LESSONS FROM MONITORING THE PERFORMANCE OF HIGHWAY BRIDGES

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ABSTRACT

Monitoring programs on four very different highway bridges originating from a range of requirements related to calibration of numerical models, assessment of load capacity and long term tracking of performance are summarized in order to draw out lessons relevant to the future development of structural health monitoring 'systems'. These lessons concern validation of structural models, appropriate methods for instrumentation, communication, data management and system identification. The paper presents experience obtained by collaboration in a form intended to educate, by example, bridge operators about potential and limitations of SHM systems.

KEYWORDS
bridge monitoring instrumentation signal processing

1 INTRODUCTION

Structural health monitoring (SHM) of highway bridges is now a major interdisciplinary research growth area, with collaborations including civil, mechanical, electrical and computer engineering. Definitions of SHM take many forms, including 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 by considering all forms of available performance indicators. 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 and in this sense many bridge SHM exercises have (had) a rather narrow focus. While vibration data remain valuable, they need to be integrated with quasi-static response data and conventional observations within an inspection-based maintenance program. Even with a representative spectrum of load and response data, 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.

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 [1-9]. One of the earliest documented systematic bridge monitoring exercises, by Carder [10], was conducted on the Golden Gate and Bay Bridges in San Francisco to learn about the dynamic behaviour and possible consequences of an earthquake.

In the 1990s, permanent bridge monitoring programs 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) [6] implemented on the Lantau Fixed Crossing has stimulated SHM research in Hong Kong not only concerning the performance of the bridges themselves but also of SHM methodologies.

Less glamorous but possibly ultimately more beneficial developments of SHM have been in optimal monitoring approaches for conventional short span bridges, yet there is a long history of research in full-scale testing for assessing such bridges e.g. [11, 12]. For these smaller bridges global response is more sensitive to defects, visual inspection is less frequent and SHM systems can and do [13] 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 [14] which is programmed to record selected waveforms of vehicle-induced response while logging statistics of strains due to such events.

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 [3, 15, 16] 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 towers and anchorages. The Bosporus (Istanbul) and Humber (UK) bridges have a common design theme and feature aerodynamic closed steel box decks and inclined hangers. Due to the similar design, faith was put in finite element simulations of the Bosporus Bridge [17] via validation of a similar model of the more accessible Humber Bridge by ambient vibration survey [18]. Humber was subsequently used for validating modeling procedures for simulating wind induced response of the performance of proposed 3300m span Stretto di Messina suspension bridge [19]. To this end, an instrumentation project was sponsored by Stretto di Messina Spa, organised by Politechnico di Milano and assisted by University of Bristol, ISMES Bergamo and Humber Bridge Board [3].

Safe (high) flutter speeds achieved through design of the deck girder shape depends on 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 and other specialized signals were recorded for a range of wind conditions, allowing for system identification of the aero-elastic components of the stiffness and damping, for comparison with values estimated from wind tunnel studies [20]. Figure 1 shows how modal frequency and damping of the first torsional mode vary with wind speed (negative wind approaches perpendicular to the span from the west). The damping increase is reassuring but the drop in modal frequency, coupled with more gentle rise in first mode frequency indicates a trend towards single-mode flutter at a rather high wind speed. The total exercise validated the procedure for predicting response based on knowledge of the structure, wind conditions and structural and aerodynamic system so that it could be applied to the much larger Messina bridge.

More immediately, the monitoring exercise provided data to establish relationships between various loading effects and static responses, identifying correlations of loading effects such as wind speed and ambient temperature with structural responses such as lateral and vertical deflection and axial rotation, and these are summarized in Figure 2. One surprise was that slowly varying deck deflections due to temperature changes were greater than static deflections due to wind.

Numerical simulations showed that observation of global response e.g. deck accelerations is highly unlikely to indicate structural damage or deterioration to the major components of the superstructure i.e. deck, cables and towers. The components that do need occasional attention or even replacement are hangers (suspenders) and bearings and these make good cases for applying SHM systems and technology. Hanger monitoring is an ideal application for low cost autonomous wireless vibration sensors [21] as there are many cases of excessive oscillation and corrosion or failure of anchorages, while the performance of deck bearings has been shown in Humber and the two suspension bridges over the Bosporus to have strong effect on the character of fundamental vertical vibration modes.

4 TUAS 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 [2] with the primary aim of establishing the structural effects of temperature variation along with the long term strain history 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 [22]. The bridge was completed in 1997 and opened to traffic in the same year, has a total length of 1.9km, comprises 27 spans and has only two expansion joints, at each end. The Singapore side is only 170m long and the main span of this section is 92m long. The bridge was cast in-situ as a post-tensioned continuous box girder using the balanced cantilever method.

The instrumentation installed to monitor its short- and long-term performance under environmental and traffic consists of four data loggers, twelve vibrating wire strain gauges, forty four thermocouples and one tri-axial accelerometer, distributed in three segments of the main span. The arrangement of installed instruments is shown in Figure 4; all the data loggers were connected to a host computer resident in the bridge and accessed via a modem.

Strain, stress and temperature data have been recorded at hourly intervals from 1997 to 2004 (but not continuously). As well as providing information long term creep and short term linear stress-strain relationships, the data have been used [23,24] for developing procedures for detecting performance anomalies. In particular, the recording during 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 that of data normalization and interpretation under a range of environmental or ambient loads or noise sources that affect the measured signals [25-27]. It is often the signal non-stationarity or deviation from the established pattern of response that may indicate an altered structural state or damage. However, such changes in the monitored signal are quite 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 construction. 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 girder. However, identification of different events, such as tensioning and formwork shifting, or even identification of casting events from the data from other sensors by simple visual examination of the time series is very difficult. Ambient noise could be partially filtered given some physical or structural model relating loads to their effects, but for Second Link, no such model is available and ‘output-only’ type models were used to detect anomalous events without any knowledge of the structure.

