
- Dumanoglu AA, Severn RT, 1987 *Seismic response of modern suspension bridges to asynchronous vertical ground motion*. Proceedings ICE pt2, vol. 83, 701-730.

- Heywood R J, Roberts W, Taylor R, Anderson R, 2000, *Fitness-for-purpose evaluation of bridges using health monitoring technology*. Transportation Research Record, v 1, n 1696, 193-201
- Lau CK, Wong KY, 1997, *Design, construction and monitoring of three key cable-supported bridges in Hong Kong*. Proc 4th International Kerensky Conference on Structures in the new millennium, Hong Kong, 105-115.
- Leitch J, Long AE, Thompson A, Sloan T D, 1987, *Monitoring the behaviour of a major box-girder bridge. Structural Assessment Based on Full and Large-Scale Testing*, BRE Garston 212-219, Butterworths.
- List D, 2004 *Rejuvenating the Tamar Bridge. A review of the strengthening and widening project and its effect on operations*. In Proc. 4th International cable supported bridge operators' conference, Copenhagen, www.icsboc.com
- Macdonald JHG, Dagless EL, Thomas BT, Taylor CA, 1997, *Dynamic measurements of the Second Severn Crossing*. Proc, ICE, Transport, 123, no. 4, 241-248.
- Miyata T, Yamada H, Katsuchi H, Kitagawi, 2002, *Full-scale measurement of Akashi-Kaikyo Bridge during typhoon*, JWEIA 90, 1517-1527.
- Brownjohn JMW, Moyo P, 2000, *Monitoring of Malaysia-Singapore Second Link during construction*, Proceedings SPIE 4317:528-533
- Moyo P, Brownjohn JMW, 2002b, *Application of Box-Jenkins models for assessing the impact of unusual events recorded by structural health monitoring systems*, International Journal of Structural Health Monitoring 1 no. 2, 149-160.
- Moyo P, Brownjohn JMW, 2002a *Detection of anomalous structural behaviour using wavelet analysis*. Mechanical Systems and Signal Processing 16 nos. 2-3, 429-445
- Moyo P, Brownjohn JMW, Omenzetter P, 2003. *Bridge live load assessment and load carrying capacity estimation using health monitoring system and dynamic testing*. 3rd International conference on current and future Trends in Bridge Design, construction and Maintenance. Shanghai
- Omenzetter P, Brownjohn JMW, Moyo, P, 2003, *Application of time series analysis for bridge health monitoring*. Proceedings 1st International Conference on Structural Health Monitoring and Intelligent Infrastructure, 2:1073-1080.
- Omenzetter P, Brownjohn JMW, Moyo P, 2003 *Identification of unusual events in multi-channel bridge monitoring data* Mechanical Systems and Signal Processing.
- Salane HJ, Baldwin JW, Duffield RC, 1981, *Dynamics approach for monitoring highway bridge deterioration*. Transportation Research Record 832, 21-8
- Sohn H, Dzwonczyk M, Straser EG, Kiremidjian AS, Law KH, Meng T, 1999, *An experimental study of temperature effect on modal parameters of the Alamosa Canyon bridge*, Earthquake Engineering and Structural Dynamics 28:879-897.
- Sohn H, Czarnecki JA, Farrar, CR, 2000, *Structural health monitoring using statistical process control*. ASCE Journal of Structural Engineering, 126(11):1356-1363.
- Sohn H, Farrar CR, Hunter N, Worden K, 2001, *Applying the LANL Statistical Pattern Recognition Paradigm for Structural Health Monitoring to Data from a Surface-effect Fast Patrol Boat*, Los Alamos National Laboratory Report LA 13761-MS.
- Stephen GA, Brownjohn JMW, Taylor CA, 1993, *Measurements of static and dynamic structural displacement from visual monitoring of the Humber bridge* Engineering Structures 3, 197-208



