Structural Health Monitoring of Civil Infrastructure

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Abstract/Summary

Structural Health Monitoring (SHM) is a term increasingly used in the last decade to describe a range of systems implemented on full-scale civil infrastructures and whose purposes are to assist and inform operators about continued ‘fitness for purpose’ of structures under gradual or sudden changes to their state, to learn about either or both of the load and response mechanisms. Arguably, forms of SHM have been employed in civil infrastructure for at least half a century, but it is only in the last decade or two that computer-based systems are being designed for the purpose of assisting owners/operators of aging infrastructure with timely information for their continued safe and economic operation.

This paper describes the motivations for and recent history of SHM applications to various forms of civil infrastructure and provides case studies on specific types of structure. It ends with a discussion of the present state of the art and future developments in terms of instrumentation, data acquisition, communication systems and data mining and presentation procedures for diagnosis of infrastructural ‘health’.

Keywords:
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1 Introduction

Civil infrastructure provides the means for a society to function and includes buildings, pedestrian and vehicular bridges, tunnels, factories, conventional and nuclear power plants, offshore petroleum installations, heritage structures, port facilities and geotechnical structures such as foundations and excavations.

Depending on importance, ownership, use, risk and hazard, such structures have inspection, monitoring and maintenance programs which may even by mandated by law. The effectiveness of maintenance and inspection programs is only as good as their timely ability to reveal problematic performance, hence the move to supplement limited and intermittent inspection procedures by continuous, on-line, real-time and automated systems.

Major drivers in this area have been the oil industry, operators of large dams and highways agencies whose installations have received the greatest attention and research effort. Residential and commercial structures have received relatively little attention due to potential obligations and consequences of owners knowing about poor structural health. In these cases SHM can only be implemented after efforts have been made to educate owners or to coerce them via building control protocols (legislation) or insurance premiums (Chang, 1999).

A significant challenge in developing a SHM strategy for civil infrastructure is that except for certain types of public and private housing, every structure is unique. This means that there is no baseline derived from type-testing or the expensive qualification procedures applicable for aerospace structures. Hence a unique feature of SHM for civil infrastructure is that a major part of the system has to be geared towards a long term evaluation of what is ‘normal’ structural performance or ‘health’, the two terms being synonymous (Aktan et al., 2001).

2 Fundamental objectives of civil infrastructure monitoring

Ross and Matthews (1995a) and Mita (1999) identified the cases where structural monitoring may be required:

1. Modifications to an existing structure
2. Monitoring of structures affected by external works
3. Monitoring during demolition
4. Structures subject to long term movement or degradation of materials
5. Feedback loop to improve future design based on experience
6. Fatigue assessment
7. Novel systems of construction
8. Assessment of post-earthquake structural integrity
9. Decline in construction and growth in maintenance needs
10. The move towards performance-based design philosophy

Historically, monitoring of structures has involved many of the ingredients of the modern SHM paradigm such as data collection and processing followed by diagnosis. At the simplest level, recurrent visual observation and assessment of structural condition (cracking, spalling, deformations) could be viewed as SHM yet the aim of present day research is to develop effective and reliable means of acquiring, managing, integrating and interpreting structural performance data for maximum useful information at minimum cost while either removing or supplementing the qualitative human element. Historical developments in SHM have generally focused on subsets of the SHM paradigm but in recent years a few research teams have begun to focus on or at least recognize (Fanelli, 1992) the need for a holistic approach to optimization of SHM.

At its core, SHM is a continuous system identification of a physical or parametric model of the structure using time dependent data. The signals used in SHM derive not only from vibrations but also from slowly changing quasi-static effects such as diurnal thermal cycles. Once a baseline system model is identified, SHM procedures are aimed to identify occurrences when output signals do not correspond to predictions based on the established form.

One of the many sub-disciplines within SHM is ‘condition assessment’ (CA), a one-off but thorough identification of the structural system. SHM should be capable of carrying out a minimal level of CA in real time but it is more likely that a follow up investigation (CA) would be triggered by the SHM system and supported by evidence it provides.

In the short term, developments of SHM for civil infrastructure may not be expected to have an inherent capability for damage location and quantification and, while many research teams are progressing in this area, it is still not a reality to recover reliable component level structural information in real time by system identification. Despite the body of research dedicated to vibration based damage detection (VBDD) (Doebling et al., 1996), success is limited to simulations, laboratory studies and well controlled experiments such as the Z24 bridge (Maeck et al., 2001), and its effectiveness still remains to be proven for operational civil structures.

Hence short term aims are less optimistic and focus on automatic provision of reliable and timely indication of a progressive or novel structural fault along with limited diagnostic information.

3 History and motives for development of SHM in 20th Century

Significant developments in SHM have originated from major construction projects such as large dams, long span cable-supported bridges and offshore gas/oil production installations. The term SHM is a recent 'standard' that has evolved from activities formerly known as structural monitoring, structural integrity monitoring or just monitoring. It is impossible to identify the first form of SHM, but discounting simple periodic visual observation, formal structural monitoring and interpretation using recording instruments began in the latter half of the last century and accelerated with the use of electronic data storage and computer data acquisition. So much recent attention in the civil SHM community has focused on bridges that it has overshadowed the formal application of SHM technology to other infrastructure such as dams (Ross and Matthews, 1995b) that has been a legal requirement in the UK at least for several decades.

3.1 Dams

Legislation mandating regular inspection of dams originated in the UK due to the failure in 1864 of a 30m embankment dam that claimed the lives of 254 people near Sheffield, UK. The most recent form of legislation in the UK is the Reservoir Act of 1975 which gives a Supervising Engineer (DETR, 2001) the responsibility for continual surveillance of a reservoir and dam, including keeping and interpretation of operational data. Thus dams are historically the first class of structure for mandated application of SHM and there should be much to learn from the experience that can be applied to other structures.

In the dam engineering community, SHM is equivalent to surveillance, and a good idea of what this entails is described for example by ANCOLD (1994) and in more detail with respect to formalized monitoring by the International Commission on Large Dams ICOLD (2000). Many of the elements of the modern SHM paradigm are in place:

1. A range of instrumentation optimized to provide safety-critical response data, supplemented by visual inspections
2. Automated data collection
3. Intelligent interpretation of data against established behaviour patterns and identification of anomalies

In the UK Item 3 is typically the role of the Supervising Engineer while research in artificial intelligence (AI) applications for this role have been spearheaded by the ISMES, the research arm of the Italian electricity utility ENEL. The extent of the ENEL dam monitoring program reported by Fanelli (1992) is worth summarizing as it embodies much of the technology being investigated for other structures.

Every major dam in the ENEL inventory of over 260 structures is equipped with transducers activated by central processor at regular intervals to measure static 'structural effects' such as:

- Relative or absolute displacements: horizontal crest displacements are most important for concrete dams
- Strains (for concrete dams) with temperature correction
- Uplift pressures quantifying loads which, for example contributed to the failure of Malpasset Dam in 1959
- Seepage rates

Transducers are also activated to record ‘external influences’ to which the dam responds with ‘structural effects’ e.g.

- Water level
- Structural temperature
- Meteorological conditions

The variations of structural effects are evaluated for acceptability in the light of the environmental variations. This is the judgment that requires deep knowledge of the dam and its structural behaviour. Traditionally this is the role of a Supervising Engineer, but this has been taken over by developments of the monitoring system. Salvaneschi et al. (1996) reported that the commercial implementation of the information system under the name of MIDAS had, beginning from 1985, been managing data of 200 dams in ten different countries.

Recognising the limitations of such a system, ENEL foresaw the need to integrate the formalized tools such as MIDAS with the non-formal information from historical observations and engineering judgment. Development of two AI applications, DAMSAFE and MISTRAL is also described by Salvaneschi et al. (1996). MISTRAL is a real-time system that considers groups of effects with or without relation to influences. In the former case physics-based or statistical models are used for comparison and identifying anomalies, whereas in the latter case it is still possible to identify anomalous behaviour. DAMSAFE (Comerford et al., 1992) is aimed at assisting engineers with dam safety management procedures. It works off-line and functions more like an ‘expert system’ incorporating past experiences into its knowledge base. This line of research has now largely disappeared from public view, but is being developed in other countries for bridges and dams (Wu and Su, 2003).

Dynamic response monitoring plays a part in dam SHM for two reasons. Firstly, earthquakes are a serious threat to safety of dams and every opportunity is taken to improve understanding of seismic dam performance specifically and generically (Severn et al., 1981) through calibration of models and simulations. Secondly, estimates of dynamic characteristics obtained from ambient monitoring (Darbre and Proulx, 2002) or deliberate forced vibration (Bettinali et al., 1990) provide a means to track the structural characteristics as indicators of structural health.

3.2 Bridges

Bridge monitoring programs have historically been implemented for the purpose of understanding end eventually calibrating models of the load-structure-response chain (e.g. Leitch et al.; 1987, Barr et al.; 1987, Brownjohn et al.; 1994, Cheung et al.; 1997, Bampton et al.; 1986, Wong, 2003; Catbas et al.; 2000, Macdonald et al.; 1997, Miyata et al.; 2002, Wang et al.; 2003, Koh et al.; 2003, Chung, 2003). One of the earliest documented systematic bridge monitoring exercises, by Carder (1937), was conducted on the Golden Gate and Bay Bridges in San Francisco in an elaborate program of measuring periods of the various components during their construction to learn about the dynamic behaviour and possible consequences of an earthquake.

University of Washington (1954) describe monitoring of the first Tacoma Narrows Bridge over its short life before it collapsed due to wind-induced instability, again focusing on vibration measurements but with an obviously warranted concern for the health of the structure. The Tacoma Narrows experience has far reaching importance since almost all of the long-span suspension bridge monitoring exercises to date have been related to concerns about wind-induced response and possible instability, for example at Humber (Brownjohn et al., 1994) and Deer Isle (Kumarasena et al., 1990). Despite great progress in understanding bluff-body aero-elasticity, there continue to be surprises in long-span bridge aerodynamics (Larsen et al., 2000) and the strategic importance and capital investment justifies the expense of the most elaborate SHM systems applied to civil infrastructure.

