A Structural Health Monitoring Paradigm for Civil Infrastructure

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Key words: bridge strain monitoring data mining

SUMMARY

The two technologies of wireless internet access and fibre optic sensors are believed to be central to future developments in sensing and data management for structural health monitoring of civil infrastructure. At the same time, IT and data mining processes are being developed to provide users with the kind of knowledge required for decision making in infrastructure management. The paper presents an ongoing program in Singapore in which an expressway viaduct has been instrumented using conventional static sensors as well as FBG arrays and data are managed by wireless and internet. Future aims of combining data mining algorithms with simulations using a dynamically validated finite element model will also be described.

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1. INTRODUCTION

Structural health monitoring (SHM) is a major and fast growing research discipline that is attracting increasing interest from research funding bodies and government agencies concerned with maintenance and safety of civil infrastructure such as buildings, bridges dams and tunnels. SHM has evolved from structural monitoring to go far beyond data collection and limited processing to include the dumb or smart sensors, the local data storage and transmission systems, central data management systems, local (embedded) or central data analysis, reporting and alerting, diagnosis with respect to structural knowledge and prognosis on future performance.

SHM also involves more than the conventional, and rather limiting, vision of damage detection. Ross and Matthews and Mita identified the cases and motives for structural (health) monitoring:

- Validating modifications to an existing structure
- Assessing safety and performance of structures affected by external works
- Tracking long term movement or degradation of materials in critical structures
- Providing a feedback loop to design
- Assessing fatigue life
- Checking novel systems of construction and new structural forms
- Assessing of post-earthquake structural integrity
- Enhancing effectiveness of resources as construction declines and maintenance needs increase
- Catering for the move towards performance-based design philosophy

Historically, monitoring of structures by their care-takers has involved all the ingredients of the modern SHM paradigm such as long-term observation of sensor data, extraction of damage sensitive features and statistical analysis to assess structural health. At the simplest level, recurrent qualitative visual observation of crack opening, concrete spalling and structural deformations constitute SHM, yet the aim of present day research is to identify the simplest and most reliable means of acquiring, managing, integrating and interpreting reliable structural performance data for maximum useful information at minimum cost. It is an optimisation problem whose solution is gradually evolving. Historical developments in SHM have generally focused on subsets of the problem but in recent years a few research teams have begun to focus on or at least recognize the need for a holistic approach to optimization of SHM.

SHM should not be equated to ‘condition assessment’ (CA) which is a one-off but comprehensive identification of the structural system that is in the authors view a prerequisite for an effective SHM system and may be triggered by the SHM system. In extreme cases CA can involve damage detection, localisation and quantisation but for civil infrastructure it is usually accepted that except for certain types of damage SHM is not optimised for this level of detail. Present aims are less optimistic and focus on providing reliable and timely indication of a progressive or novel structural fault along with limited diagnostic information. The follow up investigation (CA) triggered by the SHM system will be supported by evidence it provides, but will be a detailed investigation that may include localized short-term monitoring and inspection and possibly dynamic testing.

Because of the uniqueness of each structure, the practical impossibility of establishing baselines e.g. by structural analysis in advance of the monitoring program and the hostility of the environment, it is arguable that the greatest challenges for SHM are apparent in the civil/structural engineering community. On the other hand infrastructure SHM research stands to benefit greatly by technology transfer from electrical and mechanical disciplines, for example in areas of sensor technology, communications, data management and data mining. Meanwhile the motivation increases with the need to maintain aging infrastructure created in boom years. It is a fertile area for academic research where inter-disciplinary and collaborative projects with practical applications and industrial or agency support are actively encouraged.

This paper presents some experiences in a number of real world applications of SHM and distills the lessons into a model or paradigm of what the authors believe is the way forward for an efficient optimised SHM system making appropriate use of the latest proven technology.

Application of GPS and acceleration monitoring in a tall building is described in a separate paper in the proceedings, so this paper describes exercises in SHM of two bridges and a number of tunnels and also CA of a bridge, all in Singapore.

2. SECOND LINK BRIDGE: LONG TERM PERFORMANCE MONITORING

A monitoring program to study performance of glued segmental box-girder bridges was conducted in the UK in the 1980s with the primary aim of establishing the structural effects of temperature variation along with the long term strain history, and employing to good effect embedded instrumentation in the form of vibrating wire strain gauges (VWGs). An opportunity was provided by the consulting engineer for the second Link between Singapore and Malaysia, shown under construction in Fig. 1, to influence the tender specification for instrumentation. A sum of S$100k was available and based on the UK program, a similar instrumentation scheme was designed for and installed with the aim to provide long-term stress, strain and temperature performance data. Hence the system began life as a conventional monitoring system.