Two different analytical procedures are used for detecting anomalous behavior. The first one [28] employs wavelet transform. Raw strain data are filtered into high and low frequency components using the Daubechies discrete wavelet transform [29]. 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 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 [24] 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 7 shows an example of intervention analysis of one of the cable tensioning events. Based on this examination the impact of the event on strain values was separated from other strain variations and classified as permanent of a value of 12με (Fig. 7b).

The second analytical procedure operates directly on the strain time series and does not involve wavelet transform [30]. It was inspired by the studies of Sohn et al. [31, 32], 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 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 are 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 8 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 Second Link monitoring has closed but the data are still useful for research in the developed analytical procedures. For example, one of the topics on the agenda is the comparison of the efficiency of the two above methods. Also, the two methods, while reasonably successful, are not flawless as they may yield some spurious observations caused by non-Gaussian distribution of the strain data, which was discussed in detail elsewhere [30]. Overcoming successfully the methods’ limitations is critical for making them potentially useful to the bridge operators.

5 PIONEER BRIDGE: SHORT TERM MONITORING FOR SHORT SPAN BRIDGE RETROFIT

All but a handful of highway bridges in Singapore are reinforced or post-tensioned concrete and from around 2000 the Land Transport Authority of Singapore (LTA) operated a major program of upgrades on existing bridges to sustain higher axle loads. LTA now includes a provision for structural monitoring in the upgrade tender specifications, making the upgrade contractor responsible for producing evidence of satisfactory improvement in performance. The specifications for instrumentation and proof of structural improvement are slowly evolving, and research [33] has been conducted to identify a rational procedure for assessing the success of the upgrade, based on Heywood et al. [14]

The proposed approach has been demonstrated on Pioneer Bridge (Figure 9), 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 [14] (Figure 10) comprising four demountable strain gauges, four accelerometers and a battery powered data acquisition box was installed to log traffic-induced vertical accelerations and longitudinal strains on the soffit of selected T-beams. The sensors were mounted at the mid-span of selected girders and left in place for one month before and after strengthening works. Recording of strains and accelerations was triggered by the passage of heavy vehicles at selected levels of strain. For each record the health monitor captured the strain waveform, peak strain and acceleration with a date and time stamp assigned to each event such as for the typical strain waveform shown in Figure 11. Peak strains were 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. The first was the standard Gumbel distribution which is generally accepted as the appropriate distribution for bridge live loading [34, 35].

The Gumbel procedure selects only one peak value per sampling period, e.g. one peak value per day and as a result some high peak values may be left out resulting in inaccurate estimates of live load strains. To avoid this problem a modified Gumbel approach was also implemented [36-38]. While the modified Gumbel distribution, also known as the Method of Independent Storms, (MIS) captures most of the peak strains the distribution fit indicates a more complex distribution. In both cases however the peak strains changed by approximately 20% before and after bridge strengthening (Figure 12).

Second, modal surveys of the bridge were conducted and used with core samples to establish a validated finite element model of the bridge before and after upgrading. Figure 13 shows the frequency response functions (FRF) before and after the upgrade, indicating a considerable increase in stiffness and damping capacity due to the upgrade. This is evident from the increase of the first natural frequency from about 6Hz to approximately 8Hz. Identification of the modes is possible via correspondence of the mode shapes, which also show evidence of the stiffened supports.

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 a drop in about 20% and a improvement in the proportion of ultimate capacity for the same return period. The study showed that even before upgrading, the capacity was already adequate, hence such a procedure could be used to check the need for an upgrade.

6 PASIR PANJANG SEMI-EXPRESSWAY (PPSE): RECENT DEVELOPMENTS IN SHM

Based on the Second Link experience a program was developed for a major elevated expressway in Southern Singapore to incorporate structural modeling and improvements in communications, using wireless modems. PPSE is an extended viaduct of twin box decks supported on single central pylons above an existing main road and intended to carry heavy good vehicle traffic between two major container terminals. The viaduct is arranged in ‘bridges’ of five 20m-46m spans between expansion joints and constructed using the balanced cantilever method with pre-cast segments delivered from a casting yard in Western Singapore (via Pioneer Bridge). At the time of writing, and due to construction delays, PPSE is still under construction with only the piers in place at the western end, while span sections are already joined to form continuous bridges at the eastern end. 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 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. The patterns of the data are so far similar to those observed at Tuas, with diurnal variations and (modest) jump shifts during stitching/post-tensioning.

In order to interpret the variations of signals during and after construction, one bridge is being fully 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 to obtain free vibration properties. For this bridge, it is possible to excite lower frequency vibration modes by timed jumping or instrumented hammer. Figure 14 shows prompted jumping in action, which can either induce a broad band transient (a single jump) or specific modes (by a short sequence of timed jumps). This worked very well for the typical balanced cantilever portion shown, while ambient response due to wind and construction activity was used on a complete and relatively massive bridge.

The approach adopted for FE modeling was to build a relatively simple model of a balanced cantilever arrangement of a pier and four semi-spans and to progress to more detail and a complete multi-span bridge. Table 1 shows comparison of experimental mode frequencies with FE modes using a coarse model and one including parapets and necessarily smaller (and more) elements. Figure 15 shows the detailed FE mesh and the fundamental vibration mode, while the correspondence between experiment and analysis is illustrated in Figure 16 for two higher vibration mode shapes based on vertical response at a few points. The good agreement suggests that assumptions about material parameters and boundary conditions i.e. rigid foundation are valid as would be extrapolation, by a process of extrusion, to a model of a whole bridge. For the balanced cantilever there was no justification for FE model updating.