Figure 1 Humber Bridge midspan with targets for optical deflection tracking

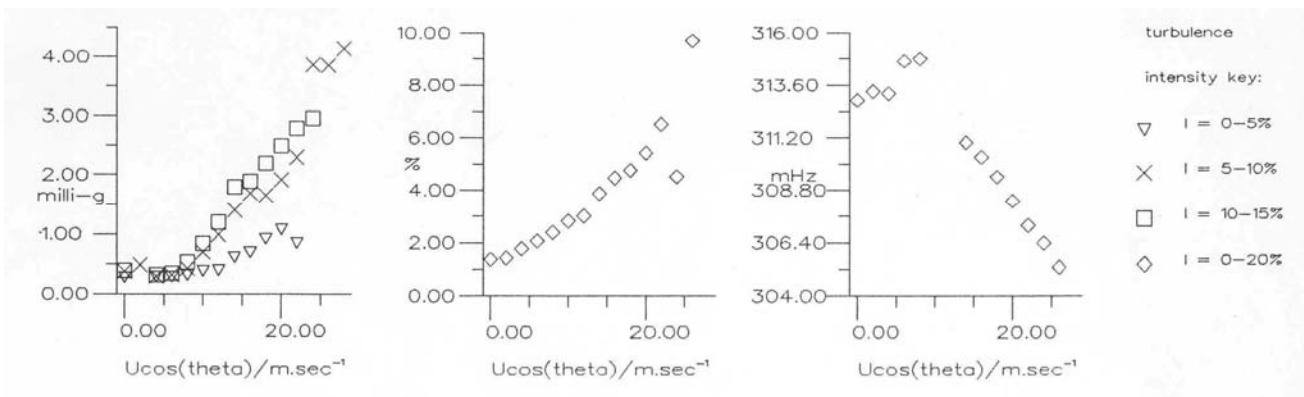


Figure 2 Variation of modal response parameters due to wind showing aero-elastic influence