An addition to the UK system was static pressure cells, previously used in monitoring of tunnel linings. The arrangement of installed instruments in a segment comprises 12 vibrating wire strain gauges, 12 vibrating wire stress cells, thermistors accompanying each of these and also laid out in vertical arrays selected webs all supplying a network of loggers managed accessible remotely via modem.

Strain, stress and temperature data have been recorded at hourly intervals from 1997 (but not continuously) until early 2004 when the system was switched off, and was used for developing procedures for anomaly detection. 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 that have analogs in post-construction activity.

One fundamental problem in SHM is that of data normalization under a range of environmental or ambient loads or noise sources that affect the measured signals, and it is necessary to compensate for or filter out these effects. Such filtering may be possible given establishment of load-effect relationships, but it is their non-stationarity that may signal an altered structural state for example by variation in terms of an ARMA model, or detection of outliers from the established pattern of response.

A load-effect relationship implies that some form of structural model is available. In the case of Second Link, no such model is available and an 'output-only' ARMA type model is used in the following procedure.

Raw strain data, shown in Fig. 2, are filtered into high and low frequency components using the Daubechies D4 discrete wavelet transform (DWT). The highest frequency component, called D1, is retained as a series of time varying coefficients and conveniently indicates discontinuities in the original time series, as shown in Fig. 3 with certain events representing construction events as segments are cantilevered out in sequence from the pier beyond segment 31. Wavelet coefficients are further processed by forming a vector ARMA model of multiple channels to represent the time series. A best fit AR(2) system model is then obtained and the more permanent innovative outliers (IOs) and transient or additive outliers (AOs) with respect to this system examined. As the data are multi-channel, it is possible to collapse the signals using variations of principal analysis to highlight outliers consistent among the channels and differentiate effects on different parts of the structure.

This procedure serves to identify occurrences of anomalous behaviour potentially useful to the bridge operators. Having identified anomalies, intervention analysis uses a Box-Jenkins model (similar to ARMAX) on original strain time series in the region of the identified anomaly to quantify and qualify the change in the strain pattern, for example, Fig. 4 shows a tensioning event characterized by a jump shift in level of response. Recent developments include vector ARIMA models incorporating Kalman filters, and will be developed into ARIMAX models to attempt to model effects of external inputs, specifically temperature.

By combination of the above procedures and past observations, anomalous events can be identified and characterized without any knowledge of the structure.

3. 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 the Land Transport Authority of Singapore (LTA) is in the midst of a major program of upgrades on existing bridges to sustain higher axle loads.

LTA now includes a provision for structural monitoring in the 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 evolving, and research has been conducted to identify a rational procedure for assessing the success of the upgrade, based on a published procedure.

The proposed approach has been demonstrated on Pioneer Bridge (Fig. 5), 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.

A multi-stage approach was used to assess the upgrade. First, a bridge health monitor 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.

The validated finite element model was used to estimate the dead load strains in the concrete and the monitoring was used to estimate the peak live strains for a given return period using statistical analysis of extreme events. 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; Fig. 6 shows the change in live loading extreme values by Gumbel analysis using the method of independent storms.

The health monitor system is simple to use to identify any improvement in performance. While the more elaborate modal survey and model updating procedures are not likely to be used in all upgrade exercises, simplified forms of testing that can show an improvement in fundamental frequency could be used to show improvements in stiffness.

4. TUNNEL MONITORING

In cities with operating tunnel networks, the construction works near these tunnels require real time continuous tunnel monitoring systems. These systems provide important data immediately for decision making, and send out alerts if the tunnel movements exceed the allowable design limits. A fully automated measuring system with real-time data communication system will provide simultaneously immediate reliable information to the relevant contractors, consultants and authorities. Provision of such data in real time is vital to provide adequate warning of possible of anomalous behaviour. Innovative technologies of smart remote telemetry units (RTUs), wire-less communications and SMS alerts are now being introduced for automated tunnel monitoring systems. With these enhancements, the measured data are automatically analyzed and SMS alerts sent to appropriate staff for corrective actions.