The exercise of detailed finite element modeling and dynamic testing of a sub-structure during the construction phase and subsequent correlation/updating is a useful technique to validate assumptions and provide confidence in modeling the whole bridge, forming a baseline for investigating any long term variations within a SHM program. Figure 17 shows one mode from the extruded full bridge model, and an experimental exercise using ambient vibration response indicated acceptable correlation between test and analysis even though due to computation limits it was only possible to use the less detailed mesh.

In the this final and effectively validated structural 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 and this integration of static stress and strain response with the validated dynamic finite element model is the significant next step in the process.

While quasi-static response data are manageable directly and arrays of accelerometers are not necessary since modal properties have been determined already, tracking dynamic performance is useful for checking live loads through spatially discrete measurements, and there is always the possibility that variations in modal frequency and damping can indicate certain forms of structural change. 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 and local processor communicating via USB will identify the peaks in the reflected light spectrum to track strain changes dynamically.

7 RECOMMENDATIONS AND DIRECTIONS FOR BRIDGE SHM

From experience of four bridge SHM systems, together with observations on other major instrumentation programs, recommendations can be made for future bridge SHM projects.

7.1 *Clarity of purpose*

There are likely to be major differences between the relatively basic requirements of bridge managers and the ambitions of systems designers, the latter usually originally from academia. Bridge managers first of all wish to know if the structure is safe for continued operation, e.g. due to high wind conditions and second to know about unusual loading patterns. They continue to rely on visual inspection and welcome and reliable procedures for assisting bridge management.

For bridges, the possibility of a SHM system being able to detect damage that is not visually obvious is apparently still some way into the future. It would be encouraging to think that designers may wish to know if the structure as built performs as per design, but the loop is rarely closed, partly because designers may prefer not to know about the degree of conservatism, even if there could be economic gains. An exception is where proof of improved performance due to upgrade or retrofit is required.

Academics are so far probably the greatest beneficiaries of SHM due to the rare and precious opportunities to gain insight into and report on performance of exotic structures, bridges being obvious and accessible choices due to being in the public domain and relatively free of legislative constraints. Such research has definite future benefits from opportunities to try out new hardware and procedures that may eventually find practical use.

The three examples of long term monitoring reported here were largely academic exercises but of course with strong user involvement, the first providing calibration of analytical tools for use elsewhere, the second making use of an opportunity to develop anomaly detection procedures and the third aiming to integrate minimal instrumentation for dynamic and static response with novel sensors, embedded systems, wireless communication and anomaly diagnosis based on a calibrated analytical model. In fact the PPSE exercise has been designed as a prototype SHM system for this class of bridge. The exercise with Pioneer demonstrated the effectiveness of combining monitoring with an experimentally validated structural model for rating a bridge.

7.2 *Novel sensors and embedded systems*

The list of sensors intended for SHM applications is growing with Fibre optics having a growing range of applications. MEMS sensors e.g. accelerometers also have potential due to low power consumption and cost.

Along with the sensor development comes local processing (embedded systems) which seeks to condense data, at source, to information to reduce data transmission overheads and aid data management and power consumption. Simple examples are peak values of strains due to passing vehicles; in-band RMS and centre frequency for modal response due to wind, earthquakes and vehicles; mean and gust values of wind data and time series model coefficients from vibration signals.

In many research communities significant investment is put into sensor development looking for a practical application yet it is relatively rare to find such sensors working ‘in anger’ and showing proven advantages over conventional systems. This should not deter development but multidisciplinary approaches involving field trials should be preferred to narrowly focused research.

7.3 *Communications*

A revolution is beginning in this area as GPRS and then 3G begin to find their way into SHM applications and help to make cabling redundant thereby removing probably the greatest headache in instrumentation. A pilot project in Singapore [39] uses a server communicating in real time with data loggers on bridges and in tunnels, and relaying to users as by e-mail or SMS. Use of LANs to connect loggers is more common yet there remain issues with synchronization for fast acquisition rates, as well as with the slowly growing catalog of wireless sensors for which there is a growing demand.

7.4 *Performance diagnosis*

This is a rapidly developing area with major challenges and opportunities for researchers. In parallel with sensors and to a lesser extent communications, it is believed that research efforts in this area will have the greatest impact not in the research community but in real-world applications with demanding infrastructure owners.

The first step in such a diagnostic approach before progression to stages of location, quantification and prediction is to identify, reliably, that an anomalous event has in fact occurred. An analytical model validated by test data and/or sophisticated system identification tools are then required to provide the diagnosis, and this requires a deep understanding of the structural mechanisms that we belief can best be provided by modal testing and finite element updating.

8 CONCLUSION

Rapid developments in the diverse area of Structural Health Monitoring (SHM) research show great promise, with extensive developments within the last decade. Even so, approaches to SHM are not standardized, academic goals are often very different from needs of the infrastructure owners and SHM is frequently mistaken for damage detection, a role rarely fulfilled by operational SHM systems. While working towards the ideal of not only detecting but also locating and quantifying damage, SHM systems have already shown great capability in providing detailed understanding of the structural mechanisms and loadings at work in a structure. To this end we advocate an integrated approach where a structural model is validated by dynamic testing prior to long or short term health/performance monitoring.