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) (Wong, 2003) 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.

Being important lifeline structures, modern long span suspension bridges typically have elaborate inspection and maintenance programs so that significant damage and deterioration of the superstructure is likely to be picked up visually, whereas a SHM system would require a high density of sensors to detect it. It is likely that only global changes such as foundation settlement, bearing failure or major defects such as loss of main cable tension or rupture of deck element are detectable by global SHM procedures with a minimum of optimally located sensors.

Less glamorous but possibly ultimately more beneficial developments of SHM would be for 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 and Jaeger, 1990) and obvious opportunities to extend such approaches to automated monitoring exercises. For smaller bridges global response is more sensitive to defects, visual inspection is less frequent and SHM systems can and do (Alampalli and Fu, 1994) make a real contribution. European research has been focused on the shorter span bridges where the BRIMOS system (Geier and Wenzel, 2002) has been used to track dynamic characteristics. 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 due to such events.

Direct motivation for monitoring is also found within bridge management programs (Yanev, 2003) and bridge upgrading projects, where some form of validation is required, even made the responsibility of the contractor, to ensure the effectiveness of the upgrade. Examples include the Severn and Wye Bridge Refurbishment (Flint and Smith, 1992), Tamar Bridge (List, 2004) in the UK and Pioneer Bridge, Singapore (Brownjohn et al., 2003). In a related sense, the role of monitoring within build, own, operate and transfer contracts can provide investors with confidence in their asses and subsequent owners evidence of good condition at the end of the concession.

3.3 Offshore installations

In the 1970s the energy crisis and discovery of large oil reserves in the North Sea led to rapid developments in offshore infrastructure, specifically the fixed steel and concrete production installations operating in water depths of 150m or more and subjected to extreme environmental loads. With mandatory requirements for inspection (Det Norske Veritas, 1977) and the expense and danger of diver inspection came a flurry of interest in vibration-based diagnostic systems (Coppolino and Rubin, 1980; Kenley and Dodds, 1980; Shahrivar and Bouwkamp, 1980; Brederode et al., 1986). For example environmental and platform performance (E- and P-) data (Spidsoe et al., 1980) were collected, under the responsibility of the platform operator according to the requirements of the Norwegian Petroleum Directorate ...”in order to assess the safety of the load carrying structure of the platforms and their foundation". The studies resulted in identification of dynamic characteristics and load-response mechanisms for a number of installations on the Norwegian continental shelf.

At about the same time a range of system identification techniques for ambient response were developed that were precursors of the modern discipline of 'operational modal analysis' (Peeters and De Roeck, 2001a). Procedures such as maximum entropy method (Campbell and Vandiver, 1980) and random decrement (Yang et al., 1981) were being applied to platform response data to improve the reliability and accuracy of dynamic parameter estimates for the vibration based diagnostics. Most of these studies concluded that while detection was possible it was either under controlled conditions or where severe and usually obvious structural damage had occurred.

The study by Structural Monitoring Limited (now part of Fugro Ltd) (Kenley and Dodds, 1980) went on to state that "techniques will not be developed further unless the offshore industry develops an integrated philosophy covering …inspection, maintenance and monitoring and works with contractors to produce an effective tool". If such effective tools now exist, it is likely that they will be proprietary, not in the public domain.

A particular problem for offshore installations is that the structure is a non-stationary system with continual changes to mass properties through structural modifications, loading or unloading of stores, fluid movements in processing plant and drilling operations. An apocryphal tale tells of a damage detection system being fooled into identifying a failed structural member because a new structural module was added without the system knowing.

3.4 Buildings and towers

Historically, developments in monitoring of buildings were motivated by the need to understand building performance during earthquakes and storms. Originally understanding of low-amplitude dynamic response was obtained from vibration testing (Hudson, 1977; Jeary and Ellis 1981), but it has always been preferable to know the building response during a typical but not ultimate large amplitude loading event and this has required long term monitoring. In California, mandatory structural monitoring is managed by the California Strong Motion Instrumentation Program (CSMIP) (California Geological Survey 2003) which uses levies on building owners to fund installation and operation of strong motion instruments on buildings and other structures of their choosing. While such data can provide some feedback on structural health the aim is to provide information on ground motions and for improvement in structure design based on performance subject to these ground motions. The need to identify full-scale structural performance has always been central to earthquake engineering research.

Hence the majority of monitoring exercises on buildings and towers have been aimed at improving understanding of loading and response mechanisms, not only for earthquakes but for wind loads, for example studies on the Bank of Commerce Building in Toronto (Dalgleish and Rainer, 1978) and Hume Point, London (Littler and Ellis, 1990). In Singapore, studies on high rise apartment blocks have been aimed at assessing wind loads on even taller blocks yet to be built (Balendra et al., 2003) where occupant comfort is a concern.

Significant motivation for SHM of buildings has also resulted from recent major earthquakes such as in Kobe and Northridge, where timely information about the condition of structures would be invaluable in assessing safety and need for repair (Mita, 1999). This is one application where SHM provides the trigger for and then assists condition assessment, and has provided an ideal opportunity for an integrated approach to SHM involving discrete autonomous novel sensors, embedded systems, communications, data management and mining etc. (Kiremidjian and Straser 1998; Lynch 2005).

Evolved out of two decades of experience on full-scale structural testing and monitoring, the approach to SHM advocated by Jeary and co-authors (Jeary at al., 1981, 2001) is a simple and pure approach to the classical SHM paradigm. The success of the approach means that it has been commercialized and details are not in the public domain. In essence the system uses high specification accelerometers and data acquisition equipment and developments of random decrement techniques to track fundamental mode damping along with building tilt. Both these parameters provide indication of structural distress and have been used to diagnose problems in tall buildings in Hong Kong. This rare application of damping for SHM is notable compared to the abundance of less successful techniques based on tracking natural frequencies.

3.5 Nuclear installations

Smith (1996) provides an overview of the inspection and monitoring regime for a sample of the UK's civil nuclear reactors. For the safety-critical structural components of nuclear reactors, instrumentation for measuring structural response is used to validate and calibrate designs during performance testing and also contributes to the condition monitoring during normal operation.

In the UK each civil nuclear power station uses a pair of reactors and all but one of these reactors is either Magnox or AGR (advanced gas cooled reactor), which is a development of Magnox. For all AGRs plus the most recently built pair of Magnox reactors, the critical structural component is the prestressed concrete pressure vessel (PCPV), which contains the reactor core and primary coolant. The PCPV is typically a very thick cylindrical vessel with massive steel reinforcement including redundant helically wound non-grouted post-tensioning cables maintaining the vessel in constant state of compression. As described by installation operators (Smith, 1996; Smith and McCluskey 1997), licenses to operate nuclear reactors are granted by the Nuclear Installations Inspectorate (NII) under the provisions of the Nuclear Installations Act (1965). One of the conditions of granting or renewing such a license is that the licensee shall have proven the performance of the PCPV during testing as well as during any previous operation. It is up to the licensee to demonstrate, within a 'safety case' presented to NII, that the reactor is fit for purpose and capable of meeting its nuclear safety role.

Reactors have 'statutory outages' or programmed shutdowns at three-year intervals for thorough inspections. As a condition for restarting the reactor a report must be submitted to NII by a responsible Appointed Examiner (AE), who has a similar role to the Supervising Engineer for dams and is nominally independent from the licensee and NII. The AE reports on results of inspections and tests during the outage together with structural and other performance data from monitoring during pre-outage operation. This report forms part of the licensee's application to the NII for a consent to restart the reactor.

Obviously the critical and constantly monitored performance parameter is temperature, while the structural performance data, from vibrating wire strain gauges play a lesser role. The primary role of the strain data is by post-processing to assess in-service structural performance and to calibrate and update analytical simulations of the temperature-depended structure performance. Hence it is fair to say, in the UK at least, that on-line monitoring of structural response so far does not play a major role in tracking the health of the PCPV. The potential is there, as the strain data are automatically logged and show clear indications of changes in other operational parameters. The discovery of a 15cm cavity in the pressure vessel head of the Besse-Davis nuclear reactor (Cullen, 2002) may motivate such applications.

3.6 Tunnels and excavations

Tunnel monitoring (Okundi et al., 2003) is aimed at ensuring tunnel deformation is within limits in terms of stability and effects on or from adjacent structures. Hence while stresses and strains may be measured the emphasis is on deflections. Monitoring of heritage and other structures during nearby tunneling or mining is a major concern; examples include the monitoring of Mansion House in London during construction of extension to an underground railway (Price et al., 1994) and monitoring of listed 19th century mining facilities in Australia close to explosive blasting in nearby open cast mining operation (Roberts et al., 2003). These ground surface monitoring exercises are temporary but feature all the technology of permanent monitoring systems.

In Singapore, tunnel deflection monitoring systems (Tan and Chua, 2003) are also required during construction activities taking place at the surface that may affect tunnel alignment and integrity. Surface and tunnel deflection monitoring employ wireless remote monitoring technology for data transmission, with internet access or text messaging to operators indicating threshold crossings of deflection parameters.

Geotechnical constructions stand to derive significant benefits from true SHM systems while offering the simplest situations to study. A recent fatal collapse of tunneling excavations in Singapore in April 2004 highlights this point (Loh, 2004). Post-accident examination of recordings from instrumentation revealed that some movements in the excavation wall had been detected two months before the accident and had exceeded trigger levels. Such relatively slow and monotonic movements and any acceleration in the movement could most likely have been identified easily and reliably by limited online processing with resulting automated alarm. This incident has accelerated the applications of wireless automated monitoring in Singapore.

SHM technology has also been applied to landslide monitoring, for example Reid & LaHusen (1998) used telemetry to monitored the Clevelend Corral landslide for five years, and Civera et al. (2003) developed MEMS inclinometers communicating by wireless to provide warning of ground movements around quarry excavations.

4 Case studies of SHM

The following examples represent the author's experience in structural monitoring and span the range of motivation for the monitoring defined by Ross and Matthews (1995a). They highlight the relevance and limitations of monitoring and illustrate the application of the latest technology.

