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Vibration-based monitoring of civil infrastructure: challenges and successes

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Abstract

Structural health monitoring (SHM) is a relatively new paradigm for civil infrastructure stakeholders including operators, consultants and contractors which has in the last two decades witnessed an acceleration of academic and applied research in related areas such as sensing technology, system identification, data mining and condition assessment.

SHM has a wide range of applications including, but not limited to, diagnostic and prognostic capabilities. However when it comes to practical applications, stakeholders usually need answers to basic and pragmatic questions about in-service performance, maintenance and management of a structure which the technological advances are slow to address.

Typical among the mismatch of expectation and capability is the topic of vibration-based monitoring (VBM), which is a subset of SHM. On the one hand there is abundant reporting of exercises using vibration data to locate damage in highly controlled laboratory conditions or in numerical simulations, while the real test of a reliable and cost effective technology is operation on a commercial basis. Such commercial applications are hard to identify, with the vast majority of implementations dealing with data collection and checking against parameter limits.

In addition there persists an unhelpful association between VBM and 'damage detection' among some civil infrastructure stakeholders in United Kingdom and North America, due to unsuccessful transfer of technology from the laboratory to the field, and this has resulted in unhealthy industry scepticism which hinders acceptance of successful technologies.

Hence the purpose of this paper is showcase successful VBM applications and to make the case that VBM does provide valuable information in real world applications when used appropriately and without unrealistic expectations.

Keywords

Vibration structural health monitoring bridge building tower case study

Drivers for vibration based monitoring

Civil infrastructure comprises the bridges, towers, buildings (and components), dams, tunnels, docks and a range of other apparently inert structures that society needs to function. Their continued well-being and safe and economical operation for the benefit of society and avoidance or mitigation of financial or human costs depends on their proper management, which includes assessment of present and future safety and fitness for purpose.

Unlike mass-produced structures for aerospace and automotive industry where extensive type testing (Lo et al., 2001) is carried out before mass production of almost identical units, or safety-critical or high cost equipment such as spacecraft (Zimmerman, 2000) or nuclear power plants where experimental qualification is essential or mandatory, civil infrastructure is rarely subjected to any kind of experimental assessment before entering service, and as a result has much larger safety factors and uncertainties in performance. Exceptions to this rule include static load proof tests of highway bridges in some countries and multi-pedestrian dynamic testing of some new footbridges. Further, while even mass-produced cars feature advanced real-time diagnostic systems for safe operation, continued in-service monitoring of any kind is still rare for civil infrastructure.

There are several reasons for this; real-estate owners would prefer not to have defects or liabilities exposed (with legal and financial consequences) and designers would prefer not to know that they either under- or over-designed a structure. Finally, engineers would prefer not to have to rely on monitoring for safe operation, since at the present state of technology the reliability of a monitoring system to protect a structure from collapse remains to be demonstrated clearly in the public domain.

High profile structural failures e.g. of the I-35 bridge have highlighted problems with ageing infrastructure, while traumatic natural events such as earthquakes and floods result in demands for rapid evaluation of structural condition. These are two of the many drivers for the growing body of research on observation and interpretation of full scale performance of civil infrastructure which is loosely termed structural health monitoring, or SHM.

The term SHM appears to have originated in the early 1990s, before which structural monitoring technologies had been widely developed for data acquisition and performance evaluation of structures. In the last decade the technology applicable to civil infrastructure has been covered by several new international journals and major international conferences.