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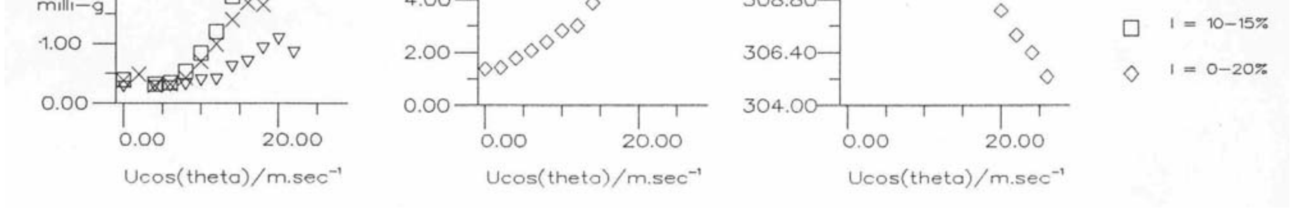
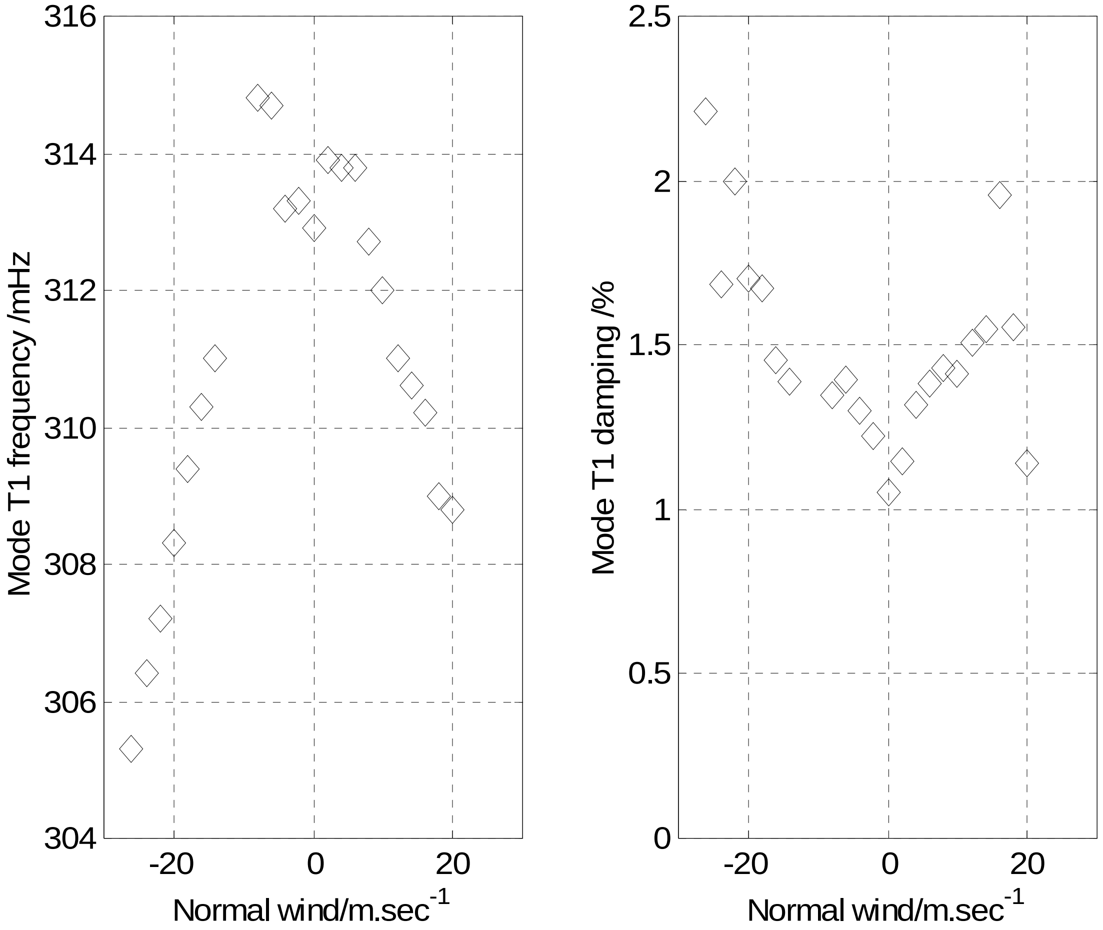
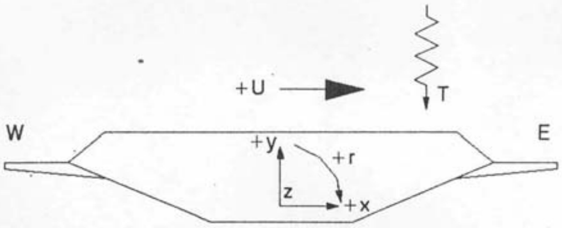
Table 1 Experimental and Finite Element Frequencies for balanced cantilever

Mode Serial Number	Frequencies (Hz)		
	Modal Testing	Approximate Finite Element Analysis	Detailed Finite Element Analysis
1	2.49	3.235	2.531
2	3.96	4.692	4.06
3	6.32	7.659	6.556
4	7.00	9.566	7.205


milli-g
1.00
0.00
0.00
20.00
Ucos(theta)/m.sec⁻¹
2.00
0.00
0.00
20.00
Ucos(theta)/m.sec⁻¹
306.40
304.00
0.00
20.00
Ucos(theta)/m.sec⁻¹
I = 10-15%
I = 0-20%


Mode T1 frequency /mHz
316
314
312
310
308
306
304
-20
0
20
Normal wind/m.sec-1
Mode T1 damping /%
2.5
2
1.5
1
0.5
0
-20
0
20
Normal wind/m.sec-1