Figure 3 Second Link bridge: instrumented section at extreme right

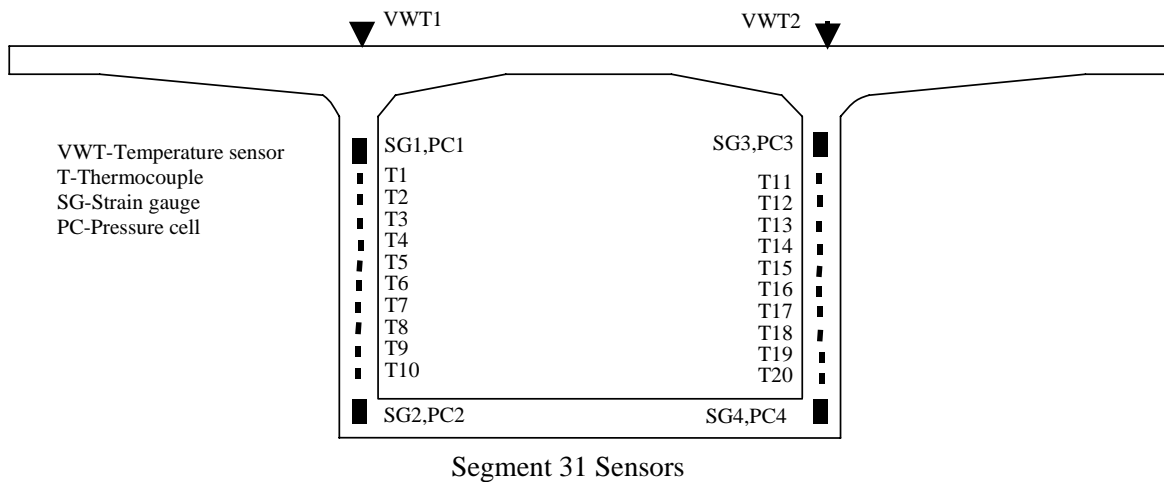


Figure 4 Instrument arrangement in one of three instrumented segments

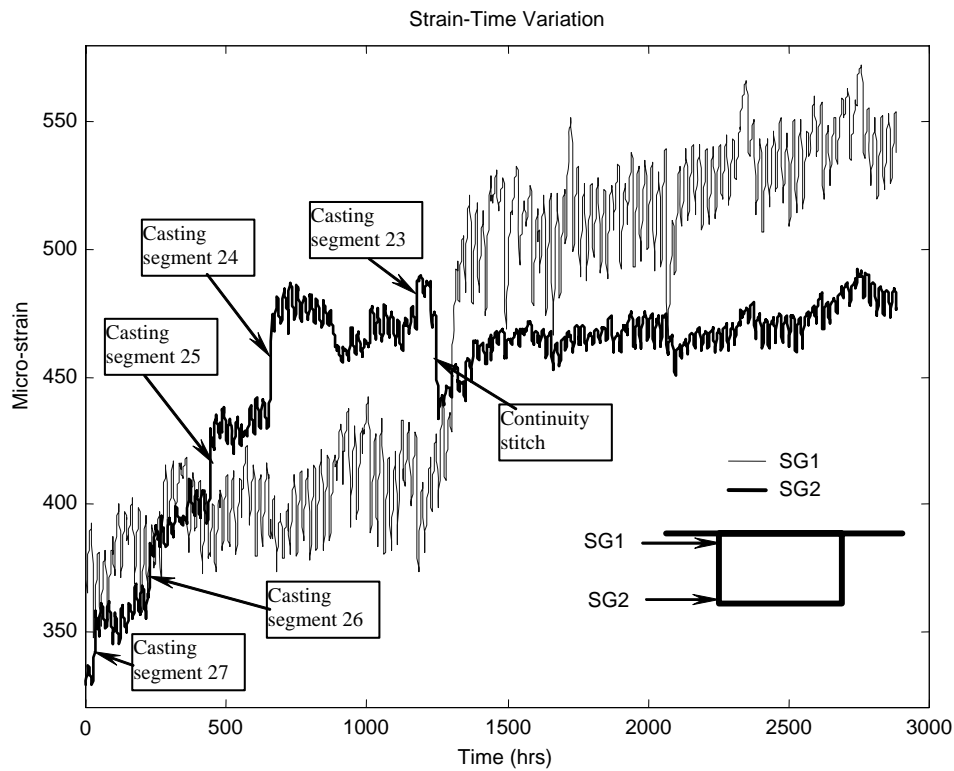


Figure 5 Strain variation in segment 31 during construction.

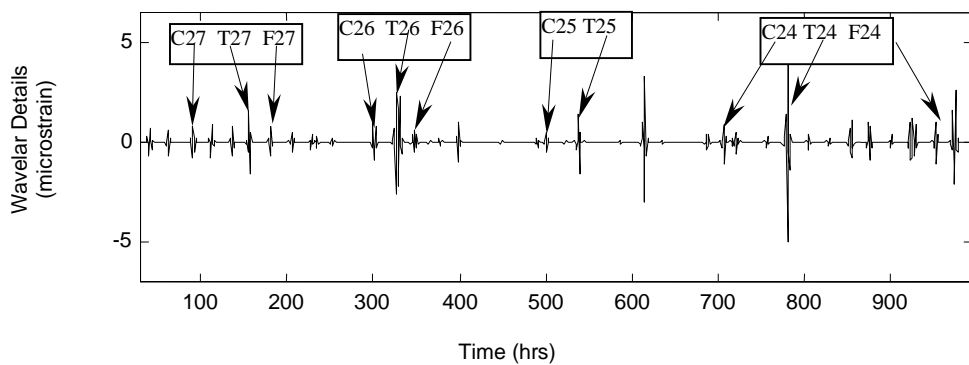


Figure 6 Wavelet decomposition of strain data (Abbreviations: C – concreting, T – cable tensioning, F – shifting of concreting form, e.g. T26 – tensioning of cables in segment 26).