In the first study, a major suspension bridge was monitored because of the novelty of the structure (the world's longest span) and for feedback to the design for a similar but much larger structure. In the second study, a concrete box girder bridge in Singapore was monitored from 1997-2003 to track performance through application of anomaly detection procedures to identify structural changes including degradation. In the third study, a short term monitoring exercise was used to check the condition of a short span bridge before and after structural upgrade. Fourth, a building response monitoring system that tracked wind load, acceleration response and absolute deflections is described; this system was useful for assessing the performance of a novel form of construction and turned the structure into a 'super-sensor' for capturing strong wind and tremor events used in calibrating loading codes. Finally a system for real-time tracking of deflections on the surface and in the tunnel during construction of an underground railway is reported.

4.1 Long span suspension 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 and Roberts 1997) which from 1984 to 1998 held the world record for largest span of any structure, 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 similar design; both feature aerodynamic closed steel box decks and inclined hangers so finite element modeling procedures applied to Bosporus Bridge (Dumanoglu and Severn, 1987) were validated by comparing ambient vibration survey data and finite element simulations of the more accessible Humber Bridge (Brownjohn et al., 1987). Humber was subsequently used in a similar mode for validating simulations of the in-wind performance of proposed 3300m span Stretto di Messina (Messina Straits) suspension bridge (Branceleoni and Diana, 1993). 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 (now ENEL) Bergamo and Humber Bridge Board. Figure 1 is a schematic of the elaborate instrumentation installed on the bridge, employing over 32km of instrument cabling.

Aero-elasticity (flutter) is always a concern for long span flexible bridges, a problem that can be treated mathematically by solving for eigen-values of the homogeneous form of the second-order multi-degree of freedom differential equations of the structure in wind:

$$M\ddot{z} + \left(C_{str} - C_{ae}\right)\dot{z} + \left(K_{str} - K_{ae}\right)z = p_{buf}(t) \qquad (1)$$

z and its time derivatives describe the structural motion, *M*, *K* and *C* are the mass, stiffness and damping matrices, terms with suffix '*str*' are purely structural, those with suffix '*ae*' represent aero-elastic functions depending on response. The term with suffix '*buf*' represents gust induced buffeting loading varying with time and space and depending on the varying 'static' aerodynamic coefficients of the structure.

Flutter instability, in different forms, arises due to changes in frequency and damping of vibration modes which are represented as ratios of either total *K/M* or total *C/M* . The aerodynamic influences in these ratios depend on wind conditions, vibration frequency, deck profile and other factors.

Achieving high flutter speeds, to ensure safe operation under normal conditions, by design of the deck girder shape depends on good understanding of the way wind interacts with such a structure. Even with reasonably accurate modeling of the structure which is possible for a suspension bridge and despite advances in computational fluid dynamics there is still great uncertainty in the loading and interaction mechanisms hence the need for full-scale studies.

In the monitoring exercise, wind, displacement and acceleration signals were recorded for a representative range of wind conditions, allowing for system identification with reference to the aero-elastic components of the stiffness and damping, for comparison with values estimated from wind tunnel studies. More importantly, simulation software used the identified structural and aero-elastic information to predict wind-induced response. Validation of the simulation using measured response allowed for the software and procedures to be applied to the much longer Italian bridge.

While providing the means to validate the wind simulations, the monitoring exercise also provided data for establishing relationships between the various loading effects and responses, allowing for identification of the various aerodynamic and structural coefficients. For example Figure 2 shows variations of modal properties of amplitude, damping and frequency with wind characteristics for the fundamental vertical and torsional modes V1 and T1, derived from analysis of wind and response data over the entire monitoring period and reflecting the effect of the aerodynamic terms C_{ae}, K_{ae} in equation (1).

Inspection and maintenance programs for Humber follow UK guidelines: Each structural component is checked every two years, with principal inspections (and any necessary testing) every six years, and special inspections e.g. after a major storm. Numerical simulations have shown 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. 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 (Tabatabai et al., 1998) and this could be an ideal application for low cost autonomous wireless vibration sensors (Lynch 2005).

One observation from the Humber monitoring and from dynamic tests on the two suspension bridges in Istanbul (Brownjohn, 1994) is that the character of deck fundamental vertical vibration modes is very sensitive to the condition of the bearings that are designed to allow limited free movement of the deck at the piers or anchorages. Hence a simple system to track fundamental vertical mode characteristics can help to assess the bearing condition.

4.2 Concrete box-girder bridge structural health monitoring

Because of the novelty of the construction technique, 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. These employed embedded instrumentation in the form of vibrating wire strain gauges (VWG). VWGs resemble a dumbbell, the ends locking mechanically into the concrete and the slender shaft housing a taut wire stretched between the ends. To obtain a strain reading, the wire is plucked by a magnet and the frequency of the vibrations in the wire recorded. Tension varies as the gauge ends move together or apart (in compression or tension). Because they are robust and installation techniques well developed, VWGs have become an industry standard.

During construction of the 'Second Link' bridge between Singapore and peninsular Malaysia, the opportunity arose to specify an instrumentation scheme to validate the design and performance, and the instrumentation that had worked so well on the UK studies was adapted for Second Link (Brownjohn and Moyo 2001), and supplemented by stress cells, previously used in monitoring of tunnel linings. The stress cells work in a similar way to a blood pressure gauge; a thin disk filled with mercury is cast into the concrete, and after the concrete has cured and shrunk away from the disk surface the mercury is squeezed into the disk to engage with the concrete surface. Stress variations, converted to mercury pressure, are read from a vibrating wire sensor. Figure 3 shows the incremental construction in progress with a new segment being cast, and the arrangement of installed instruments in segment 31, which is closest to the pier. Instrumentation in this segments comprises 12 vibrating wire strain gauges (SG), 12 vibrating wire stress cells (PC), thermistors (T) accompanying each of these and additionally laid out in vertical arrays in selected webs, and a triaxial accelerometer, all supplying local loggers managed by a local computer accessible remotely via modem.

The most seful data were retrieved from the strain, stress and temperature cells, read at hourly intervals over long periods during the monitoring, and great use of these data has been made (Moyo and Brownjohn 2002a,b, Omenzetter and Brownjohn 2006) for developing procedures for anomaly detection. In particular, the continuous recording during the construction process provided reference characteristics for events such as post-tensioning and concrete pouring that have analogs in post-construction activity.

One of the fundamental problems in SHM is that of data normalization under a range of environmental or ambient loads or noise sources that affect the measured signals (Cornwell et al., 1999; Alampalli, 1998), 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 auto-regressive moving average (ARMA) model of the system or detection of outliers from the established pattern of response.

A load-effect relationship implies that a structural model, either physics-based or parametric, is available. In the case of Second Link, no such model was available and an 'output-only' ARMA type model is used in the following procedure (Omenzetter et al., 2004).

Raw strain data are filtered into high and low frequency components using the Daubechies D4 discrete wavelet transform. 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 Figure 4, in which C27 …F24 represent construction events associated with segments cantilevered out in sequence from the segment 31. Wavelet coefficients are further processed by forming a vector ARMA model of multiple channels to represent the time series. A best fit second order AR system model is then obtained and the more permanent innovative outliers and transient or additive outliers with respect to this system examined. As the data are multi-channel, it is possible to collapse the signals to fewer dimensions using principal component analysis to highlight outliers consistent among the channels and differentiate effects on different parts of the structure.

This procedure served to identify occurrences of anomalous behaviour potentially useful to the bridge operators. Given the occurrence of such anomalies, the next stage is intervention analysis (Moyo and Brownjohn 2002b) which 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, Figure 5 shows how one tensioning event is characterized by rapid change of level (b). Asymptotic change, asymptotic recovery from change and gradual monotonic change can also be identified and characterize events in construction and degradation. By combination of the above procedures anomalous events can be identified and characterized without any knowledge of the structure.

4.3 Short term monitoring for short span bridge retrofit

All but a handful of highway bridges in Singapore use reinforced or post-tensioned concrete and the Land Transport Authority of Singapore (LTA) recently conducted a major program of upgrades to strengthen existing bridges to sustain higher axle loads. The upgrade program has include desk-based structural assessment according to applicable codes of practice together with visual inspection and sample testing, followed by tendering for the necessary works. LTA included 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 (Moyo et al., 2004) has been conducted to identify a rational procedure for assessing the success of the upgrade, based on the procedure proposed by Heywood et al. (2000).

The proposed approach has been demonstrated on Pioneer Bridge (Figure 6), (Brownjohn et al., 2003; Moyo et al., 2004) an 18m span bridge comprising parallel pre-stressed inverted T-beams tied together by transverse tendons and deck slab and all 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 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. The fifth stage combined statistics of live strains with dead loading characterized using the validated finite element model to estimate extreme strain values compared to capacity.

Figure 7 shows the driving point frequency response functions (FRF) for the same testing and measurement point on the bridge before and after the upgrade using a portable shaker, together with the set of the lowest clearly identifiable vibration mode shapes. The ordinates of the FRFs are inertance (or accelerance), the ratio of acceleration to force at the location of the shaker and inverse of apparent mass.

Mode shapes were obtained from vertical acceleration measurements using a grid of accelerometers, and in order to obtain finer spatial resolution to detect changes in curvature at the abutments after the upgrade, a denser array of sensor locations was used. Pairing of similar mode shapes before and after upgrade showed that corresponding vibration modes increased in frequency due to the upgrade, indicating a considerable increase in stiffness. System identification applied to the FRFs also shows an increase in damping capacity for all modes. The FRF and mode shape data were used to update finite element models for the structural assessment.

The effect of the upgrade on strains induced by passing vehicles is shown in Figure 8. Strain waveforms for passing vehicles are captured using the HMX and peak values saved to produce a 'Gumbel plot' for estimating extreme values for specified return periods (or probabilities) as follows. The maximum strains for N successive days are ranked in ascending order of size so that rank $m=1$ is assigned to the smallest value and rank $m=N$ to the largest. The values are plotted against the reduced variate $y=-\ln\left(-\ln\left(m/N+1\right)\right)$ and the line of best fit is extrapolated, in this instance to determine the '200,000 year strain' equivalent to the value of strain for which the probability of being exceeded in 120 years is 0.06. Since the observation period was short, a procedure called the Method of Independent Storms or MIS (Cook, 1982) was used to make use of independent extreme values occurring within shorter but variable periods.