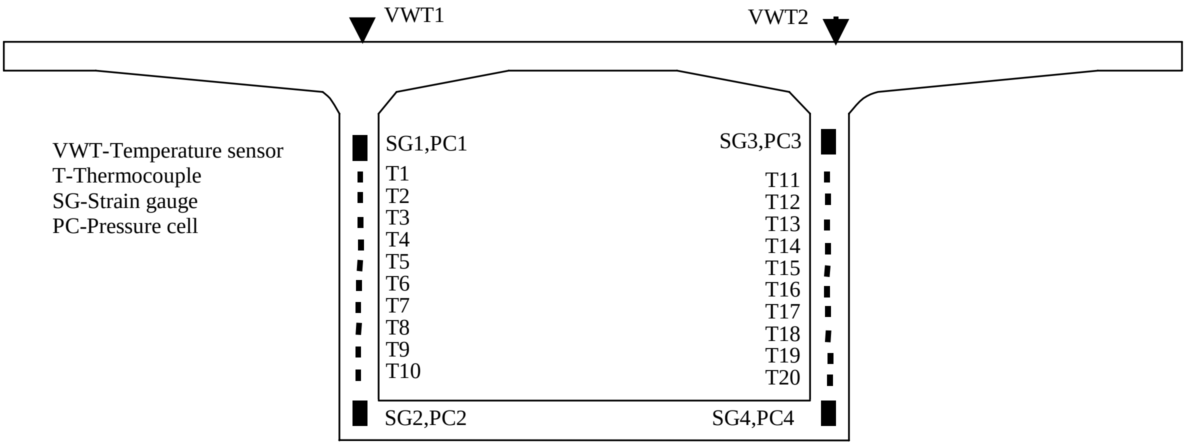
$$x/\mathrm{mm} \approx 17\ T/{}^\circ\mathrm{C} + 0.69\ U|U|/(\mathrm{ms})^2$$
$$y/\mathrm{mm} \approx -65\ T/{}^\circ\mathrm{C} + 0.41\ U^2/(\mathrm{ms})^2$$
$$z/\mathrm{mm} \approx 10.9\ T/{}^\circ\mathrm{C}$$
$$r/{}^\circ \approx +0.00025\ U|U|/(\mathrm{ms})^2$$

Figure 2 Correlations of external influences and structural responses

Figure 3 Second Link bridge: a) under construction, b) completed structure.

a) b)

Figure 4 Second Link segment instrumentation.



Segment 31 Sensors

Figure 5 Strain variation in segment 31 during construction.

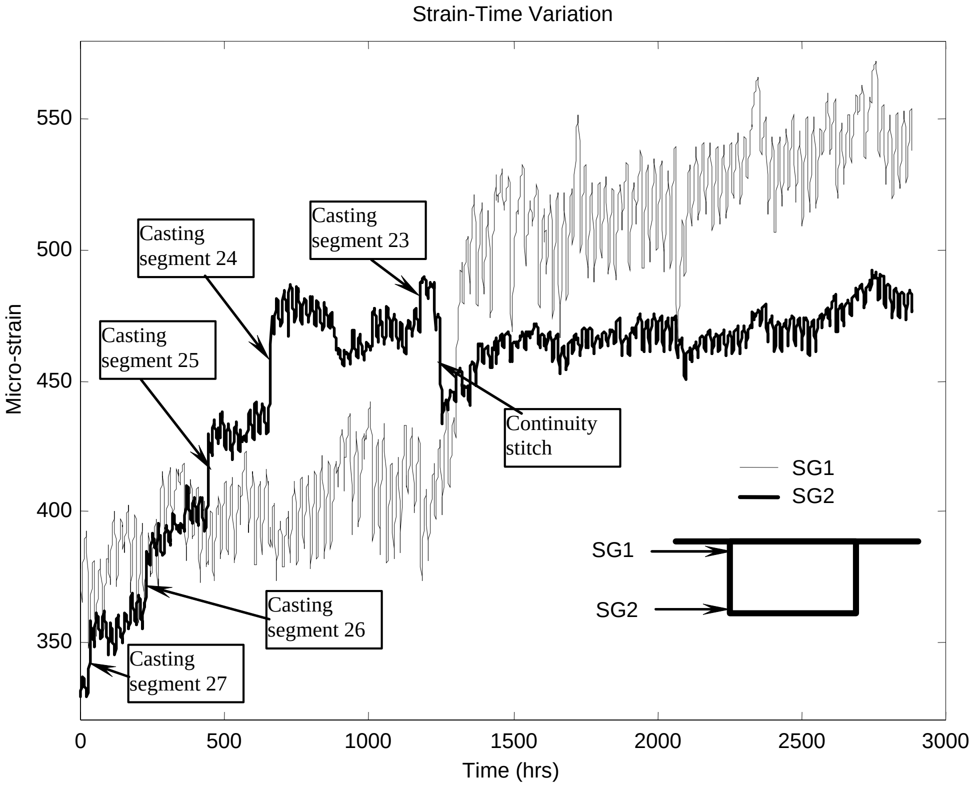


Figure 6 Wavelet decomposition of strain data (Abbreviations: C – concreting, T – cable tensioning, F – shifting of concreting form, e.g. T26 – tensioning of cables in segment 26).