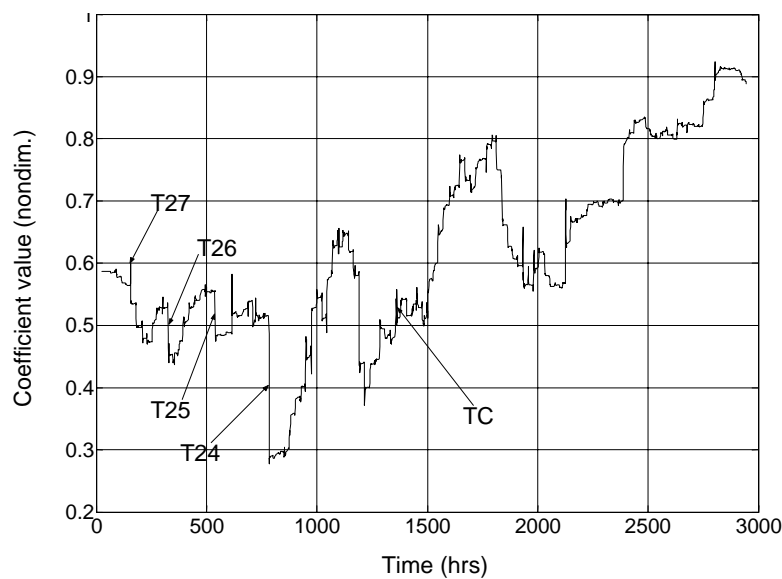


Figure 7 ARIMA model coefficients showing changes due to cable tensioning



Figure 8 Pioneer Bridge: Top from side, below, view along footpath showing shaker and accelerometer

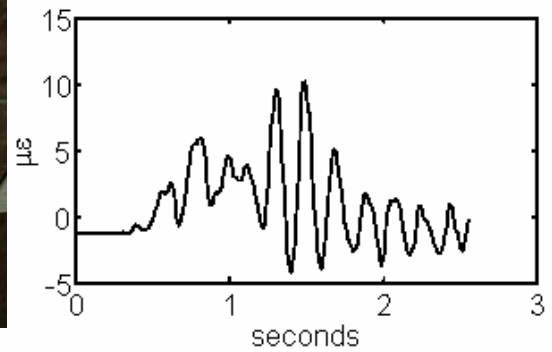


Figure 9 Demountable strain gauge attached to inverted T-beam soffit and typical strain time series due to passing truck