The validated finite element model and information about the tensioning tendons was used to estimate the dead load strains which were then added to the peak live strains from the Gumbel plots, accounting for load distribution between the beams. Comparison of dead and live strains to the allowable yield strains showed an effective improvement in load capacity after the upgrade.

While the more elaborate modal survey and model updating procedures are not likely to be used in all upgrade exercises, simplified forms of testing including operational modal analysis (Peeters and De Roeck, 2001) that can show an improvement in fundamental frequency could be used to show improvements in stiffness.

4.4 Tall Building load and response monitoring

The contractor for Republic Plaza (Fig. 9), a 65 storey, 280m office tower in Singapore provided a valuable opportunity to monitor the performance of the structure during and after construction by installing stress and strain gauges in structural components in a representative one-eighth segment around the 18th level of the building. Strain gauges were installed on the main beams of the horizontal framing system of two floors and on the steel tubes of the external ring of vertical load bearing columns, while stress and strain gauges were installed in the concrete shear core and in the concrete within the steel columns.

The static gauges were read manually at intervals during the construction and for a while following completion, while the fundamental translational frequencies were tracked by free vibration measurements during the latter part of the construction and beyond. During its operational life this instrumentation revealed clearly the way in which the structural components distributed the structural dead load (Brownjohn et al., 1998) and how the load distribution changed over time. For example Figure 10 shows the variation of stress and strain within the core wall during and after completion. These data indicate a degree of creep and redistribution of vertical load from concrete core to outer columns, a conclusion supported by development of consistent bending moments in the horizontal beams.

In order to validate finite element modeling, a set of modal parameters for the completed structure was obtained from vibration survey of the completed building, and followed by installation of a dynamic response monitoring system (Brownjohn and Pan 2001) which was updated progressively from 1996 until the system was shut down in 2005. In its final form the system sensed horizontal accelerations at roof and basement levels, wind vectors at opposite corners of the roof and absolute displacements of the roof via a dual rover GPS system. The system had two purposes: to capture ground vibrations caused by large earthquakes occurring at least 400km from Singapore and to determine the characteristics of wind loading in Singapore (Brownjohn, 2005)

Together with the validated baseline structural model shown in Figure 9, the system provided the means to track any variations in the structural system, but the greater need was to determine by direct measurement or inverse techniques the character of horizontal loading experienced in an environment where normal design code approaches are inappropriate. For example with the risk attached to a major financial centre close to an area of significant seismic activity, there is a need to consider seismic response in design, and this need has been more keenly felt since the 2004 Aceh earthquake. However there are no design codes for the case of remote but not local earthquakes. The strongest wind loading in Singapore is due to thunderstorms and squalls but no wind codes so far make for this type of wind system. Hence lateral loads due to earthquake and wind are not dealt with appropriately or at all, other than by over-conservative prescriptions and there is (still) a need for more rational code provisions.

One of the signals used to help characterize seismic loading is shown in Figure 11 which resulted from a magnitude 8 Indonesian earthquake in 2000. Like all other regional tremors, this generated a very low frequency rigid body movement of the whole building. The effects of minor earthquakes are not so strongly felt and cannot usually be distinguished from other signals at ground level so the ringing of the upper level of the building in its second mode of vibration was used to trigger selective recording of tremors.

4.5 Deflection monitoring system for underground railway construction

In recent years, limits on space above ground in Singapore have meant that new expressway and railway projects involve tunneling. As such, deflection monitoring of tunnel lining and surface structures are both required. For example the new mass rapid transit (MRT) line to Changi Airport passes below the main runway, whose surface deflections were continuously monitored during construction. In this application, automated ‘total stations’ or motorized optical surveying instruments scanning arrays of reflective targets at intervals were used to monitor the deflections continuously and warn of excessive values and danger to aircraft safety.

An advanced version of such a system is described by Tan and Chua (2003) where the system was extended to include transmission of data via public low cost wireless networks, automated updating of deflection databases, automated e-mailing of data to users and issue of SMS (text) alerts upon threshold crossing or other alarm states. Figure 12 shows a MRT tunnel with an array of optical targets (the bright dots) and Figure 13 shows the schematic of the system in operation sending a text message alert that a trigger level has been exceeded. GPRS communications that are ‘always on’ have now replaced early GSM systems so it is no longer to wait for the next dialup, and the system is as near real-time as the sensor reading cycle permits.

Although the total station optical system is here used as the front end, the wire-less system, server architecture with e-mail and SMS alerts is now being applied to a range of other instrumentation systems including bridge monitoring.

5 Application of Novel Sensors for SHM

Robust and established sensor technology for civil SHM is well described elsewhere (Ross and Matthews, 1995a) and for geotechnical applications by Hannah (1973) and Dunnicliffe (1994) and novel SHM sensors are described elsewhere in this journal issue, so only two new developments that have potential for SHM of civil structures are discussed here.

One of the major focuses of SHM research, particularly in North America, has been advanced sensor development, and as a classical example of technology transfer, sensors developed within other engineering disciplines are now finding their way into civil applications. Particular examples are fibre optic sensors (FOS), global positioning system (GPS) and piezo-impedance transducers (PZT patches), but specialized sensors continue to be developed for civil applications e.g.Mita and Takahira (2003), Iwaki et al., (2001), Sumitro and Wang (2003).

Such sensors need to have proven reliability and advantages over conventional sensors, and major SHM exercises, particularly those with academic origin provide real-life (not laboratory) situations for their evaluation. Two particular types of sensor appear to have a bright future, and while the technology of the systems is beyond the scope of this paper, some applications to full-scale monitoring programs are reported.

5.1 Fibre Optic Sesnors

As can be seen from proceedings of various conferences organized by the International Society for Optical Engineering (SPIE), the majority of civil SHM sensor research is on fibre optic sensors (FOS) (Udd, 1991). The advantages have often been stated e.g. (Ross and Matthews, 1995a):

- Precision and sensitivity over large measurement ranges
- Immunity to electromagnetic interference
- Versatility of application
- Stability of material
- Operability under extreme climatic conditions (temperature, moisture)

The fiber Bragg grating is widely used in civil SHM (Moyo at al., 2005) because of its multiplexing capability. This provides for the possibility of strain measurement with high resolution in time and space from a single fibre, so that separate and discrete strain gauges and accelerometers will be redundant. A number of civil SHM systems have employed FBG sensors, for example in the Confederation Bridge (Mufti et al., 1997). Like VWGs, FBGs can be adapted to read a range or response parameters. One impediment to more extensive use of FBGs for civil infrastructure SHM is the availability of robust and affordable loggers for field applications, as FBG technology has developed from communications research which appears to enjoy greater funding and more benign operating environments. Other impediments, also diminishing, are fragility of fibres, unfamiliarity and reluctance to use new technology,

The commercially available SOFO system (Inaudi et al.; 1996, Inaudi, 1997), which uses a Michelson interferometer to measure length changes in a tube installed in a structure, has gained wide acceptance for application in bridges, dams, ports and heritage structures in Europe. It also been accepted by the traditionally conservative public housing authority in Singapore and recent developments allow for use in dynamic measurements (Inaudi, 2004).

5.2 Global Positioning System

The global positioning system (GPS) has provided new possibilities for direct measurement of infrastructure deflections, which had until recently required solutions such as liquid levels, plumb lines, laser interferometry, digital image processing for real-time target tracking and variations on analog detection of moving director reflected light sources. Differential GPS, which depends on accurate measurement of transit times for radio waves from satellite to receiver, promises direct and absolute measurement of deflection without many of the problems associated with the optical systems.

A ‘base station’ GPS antenna and logger is set up on a stable ‘fixed’ reference location as close as possible to the monitored structure, with line of sight to at least five orbiting GPS satellites. A ‘rover’ antenna and logger are installed on the structure, also with satellite visibility. The locations of rover and base station are obtained in the appropriate geodetic coordinates, but each will have a measure of inaccuracy depending on factors affecting radio transmission times between satellites and receivers. Provided base station and receiver are close, the factors should affect signals in almost the same way and differences between known position of the reference base station and the position computed by GPS can be transmitted as errors, in real time, to the rover, whose calculated location is corrected to determine a far more accurate fix. This real time kinematic (RTK) form of GPS position measurement (Rizos, 2002), should be capable to provide positional accuracy better than 1cm at rates of up to 10Hz. Positional errors increase with rover-base station separation but it has been claimed (Ashkenazi and Roberts, 1997) that accuracy of the order of 1mm can be obtained using GPS, although not necessarily with real-time systems. The alternative to the real-time mode is processing of data saved by separate receivers. These data provide full information about signal transit times and satellite parameters enabling the use of research-level processing algorithms and derivation of positional quality indicators. A recent development by major GPS equipment suppliers is the ‘virtual reference system’ with which location-specific corrections are available from a national network of supplier-managed receivers so there is no need for a dedicated base station.

An extension of the Republic Plaza system (Brownjohn et al., 2004) shows that real time solutions can detect displacements of the order 2-3mm. The accuracy is difficult to evaluate due to the absence of reliable alternate measures, although having two rovers installed (separated by about 11m) indicates the likely errors. Experience in this trial is that variance errors can be as large as the range of normal movement for the building, which is in the range of a few centimeters.

Other recent projects which demonstrate the potential of GPS for performance monitoring include the Chicago project (Kijewski-Correa and Kareem, 2003) in which fast offline processing is applied to GPS data from three skyscrapers and measurements of a radio mast in Japan (Li et al., 2004). What is remarkable about the latter study is the identification of the mast response in the second vibration mode response at 2.16Hz, from 10Hz GPS data recorded during an earthquake signal

If slower sample rates are required, adaptive filtering can be implemented to remove noise and obtain more accurate ‘static’ solutions, a possibility not lost on the operators of dams and other structures where slow movements are of particular concern as indicators of structural health (Hillman et al., 2003).