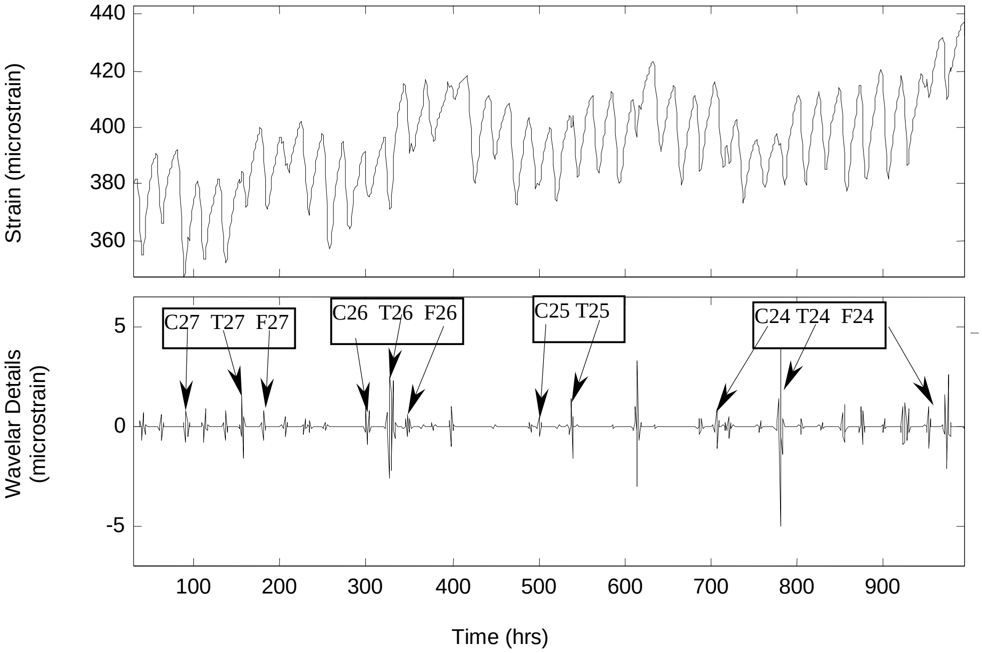
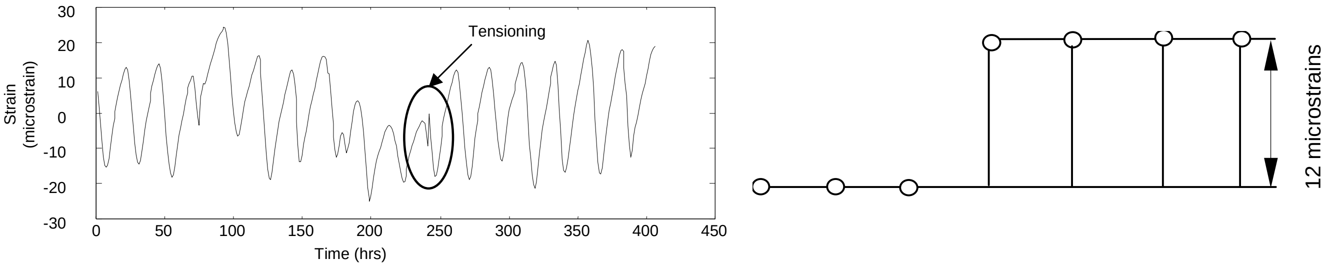


Figure 7 Intervention analysis of a cable tensioning event: a) strain time series, b) impact of tensioning on strain time series.



a)

b)

Figure 8 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).