The Leica Total Station TCA2003 is the key instrument for tunnel XYZ coordinate measurements using prisms mounted along a tunnel. This instrument has been used extensively before and is a proven instrument for such monitoring applications. A fully outdoor-automated wire-less system was developed for monitoring deflections of Changi Airport runway during MRT (mass rapid transit) tunneling in 2000, and recent developments have provided for use in monitoring the MRT tunnels themselves to check for effects of other construction activities. Figs. 7 and 8 show the system; tunnel segments are instrumented with prisms either side (left/right) and at crown and track levels, the total station scans the four prisms for each sequence and records positions.

At the monitoring site, the RTU sends the measured data to the office computer system using a public data network. Telephone lines have been a preferred choice due to reliability and speed advantages but in most MRT tunnels, the costs of cabling additional telephone lines to the temporary monitoring sites are just too high; hence wire-less GSM lines are more cost effective for temporary real time applications such as during external constructions in the vicinity of the tunnel. GSM signal disruptions are site dependent; this signal disruption increases the time to transfer the measured data file as the number of error correction increases within that transmission duration. For some cases, the signal disruption is so high that the GSM signal line is cut off completely (e.g. due to passing train), requiring a GSM line re-connection, hence restarting the file transfer and delaying the file transfer process until complete fault-free transmission of the entire data. An algorithm was specially developed such that only the corrupted data packets are resent.

Some supervisory features are built into system components to achieve higher reliability as outdoor conditions have many unpredictable challenges when the system suitable for indoor moves to the real outdoor conditions including automatic system reset in case data loss.

For one direction of tunnel, there are 24 (segments) x 4 (prisms) reference measurement points and 204 (segments) x 4 (prisms) monitoring points being measured three times per day. The measured data file size is 95 Kbytes per measurement cycle. During each measurement cycle, the prism XYZ positions for each of the four prisms on each segment are measured and then corrected with the reference prisms. Only the X and Z-axes movements are of major interest. For each of the three daily measurement cycles, the 2,736 data points are analyzed automatically within 3 minutes and if any of the points exceed their limits, the user is sent an SMS alert within 1 minute. The process of analyzing the measured data and users receiving the SMS alerts is achieved within 4 minutes.

Until now, individual data points have been tracked, but this can lead to false alarms which can only be avoided by manual cross checks with other prisms and past records.

Development of the system will combine the data points into a 3-dimensional representation of the tunnel deflections such as in Fig. 9 in order to highlight:

- Movements of all 4 prisms on a segment
- Vertical Movements in the Crown and Track for vertical loading
- Horizontal Movements in the Left and Right for horizontal loading across-segments
- Movements in the prisms along the same axes in tunnel

Following recent high profile failures in Singapore such as collapse of temporary works for a new MRT tunnel in Singapore causing collapse of a busy highway and death of a number of workers, and also differential settlement of a tall building in the central business district, there has been an increase demand for instrumentation and monitoring of movement of structures and foundations. The ability to provide instant alert of impending disaster by tracking trends in such data are self-evident and have attracted attention for construction and infocom authorities in Singapore.

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

A number of immediate lessons have been learnt from the previous exercises. First, the Tuas exercise showed that vibrating wire gauges are reliable and proven instruments for providing long-term information about the global structural state and that a great deal can be learnt from 'output only' static response data. A separate logger was available for logging acceleration response at Tuas but did not interface well with the total logging system and was not used systematically. Also, without a reliable structural model of the bridge it was not possible to interpret performance data in direct structural terms. Second, the Pioneer exercise showed that dynamic assessment (with or without controlled excitation) that used measured modal parameters to adjust systematically a finite element model was a very valuable tool leading to deep structural knowledge about the bridge, in this case the load capacity, via additional short-term live-load monitoring. Last, the Tunnel monitoring exercise showed the potential of real-time monitoring using public data networks and highlighted the need for intelligent and real-time interpretation of data via some form of physical and/or geometric model to reduce data to reliable information about the deformation of the tunnel.

Some of these lessons have been taken on board in designing a monitoring system for a major elevated expressway in southern Singapore. The original aim was to install a limited number of VWGs in the same manner as in Tuas, to embed fiber Bragg gratings (FBGs) in parallel and transverse across the span and to obtain dynamic response data from FBG arrays arranged longitudinally on the soffit of the box deck interior. Collected data would be periodically sent by wireless to a central server and e-mailed to the user for interpretation. To aid the interpretation, dynamic assessment exercises would be carried out on span segments before and after construction to validate and fine-tune finite element models for performance diagnosis.