For further reading, proceedings of symposia and conferences organized by the International Federation of Surveyors (FIG) present a growing number of applications of GPS to civil SHM on many classes of structure. The most successful SHM applications are where the base station can be located close to the structure and where structural movements can be measured in centimetres with very slow dynamic or static movements. This makes GPS ideal for tracking performance of long span suspension bridges such as Akashi-Kaikyo and Tsing Ma (Wong et al., 2001), due to low natural frequency, or dams, due to the very slow movements arising from the environmental loads.

6 Problems and limitations in development of civil infrastructure monitoring system

Directions in SHM research and development toward the goal of autonomous systems for assisting structure managers maintaining their structures safely and efficiently will depend on dealing with key problem areas in SHM.

6.1 System reliability

As SHM systems are intended to assist infrastructure operators/owners in managing their facilities, an exhaustive cost-benefit analysis will be required to show that benefits outweigh costs. Apart from the initial outlay in planning, purchase and installation, operation and maintenance cost of the system should be low.

6.2 Inappropriate instrumentation and sensor overload

In the growing number of instances where a tender specification for structural works includes a requirement for instrumentation and monitoring there may be no incentive for careful selection of sensors and locations with a mind to obtaining useful information about the performance of the structure. There is a tendency to over-instrument, as installation post-construction will usually be more troublesome. For a given budget this will affect the quality of the instruments and their survival rate, so an understanding of expected performance and critical locations in the structure will help plan for fewer but more reliable sensors.

Inappropriate instrumentation often results where the end user is separated from the instrumentation contractor by layers of main contractor and consultants; a specialist consultant should oversee the design, implementation and early operation of the instrumentation system.

6.3 Data storage and data overload

A corollary of over-instrumentation is data overload, more data than can be assimilated without an elaborate database management system. Limited research has been done on optimal placement of sensors, and careful planning using scenarios of detectable degradation or damage, together with examination of similar operational SHM systems will lead to more efficient sensor deployment.

6.4 Communications

Wireless or land links are a necessity for remote un-manned installations; dial-up modems or permanently connected leased lines may be used. These may not be 100% reliable so allowance had to be made for their fallibility. Robust low-cost wireless systems play an increasing communications role but due to present limited data capacity, data compression or pre-processing will be necessary unless data are slowly sampled static signals. The most widely used public network is the 9.6Kilo-bit per second GSM data communication system, but as the 30Kbps GPRS network increases in popularity, the cost of real time monitoring using wire-less technologies for

SHM will reduce. The 700Kbps 3G networks will provide the possibility of simple, cost effective, real time wireless dynamic response monitoring from PDA, laptops and cell-phones. Zigbee is used in some commercial wireless SHM solutions (Edwards, 2005).

6.5 Environmental factors and noise

Vibration-based damage detection using accelerometer signals may work in controlled conditions but, as many exercises on full-scale structures have demonstrated, changes in modal properties due to environmental conditions will greatly reduce the probability of successful damage detection and location. Partial mitigation of such effects can be achieved though physics-based or statistical models of the environmental effects but a level of noise will still remain, even with slowly varying 'static' signals. Successful SHM procedures will incorporate the means to compensate for or filter out the environmental and noise effects (Peeters and De Roeck, 2001b) or at least establish confidence levels for anomaly detection against noise.

6.6 Data mining and information presentation

One of the most significant issues with SHM is converting data to information, an issue addressed in detail elsewhere in this set of papers. Not to be overlooked is the charting or presentation of information to operators who are very unlikely to be familiar with the sophisticated underlying numerical procedures.

6.7 Funding and vested interests

Informed research communities and their funding agencies have begun to realize that as infrastructure development slows and existing stock ages (Wenzel, 2003), there is a growing need to support research programs in SHM. The fruits of such research are slow to grow and funding applications have to compete with the more fashionable and immediately productive research areas. For this reason present mono-disciplinary and single-institution paradigms for SHM research with narrow focus may have lower chances of survival. Approaches to SHM developing in the 21st century involve the whole spectrum of the problem from sensors to data mining via advanced sensor technology, embedded systems, communications, IT, expert systems and AI. They involve collaborations across disciplines and institutions, as well as across national boundaries and are ideal cases for industrial support. In the European Union, the SIMCES project (De Roeck, 2003) was funded under the 4th Framework of the EU CORDIS research program, while the US National Science Foundation continues to fund research in 'smart structures' (Flatau and Chong, 2002). Within North America, research on a VBDD approach to SHM is being coordinated by the American Society of Civil Engineers (Dyke et al., 2003).

Serious research (that is likely to end up being applied) into SHM for legally mandated applications (dams, offshore and nuclear installations) is generally conducted by owner-operators and the bulk of SHM research reported by academia relates to bridges, buildings and geotechnical installations where infrastructure owners lack capacity for in-house research and stand to benefit, with universities, from collaboration. Without financial or legal pressure on private owners, SHM studies on tall buildings will be limited to cases where there is positive publicity or a specific problem. Owners would simply prefer that any defects do not become public knowledge, as knowledge leads to liability.

6.8 Lack of collaboration

Clearly, different levels of progress have been made for different classes of structure and there is much to be learnt from studying procedures not only in other disciplines (such as condition monitoring of rotating machinery) but also within the various branches of civil-structural engineering. The experience of dam monitoring is transferable to other structures, particularly bridges. However, once a solution has been found for a problem in one part of the industry, only those with academic background would wish to make technology available elsewhere. Hence as research converges on a solution, so it becomes invisible making the ideal even less attainable without large resources for a single group.

7 Present state of the art and directions in civil SHM

SHM can have a very wide definition and be implemented in many different ways for varying motives, but all approaches have common component classes at different levels:

1. Sensors
2. Data storage
3. Data transmission
4. Database management leading to feature extraction
5. Data mining for feature extraction
6. Load/effect model development from study of data
7. Learning from past experience (heuristics)
8. Decision making based on identified features in combination with identified models

As well as the huge volume of literature published relating to civil SHM, there is also a body of published work that discusses developments of SHM (Aktan et al., 2001; Maguire 1999, Ross and Matthews 1995b). Concensus appears to be reached on a number of issues:

- Consideration for SHM needs to be incorporated at the design stage, so that sub-structures whose performance is uncertain or critical can be monitored in-service.
- Measures of sub-structure performance (such as strain) and priority for monitoring should be stated to aid choice and optimization of sensors.
- The design should allow for access to sensors via personnel, cables or radio signals.

It is universally agreed that gigabytes of data are useless until distilled into manageable amounts of information. Either signals are acquired selectively or conversion of data to information should begin with pre-processing in the data logger. Hence, for example, time series of acceleration are converted to mean and variance values, discrete Fourier transforms to determine peak frequencies or auto-regressive model coefficients. This is a form of 'embedded system' and with time, sensor, logger and pre-processor will merge with the communication device. Such systems are already being built (Lynch 2005).

For performance measurements on full-scale structures in real-life conditions, the greatest practical problems have often been with cabling and difficulty in establishing reliable communication for data transmission and control. In recent years development of wireless local area networks and public radio systems have mitigated these problems, lowering setup and maintenance costs.

Management of data/information depends on application and operator, but this is probably the key area for future research, as various tools of IT are applied to merge and manipulate information to support decision making by infrastructure operators. The most productive future SHM research will probably go with the database management, system identification and AI procedures representing the 'back box' interface with the operators, an area in which dam engineers already have a head-start.

Lessons learnt from SHM experiences are beginning to find their way into guidelines and codes of conduct (BSI 2004, ISIS 2001, Fib 2003, Rucker et al., 2006). Also, a number of national and international SHM interest groups and networks have formed. Some, like SAMCO (www.samco.org), ISIS (www.isiscanada.com) and ITR (healthmonitoring.ucsd.edu) have evolved from funded initiatives, others like ISHMII (http://www.ishmii.org/) have developed from the interests and meetings of key international experts. ISHMII has general aims that include provision of a focal point for sharing SHM knowledge and experience, promoting international collaboration, fostering harmonization of design and application standards and showing the benefits of SHM in civil infrastructure management.

Acknowledgements

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Figure 1 Instrumentation configuration for Humber Bridge monitoring
LVDT=linear variable differential transformer, to measure relative displacement

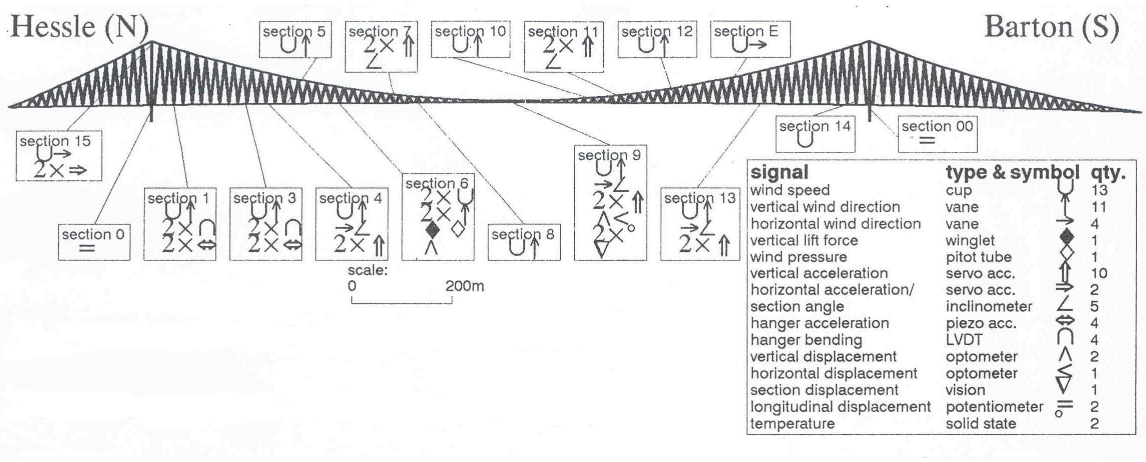


Figure 2 Variation of Humber Bridge modal parameters with wind speed. Upper, first vertical mode (V1) response levels for different wind speeds and turbulent intensities I, middle, mode V1 damping ratio and, lower, first torsional mode (T1) natural frequency