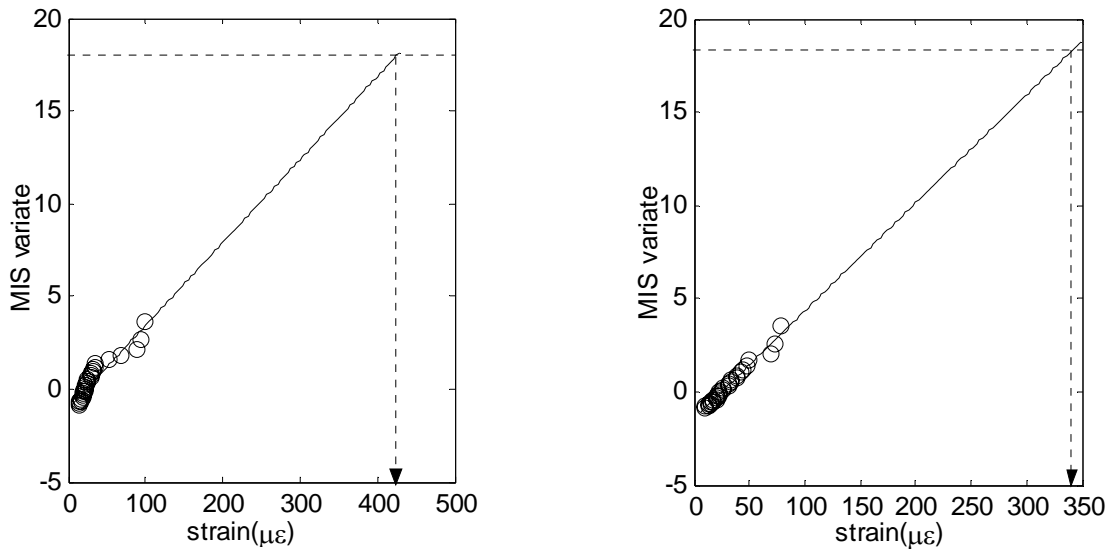


Figure 10 Extreme value strain statistics using method of independent storms (MIS)
 (a) 120 year strains before upgrading. (b) 120 year strains after upgrading