PPSE (Fig. 10) is an extended viaduct of twin box decks supported on single central pylons above an existing main road. The viaduct will carry heavy goods vehicle traffic between two major container terminals and is arranged in 'bridges' of five spans (normally) between expansion joints, and spans range from 20m-46m. Box decks are 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, PPSE constructions has slowed and some of the instrumented spans have been connected, with no confirmed date for completion and opening. The aim of the monitoring program has been to develop a system that will track the performance of complete by instrumenting one span at two segments together with the adjacent pier.

Ten segments and adjacent piers have been instrumented in this way. Instrument cables from two segments and pier per span 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. Data are manually spliced into a database for visualisation and interpretation, which so far shows patterns of the data so far similar to those observed at Tuas, with diurnal variations and 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 was possible to excite lower frequency vibration modes by timed jumping (to excite specific modes, Fig. 11) or single jumps (to excite a range of modes). This approach worked very well for unconnected balanced cantilever portions, while ambient response due to wind and construction activity was more appropriate for a complete and relatively massive ’bridge’.

The approach adopted for FE modeling was to create a model of a balanced cantilever arrangement of a pier, hammerhead, and four semi-spans (looking like H in plan) and to progress to more detail with a complete multi-span bridge. The correspondence between experiment and analysis is illustrated in Fig. 12 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.

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. Fig. 13 shows one mode from the extruded full bridge model, which was validated by an experimental exercise using ambient vibration response.

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.

Our approach to SHM focuses on quasi-static response data which are generated in manageable quantities, and, where appropriate to capture extrem events of acceleration or strain which can be expanded (up to a point) to the whole structure via normal mode analysis based on the validated modal model, while frequency and damping values that are often used as features sensitive to damage or detorioration can be recovered from the time series. Hence arrays of accelerometers are not strictly necessary with linear behaviour as the complete dynamic performance can be reconstructed from mode shapes and modal amplitudes, but there are potential benefits in tracking changes in quasi-static and modal deflections via distributed sensors, for which fibre Bragg grating (FBG) strain sensors seem to be ideally suited. As they fulfill the role of both conventional static gauges and accelerometers, their ability for spatial multiplexing and their immunity to wet and hostile environments supports furtehr developments in their application to SHM. For PPSE, two arrays of 11 FBG sensors have been attached to the inside box soffit. A ruggedised logger will capture the light spectrum around the FBG frequencies, and local processor communicating via USB will identify the peaks in the reflected light spectrum to track strain changes dynamically. Due to construction delays this system has not yet been used 'in anger'.

6. CONCLUSION

A number of SHM exercises on major infrastructure projects in Singapore have been reported here and some observations presented. From experience we have the following comments:

- Acceleration data are not universally useful and need to be treated as just another signal, albeit one generating potentially unmanageable quantities of data that need to be compressed into parametric form (e.g. AR coefficients, frequency and amplitude values). We have found great value in interpreting static data even on their own.

- Deep diagnosis of performance anomalies requires either observed similarity with past events of known cause or a validated analytical model, the latter being the result of a dynamic testing and model updating exercise with varying levels of detail and complexity.

- Infrastructure managers require information, not data, pushing the onus onto SHM system designers to incorporate data mining and diagnosis procedures together with a well-designed graphical interface.

- Real-time alerting of anaomalous structural performance (routine in many safety-critical facilities like nuclear reactors or dams) is increasingly available via portable wireless systems using public data networks. Smart diagnosis algorithms can work in background to augment simple threshold-crossing alarms.

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BIOGRAPHICAL NOTES

Professor Brownjohn begun his acadmic career at Bristol University in 1984, working on systems for operating and managing data from the EPSRC earthquake simulator and managing full-scale vibrtion survey and health monitoring exercise on several dams and suspension bridges around the world. Moving to Singapore in 1992 he developed monitoring systems for three large structures and conducted full-scale static and dynamic performance assessment studies on a large range of civil structures. He returned to a chair in structural engineering at Plymouth in February 2004. He is member of Insitutions of Mechanical and Structural Engineers and has published widely on a range of topics related to full-scale structural performance.