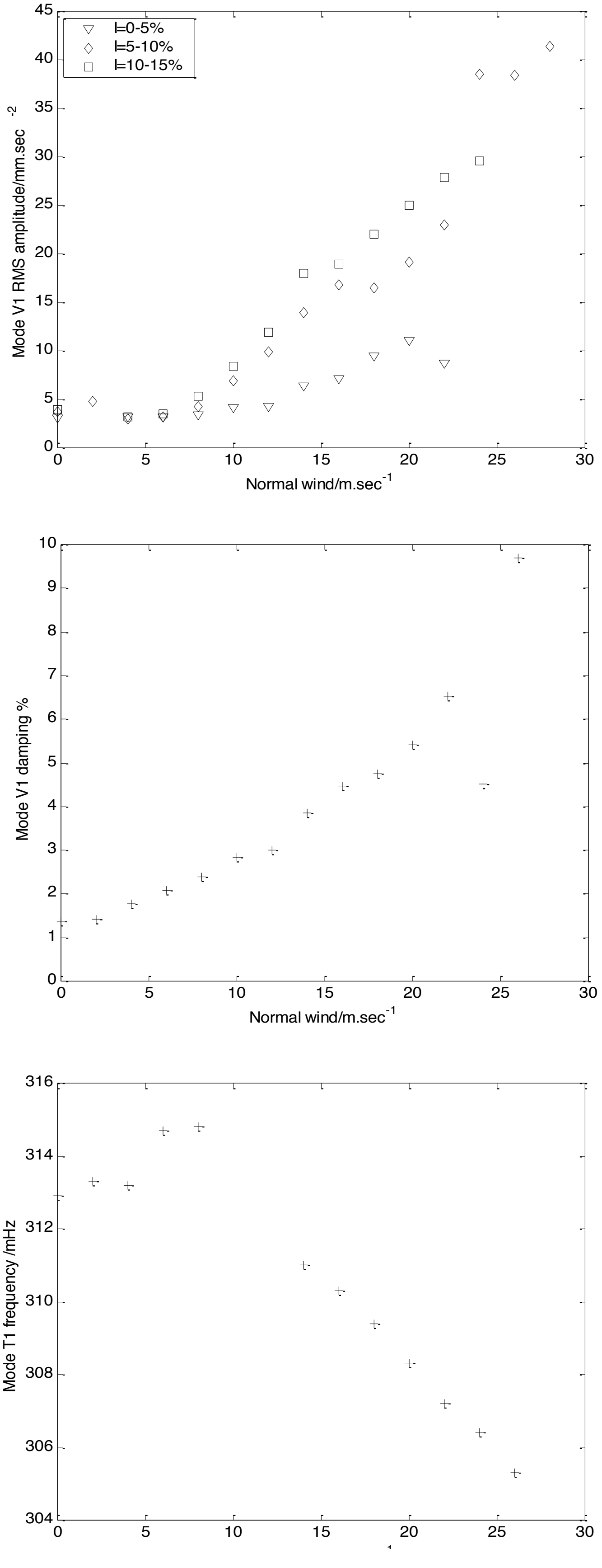
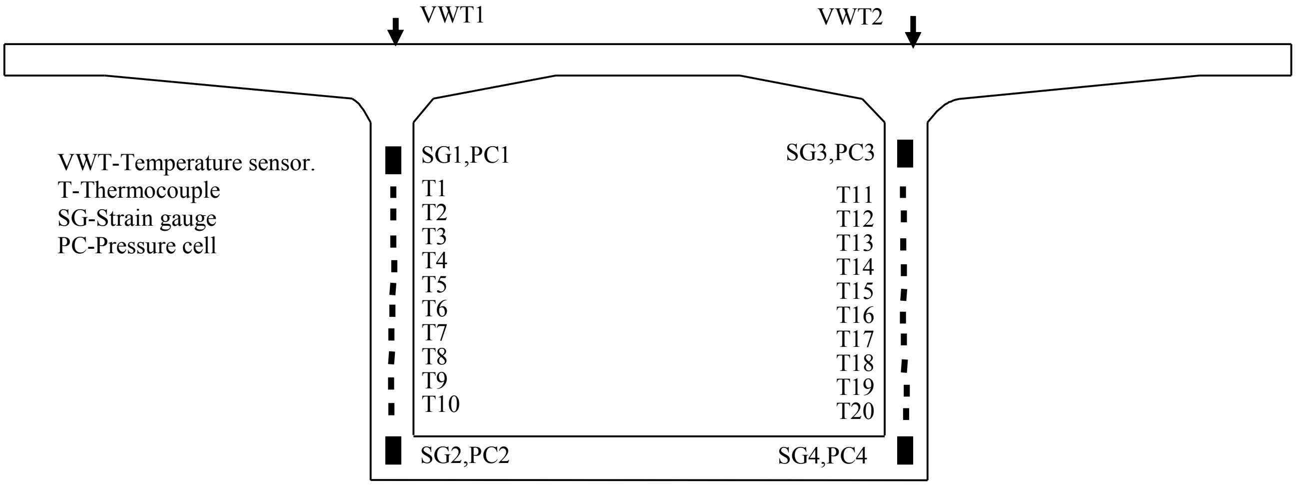


Figure 3 Tuas Second Link under construction, with instrumented segment nearest



Segment 31 Sensors

Figure 4 Strain data from segment 31 SG1 and discrete wavelet transform (DWT) level 1 details,.identifying discontinuities in strain time series corresponding to construction events: C – concreting, T – cable tensioning, F – shifting of concreting form, e.g. T26 – tensioning of cables in segment 26

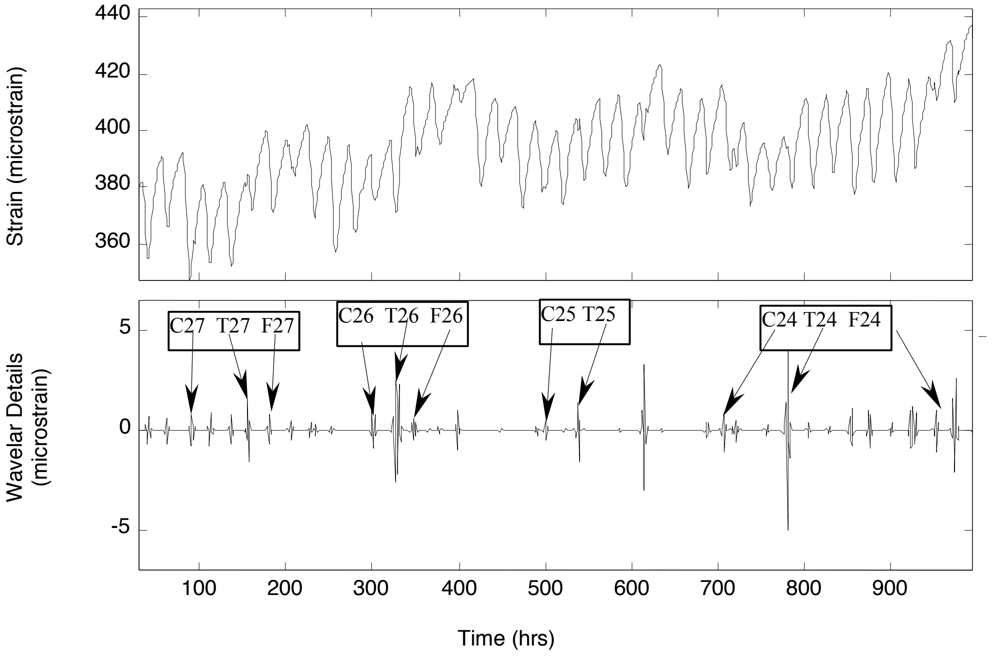


Figure 5 Intervention analysis of a cable tensioning event: strain time series, and types of change in response. a) transient change, b) level shift, c) gradual change, and d) linear trend