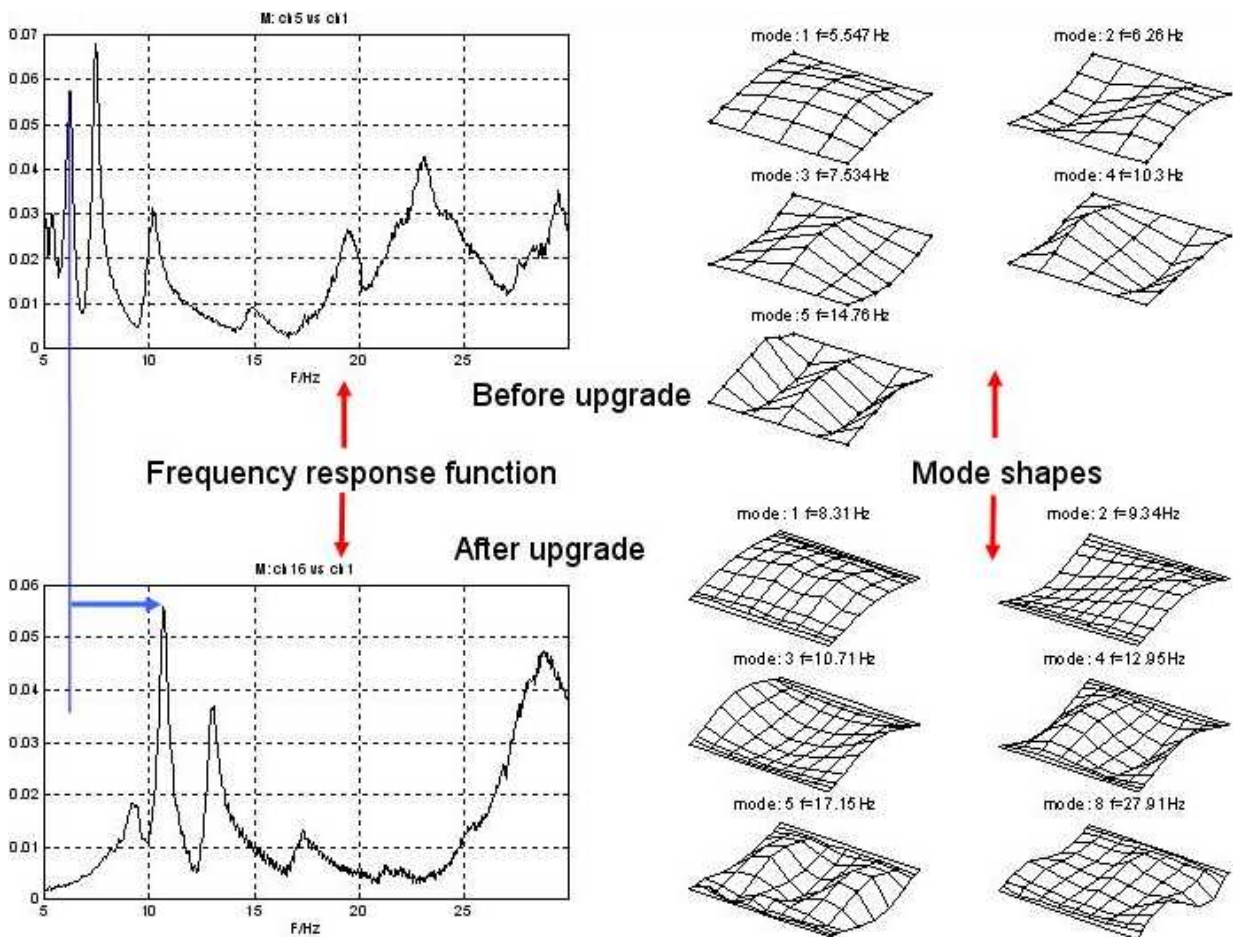


Figure 11 Pioneer Bridge FRF before and after upgrade showing increase in stiffness and damping capacity. Mode shapes are used to match frequencies



Figure 12 Tamar Bridge

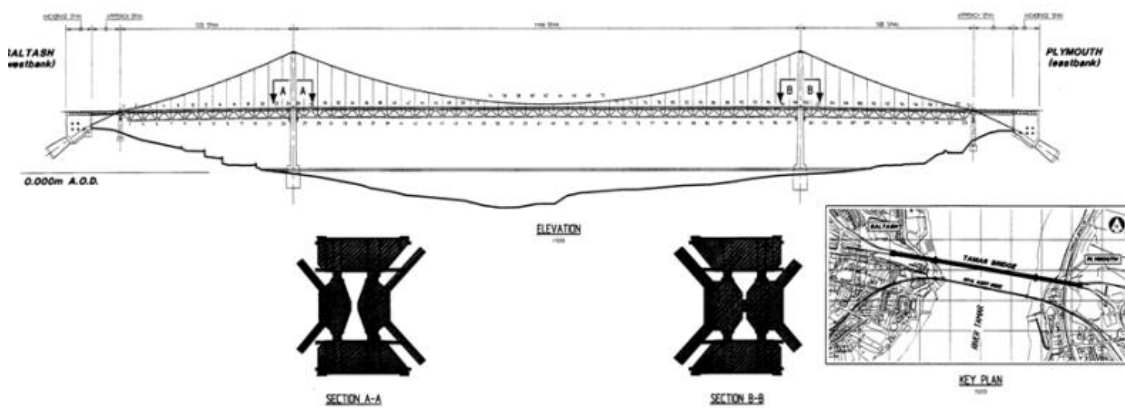


Figure 13 Deck main bearing arrangements at tower before upgrading

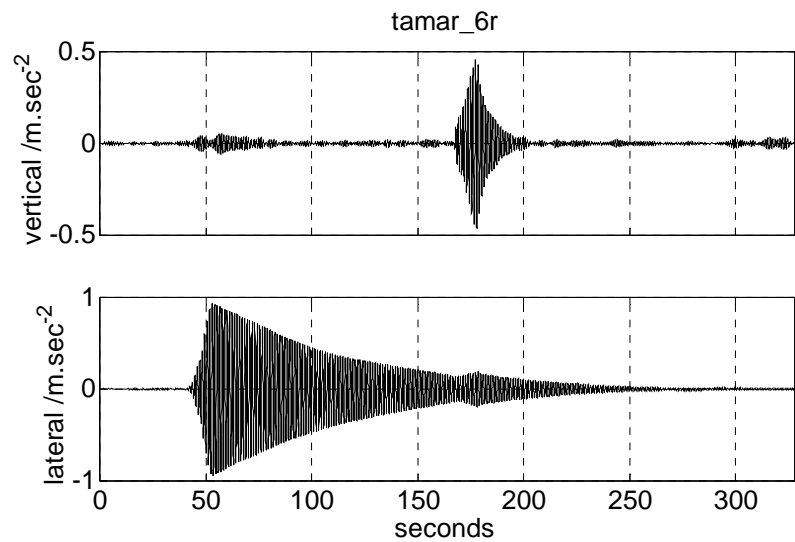


Figure 14 Free decay of damped and un-damped stay-cable vibrations