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Figure 1: Tuas Second Link bridge under construction

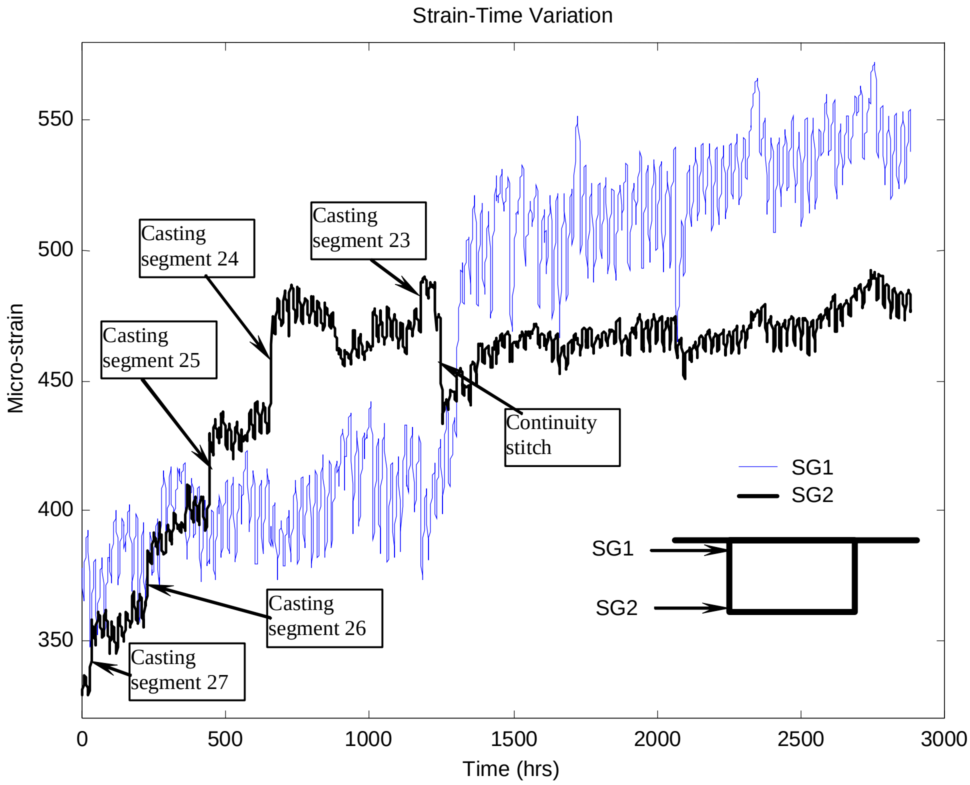

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Figure 2: Strain variation in segment 31 during construction.

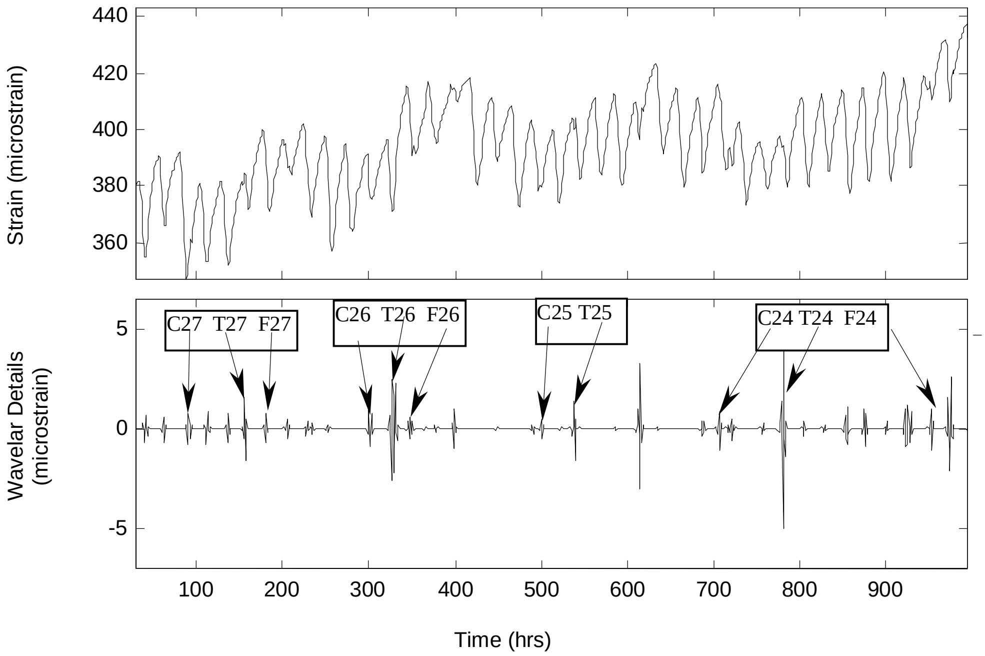

Figure 3: Wavelet decomposition of strain data. C – concreting, T – cable tensioning, F – shifting of concreting form, e.g. T26 – tensioning of cables in segment 26.