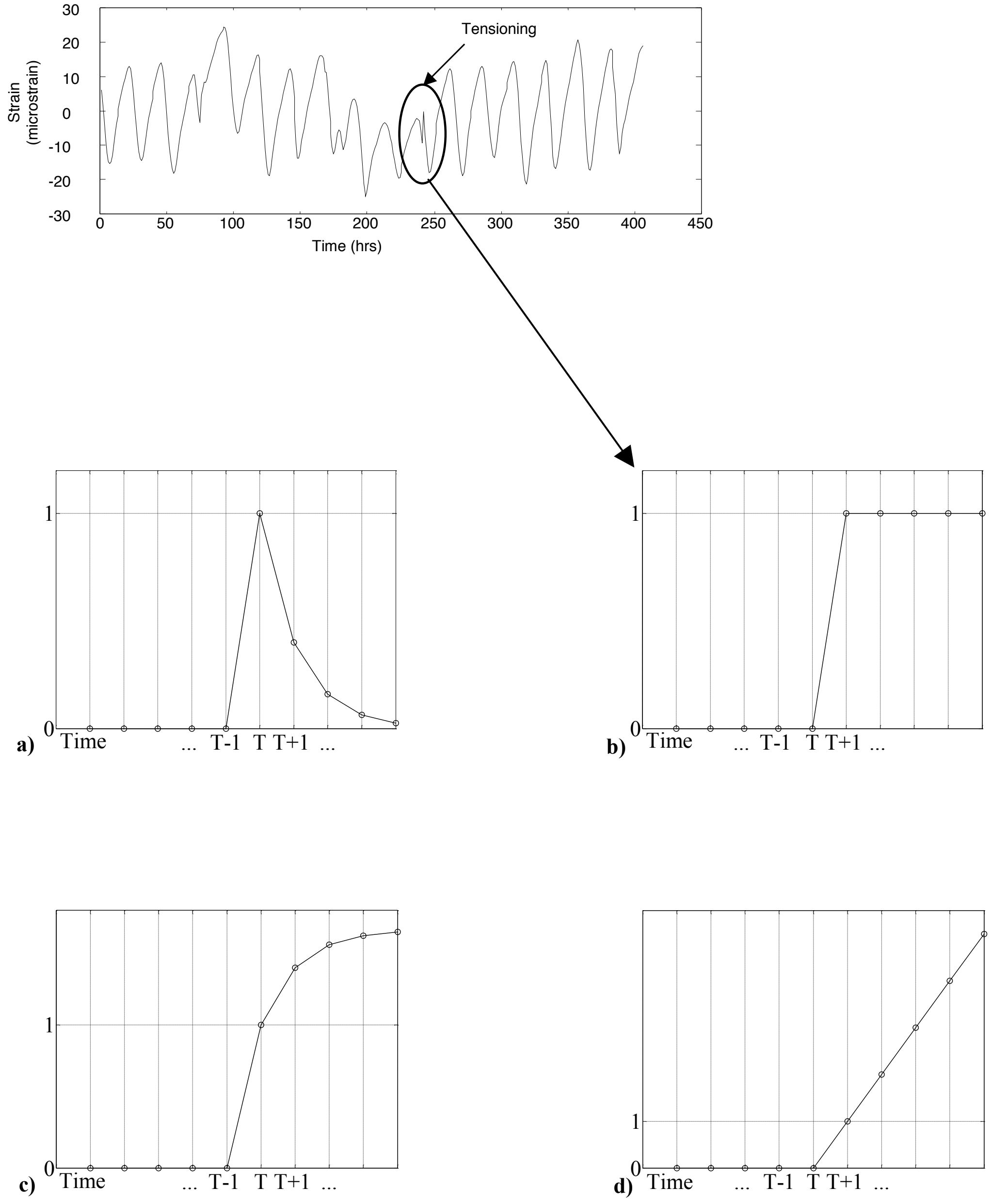
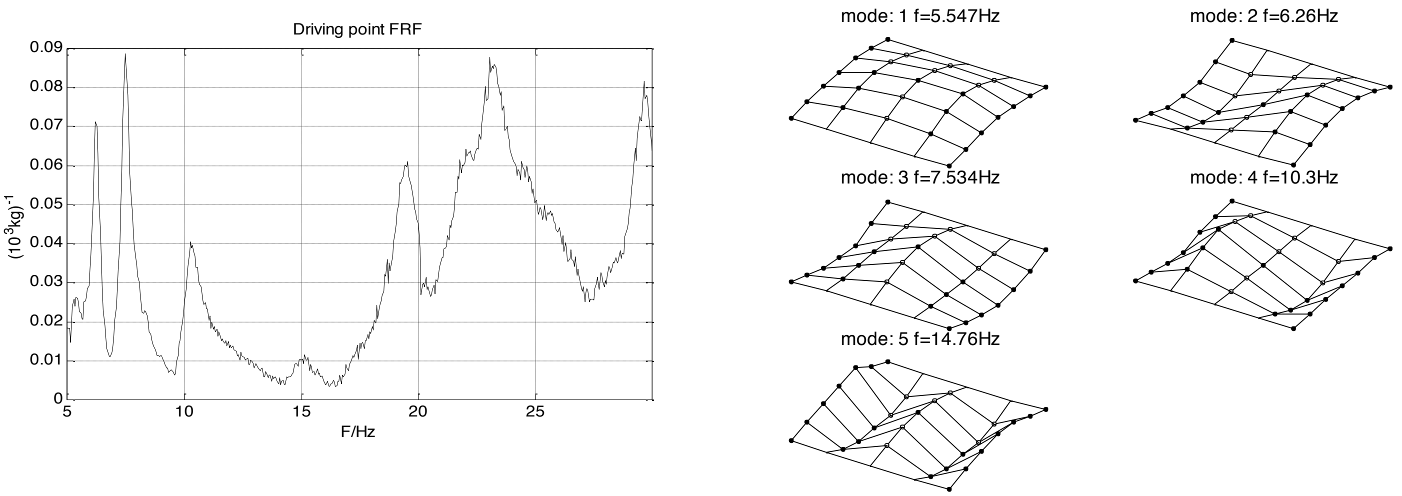


Figure 6 Pioneer Bridge (upper) general view showing bridge with accelerometers and strain gauges mounted at midspan on upgraded bridge and (lower) showing strain gauge attached to soffit of inverted T-beam before upgrading.

Figure 7 Pioneer Bridge 1/3rd span driving point frequency response functions and mode shapes before (top) and after (below) upgrading. Similar mode shapes identify corresponding modes before and after uprade.



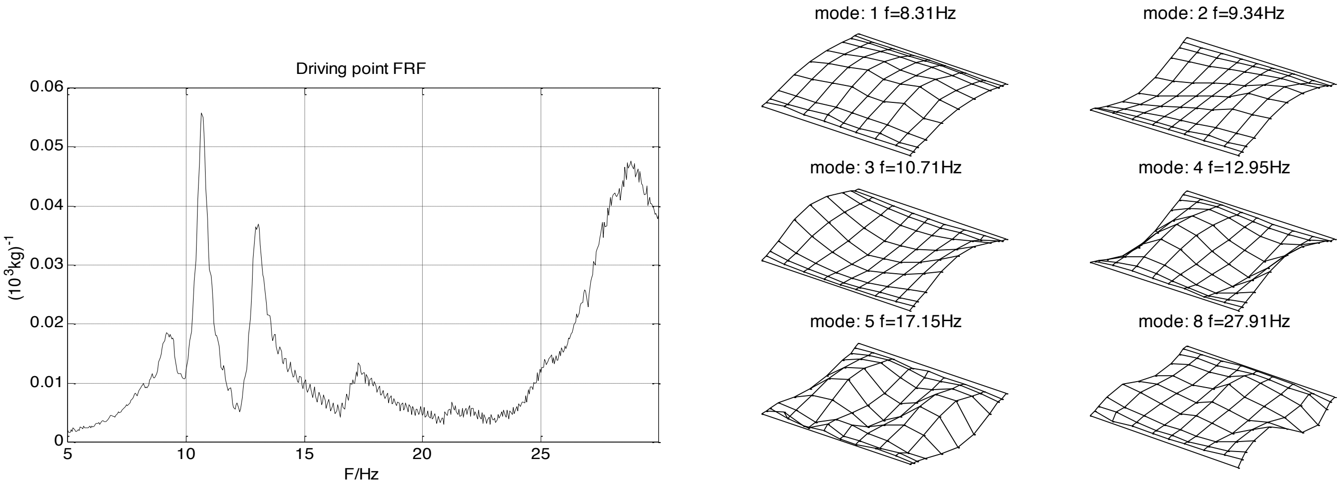
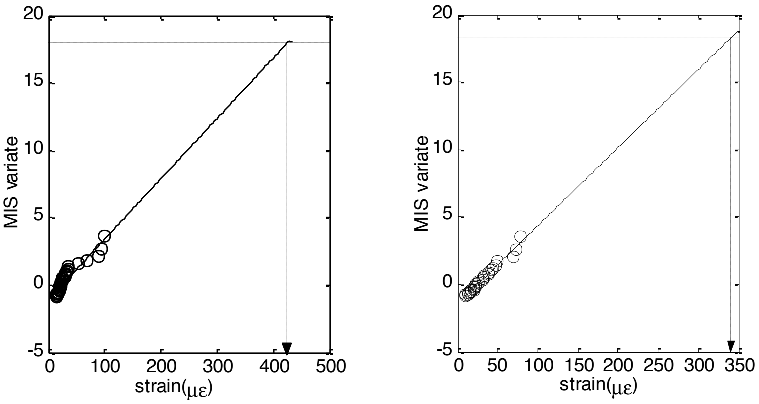


Figure 8 Gumbel probability plots for Pioneer Bridge girder strain before (left) and after (right) upgrading. MIS variate reflects extreme value probability density function obtained using the method of independent storms.



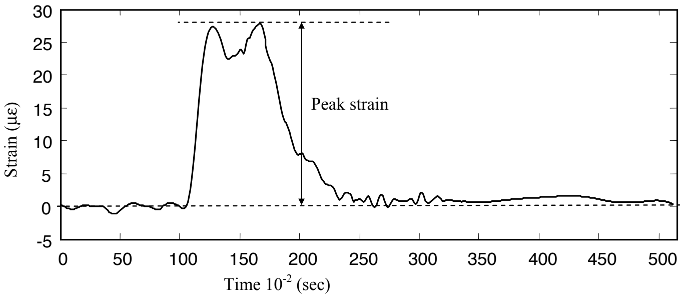


Figure 9 280m Republic Plaza building; under construction, finite element model showing structural elements, and (right) after completion

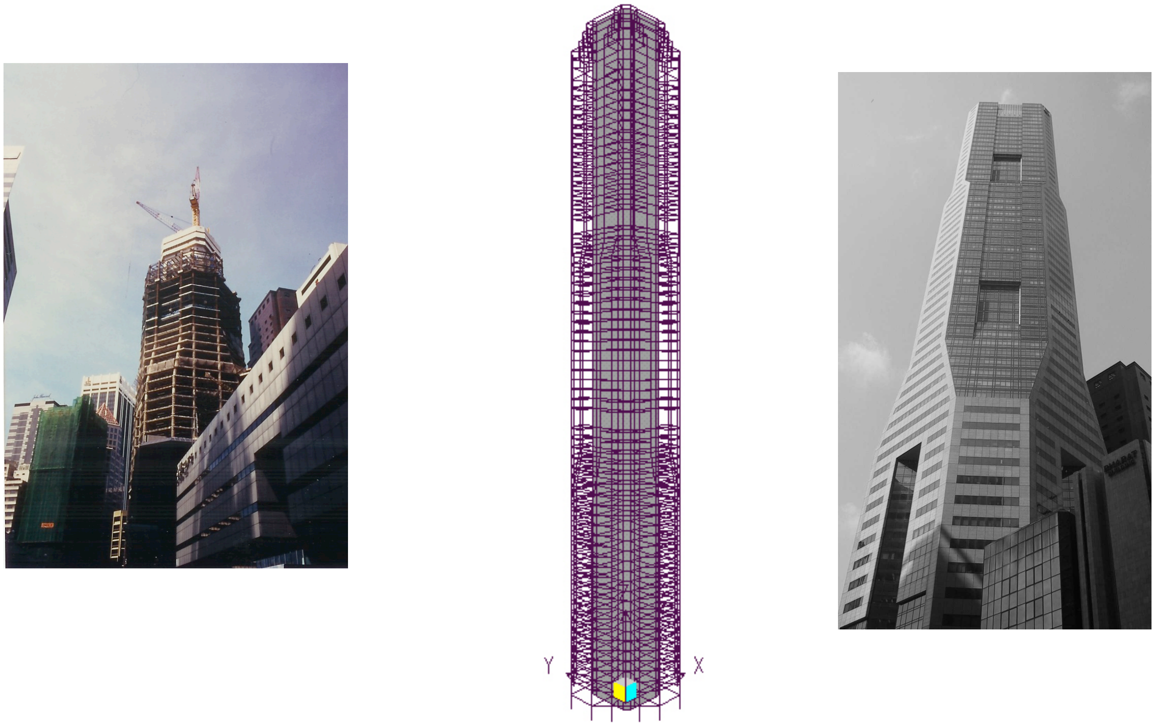


Figure 10 Stresses and strains (right) in core wall before and after construction show respective decrease and increase indicating creep and load redistribution