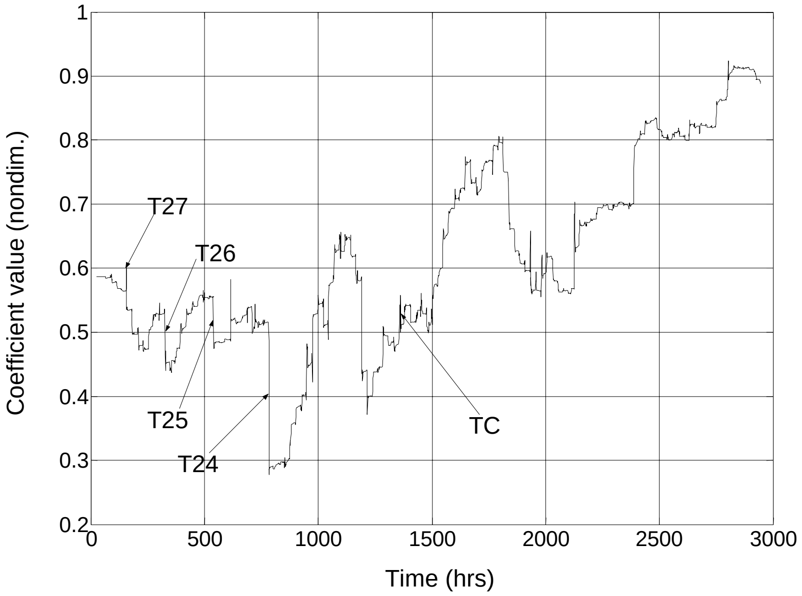


Figure 9 Pioneer Bridge

Figure 10: Bridge monitoring system

(b) Demountable strain gauge

(b) Data acquisition system

Figure 11: Typical strain record

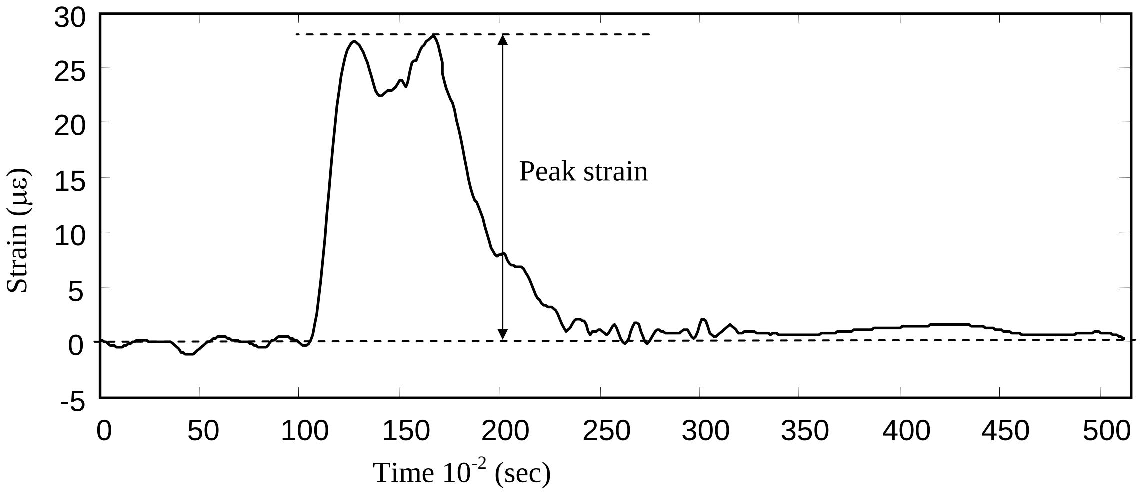
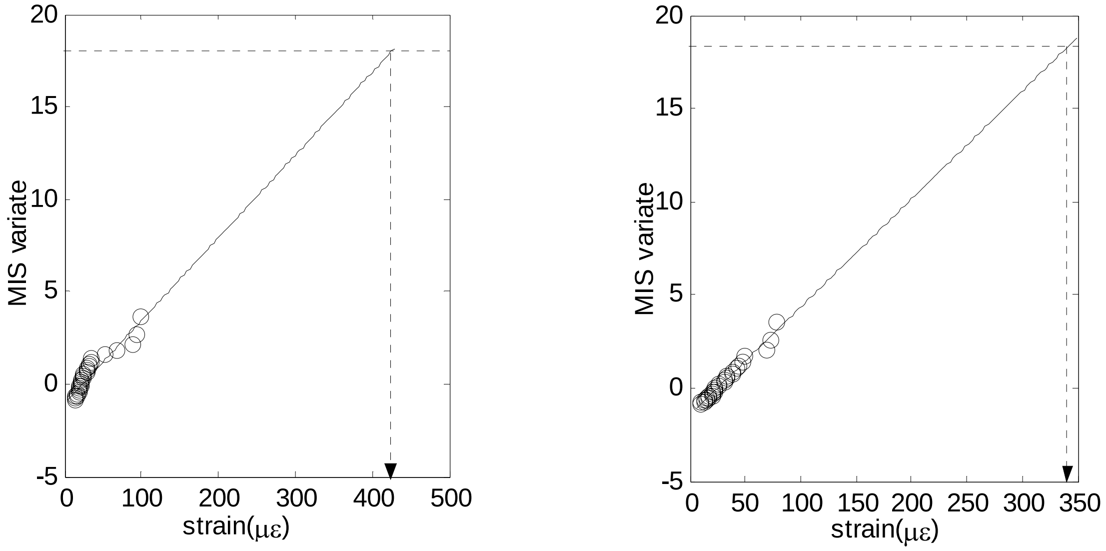


Figure 12: Extreme value statistics for a selected location using method of independent storms (MIS)



(a) 120 year strains before bridge upgrading. (b) 120 year strains after bridge upgrading