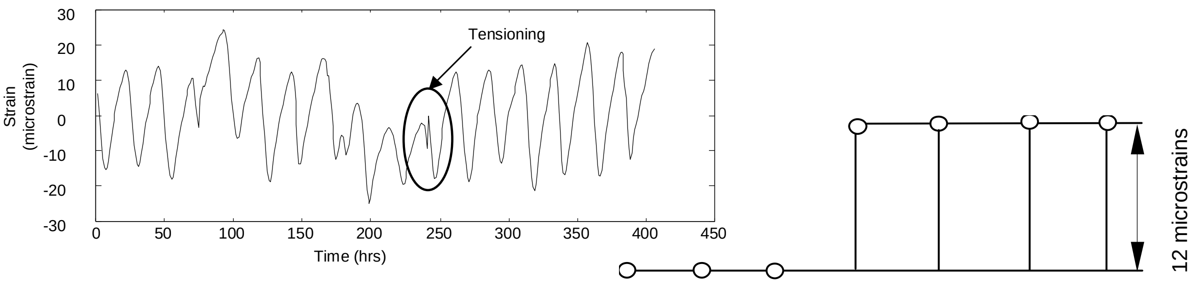

Figure 4: Intervention analysis of a cable tensioning event: strain time series (left), impact of tensioning on strain time series (right).

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Figure 5: Pioneer Bridge

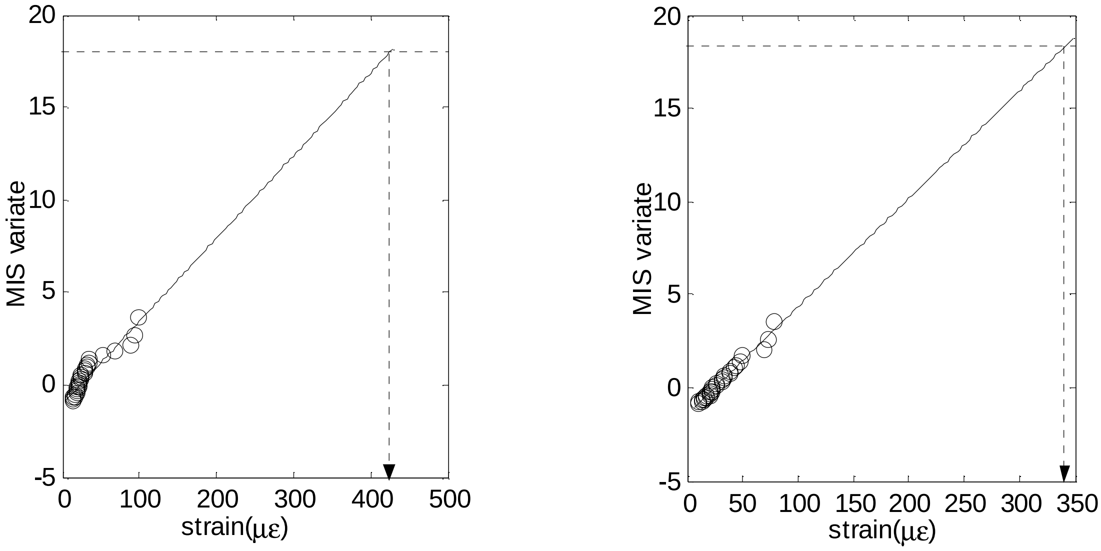

Figure 6: Extreme value statistics for a selected location using method of independent storms
left: 120 year strains before upgrading right: 120 year strains after upgrading