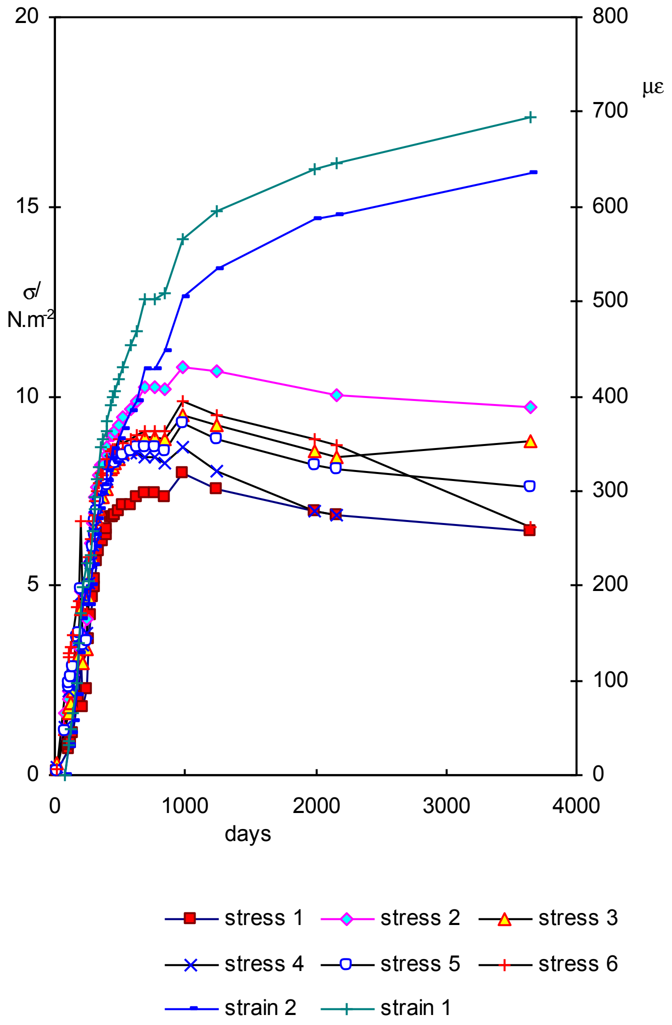


Figure 11 Republic Plaza rooftop acceleration response (top view) and basement signal (lower view) due to tremor in remote Indonesia

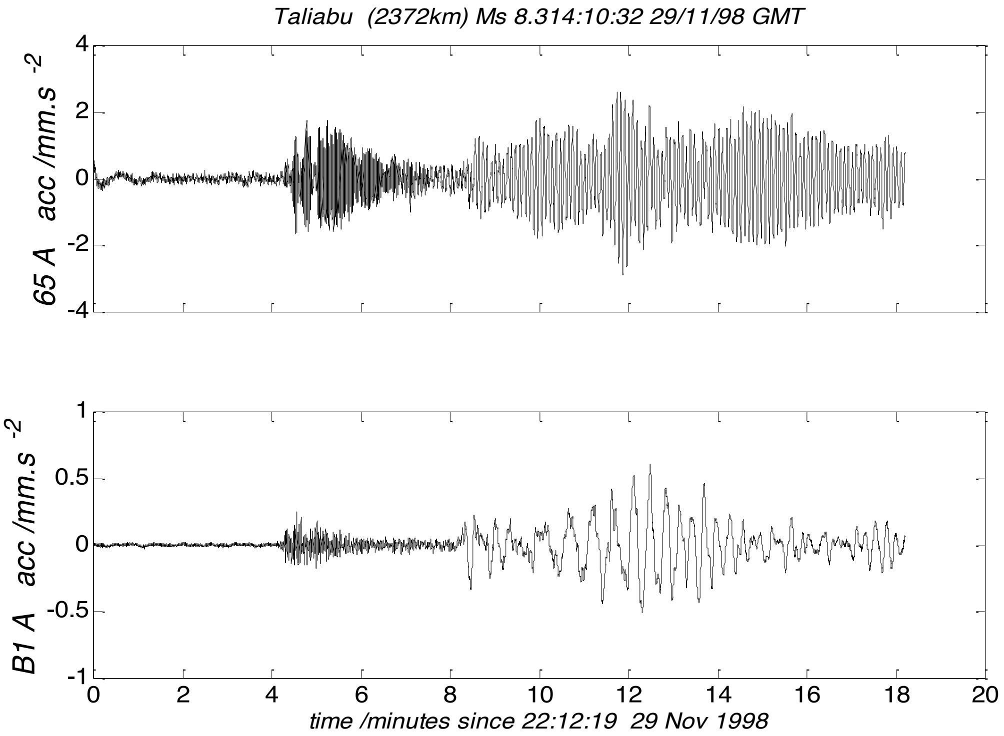


Figure 12 Tunnel monitoring: left total station with bright spots showing reflectors (right) located around tunnel section (below right)

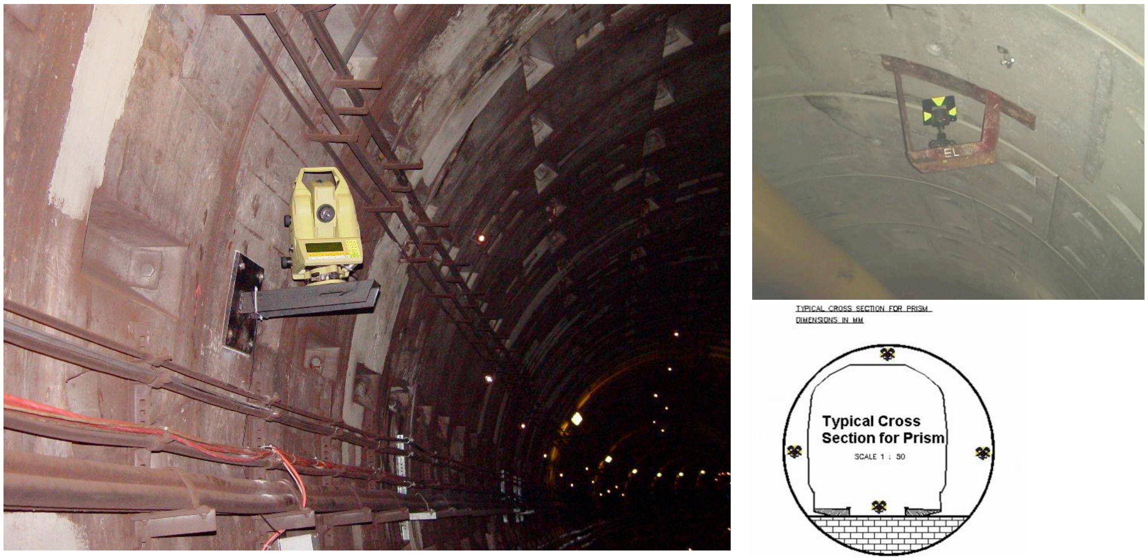
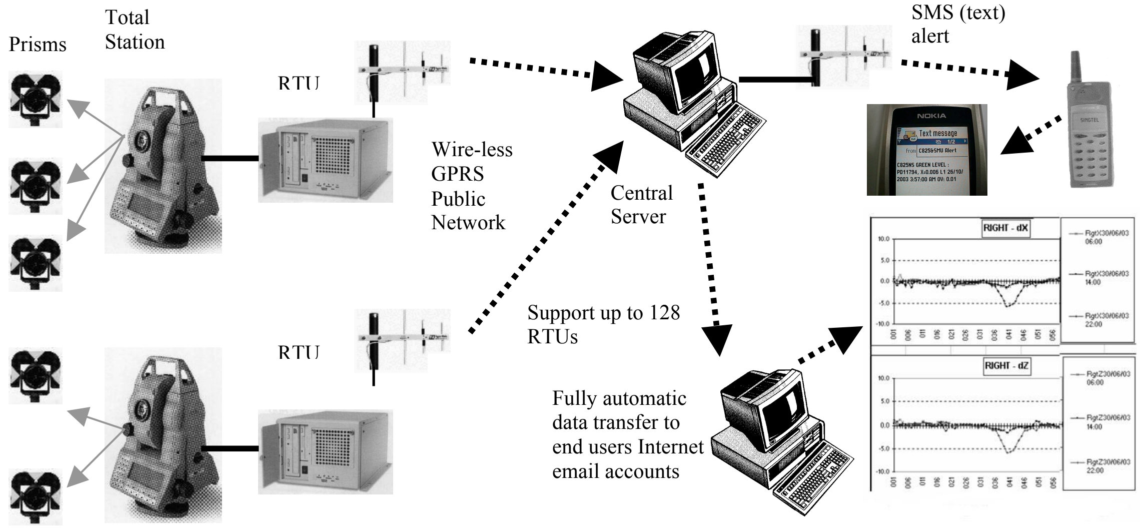


Figure 13 Real-time automated monitoring of tunnel movements using wire-less GPRS and SMS alert due to deflection exceeding setpoint



Text message

From C825&SMU Alert

C825NS GREEN LEVEL : PD11794, X=0.006 L1 26/10/2003 3:57:00 AM OV: 0.01