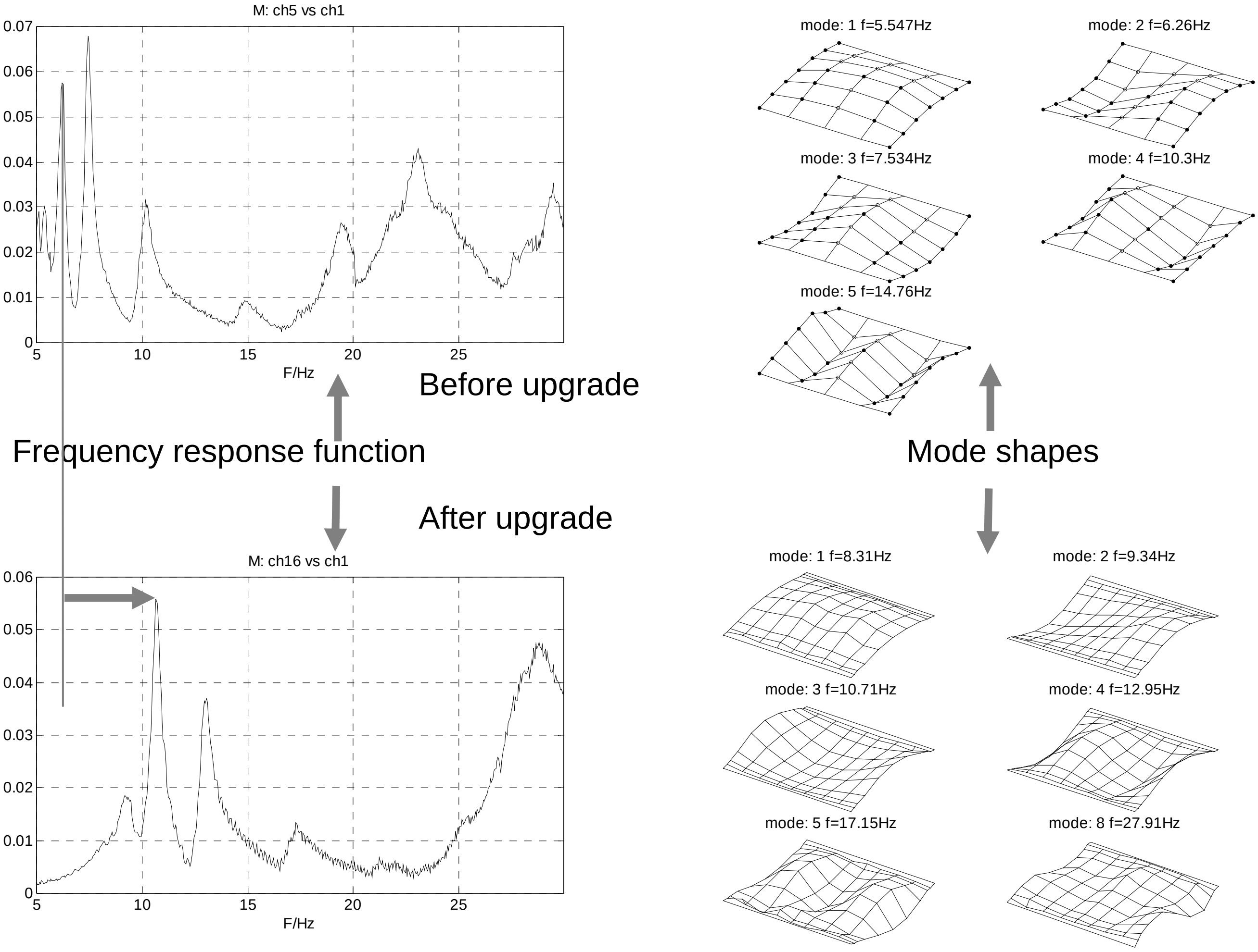


Figure 13 Pioneer Bridge FRF and mode shapes before and after upgrade showing increase in stiffness and damping capacity. Sequences of mode shapes correspond before and after upgrade

Figure **14** Jumping to excite vibration of balanced cantilever

Figure **15** Fundamental vibration mode for cantilever

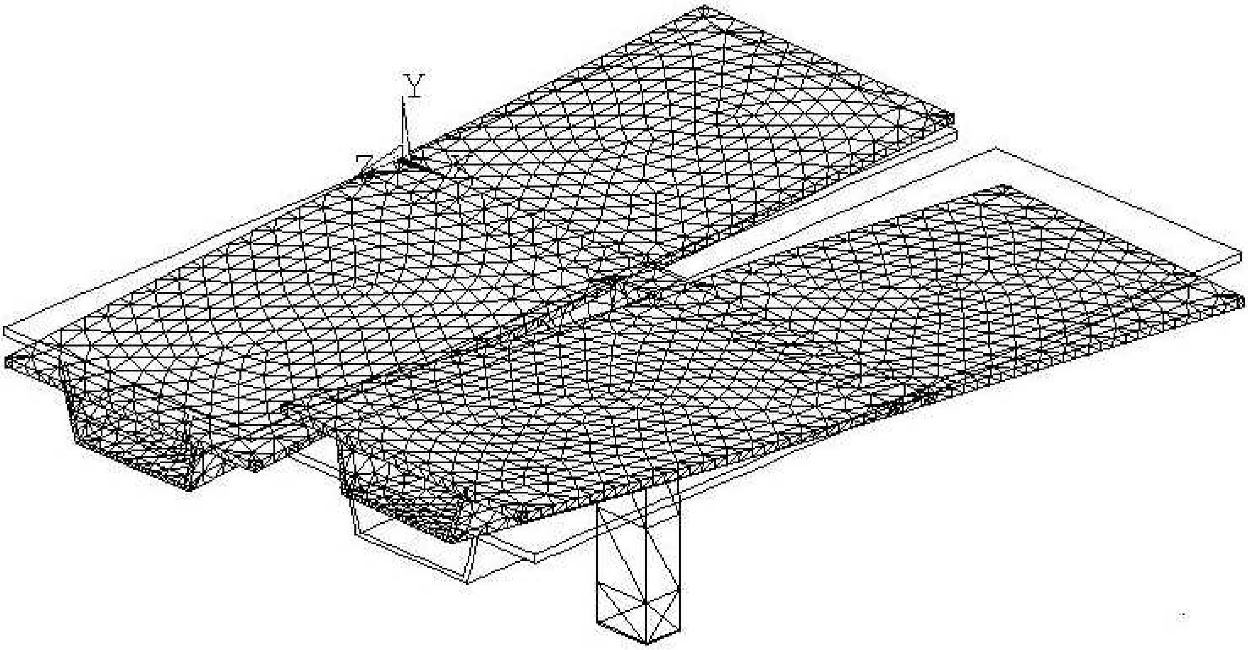


Figure 16 Correlation of experimental (dotted) and analytical vibration modes for balanced cantilever

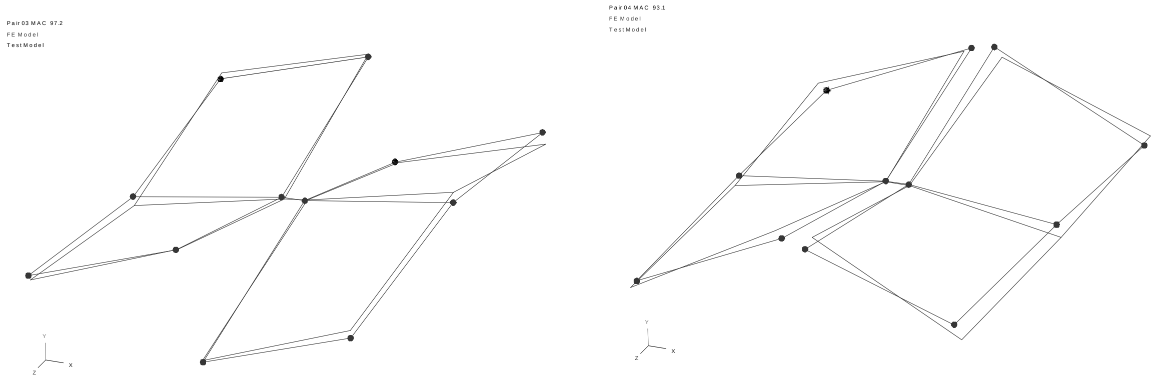


Figure 17 Extrusion of FE model to complete ‘bridge’