Figure 7: Total station and reflectors in MRT tunnel

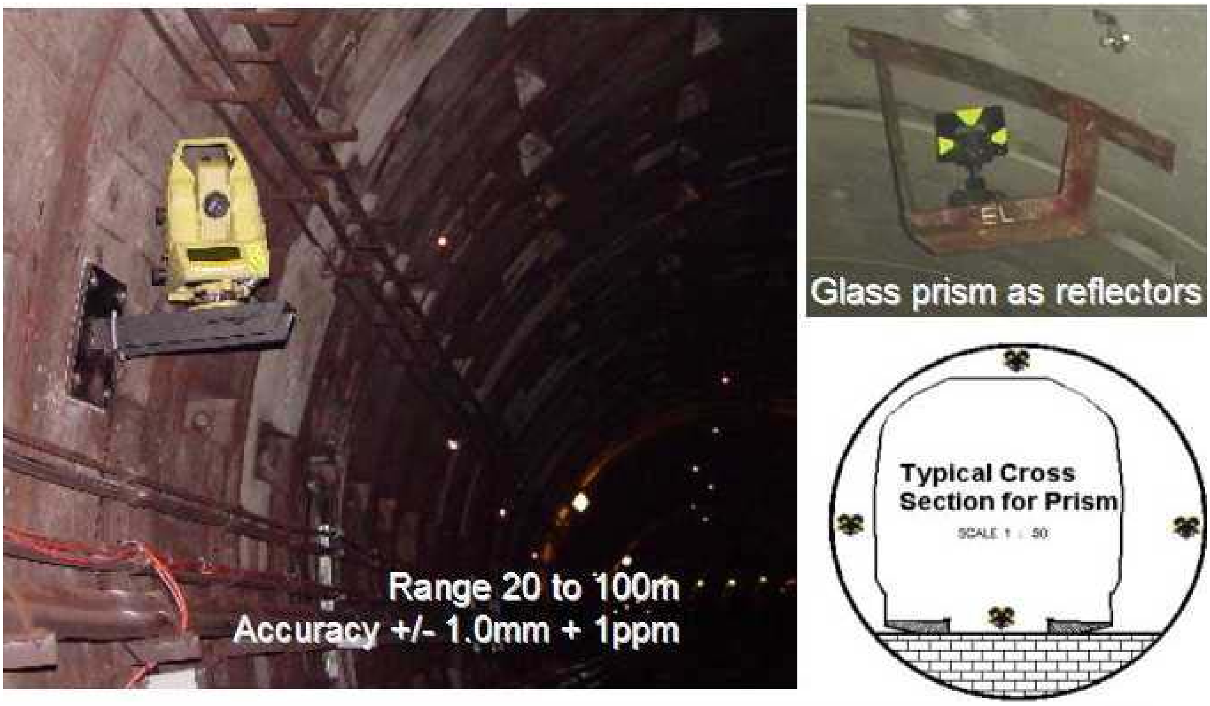

Figure 8:Wireless tunnel monitoring m

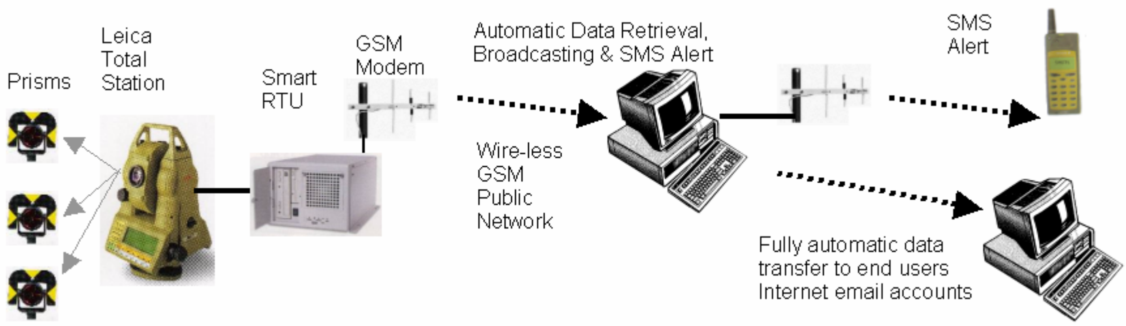

Figure 9: Snapshot of tunnel deformation

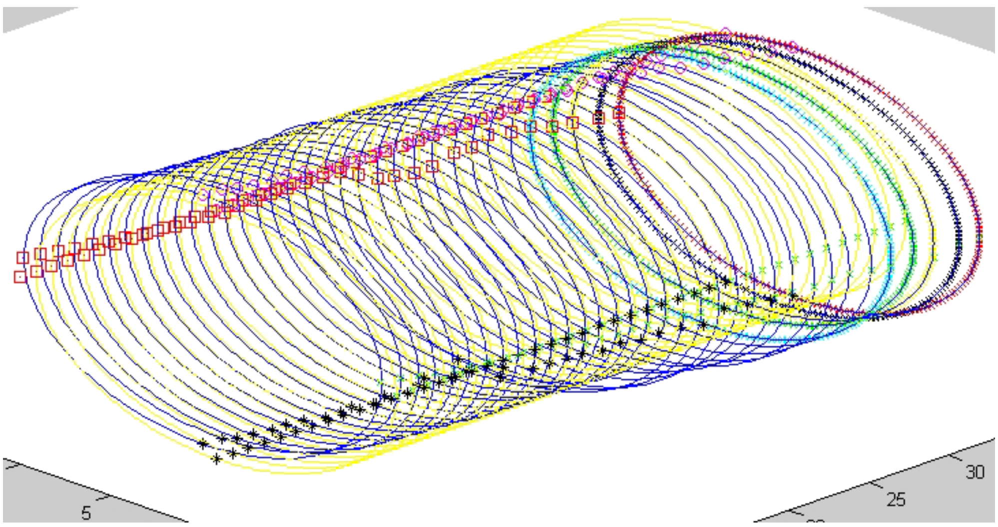

Figure 10: Pasir Panjang Semi-expressway under construction

Figure 11 Forced vibration testing to validate FEM of balanced cantilever

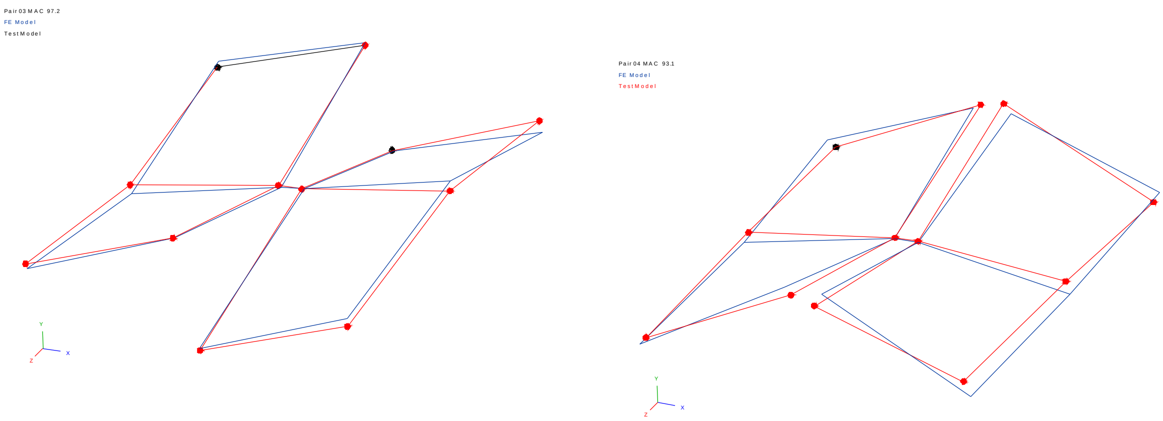

Figure 12: Correlation of experimental (dotted) and analytical vibration modes for balanced cantilever

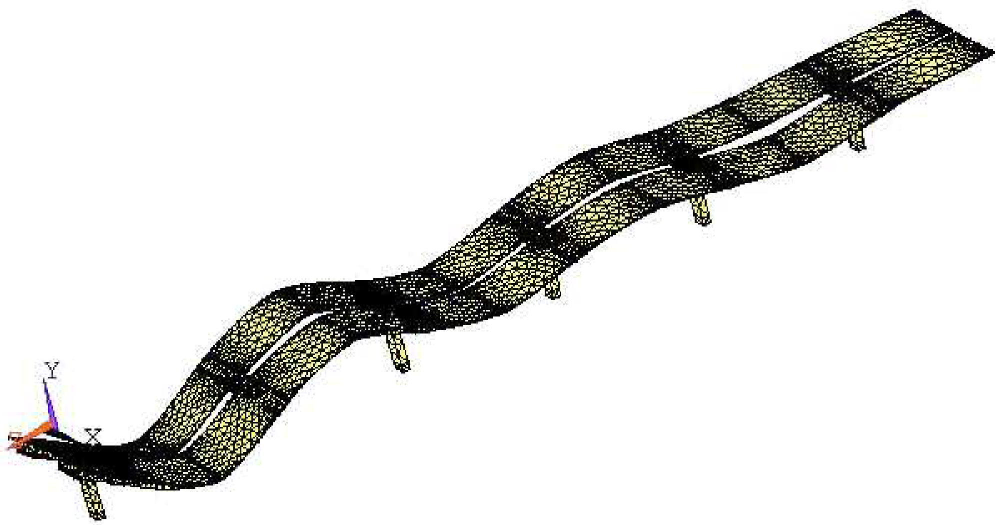

Figure 13: Extrapolation of validated FE model to complete 'bridge'