Modern SHM integrates sensing, communication and computing systems with non-destructive evaluation including geometric surveys and vibration measurements and practical applications come in many forms. At one extreme are the tiny minority of structures having elaborate monitoring, data management and real-time diagnostic systems, for example in the Stonecutters Bridge (Wong, 2010), Rion-Antirion Bridge (Le Diourion and Hovhanessian, 2005) and the Donghai bridge http://zone.ni.com/devzone/cda/tut/p/id/6624. At the other extreme, there is some form of (mandatory) routine surveillance or structural monitoring for certain types of structure such as dams (CIGB ICOLD, 1988). There is also ‘routine’ instrumentation of selected buildings -and occasionally bridges (Masri et al., 2004)- in local or national strong motion instrumentation programs and there is ‘static’ instrumentation (e.g. with strain gauges and surveying technology) during infrastructure construction, usually for geotechnical applications (Smethurst and Powrie, 2007).

In special circumstances, e.g. during assessment with respect to possible upgrade, or following a major disaster (e.g. earthquake) more elaborate short-term assessment procedures may be employed. Such assessments are necessarily non-destructive (since every structure is a prototype) and employ a wide range of non-destructive evaluation techniques (Sohn et al., 2003).

Among these techniques, one of the forms that has found favour and generated great interest in the academic research community, with some commercial applications, involves using forced or ambient vibration response data to identify modal characteristics (Catbas et al., 2011). These modal parameters and their derivations reflect the structure mass, stiffness and damping properties which depend on the condition of the structure. Changes in modal properties may indicate changes in the structure leading to the possibility (Adams et al., 1978) that such changes can be used to detect, possibly locate and even perhaps quantify ‘damage’. Damage is usually defined in a classical sense as reduction in local stiffness due to formation of cracks and spalling of concrete or even total failure of a structural member such as a brace in a steel frame or a column, beam or joint in a building.

There are other potential indicators of damage that can be derived more directly from vibration data, for example evaluation of inter-storey drifts in a building derived from accelerations (Radulescu et al., 2003) is shown to correlate well with levels of earthquake-induced damage, leading to a method of probabilistic damage assessment for post-earthquake building classification (Naeim et al., 2005). Using inter-storey drifts with mass properties of a building can be used to reconstruct the hysteric behaviour (Iwan, 2003) which also correlates with damage.

Vibration data in fact have a wide range of more immediately practical uses. Simple characterisation of vibration signals (peak levels, RMS, one-third octave velocities, response spectra etc.) is frequently enough to indicate ‘bad behaviour’ or poor performance requiring attention. A classic but by no means isolated example is the London Millennium Bridge (Dallard et al., 2001): vibrations were too high, the structure was not fit for purpose and required a costly retrofit. Such poor performance is not always obvious and the causes are even harder to identify so that continuous recording of response levels (i.e. monitoring) may be needed to provide evidence. This evidence is not just for structural diagnosis; data from vibration monitoring is sometimes used to support legal action relating to unsatisfactory performance or even failure.

For the case of super-tall buildings having very low natural frequencies, the link between wind-induced response and discomfort to occupants or disruption to machinery (such as lifts) can be evaluated using vibration monitoring. With the lack of information about the performance of these structures, monitoring provides useful validation of predictions using wind-tunnels and supports better understanding of the load-response mechanisms (Kijewski-Correa et al., 2006; Kwon et al., 2010).

Short term vibration measurements campaigns (modal tests) are also used to check key modal parameters used at the design stage and to verify the design and can be repeated during construction stages in order to influence final design while changes are still possible, for example introduction of mitigation measures. In some cases short experimental campaigns with high sensor density provide a starting point for long term monitoring with a small set of instrumentation (Brownjohn and Pan, 2001).

Hence there is a broad spectrum of activities for which structural vibration monitoring has tangible benefits. This paper was prepared as a report from a task group of the International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII, www.ishmii.org). It describes vibration based monitoring (VBM) technologies ranging from the simple (level assessment or threshold crossing) to complex (data mining and performance prognosis) based entirely on vibration measurements.

Structural health monitoring (SHM), Vibration based monitoring (VBM) and vibration-based damage detection (VBDD)

SHM has already been defined loosely as the observation and interpretation of performance of civil infrastructure. The exact definition remains open to interpretation but it at its core is the continuous identification of a physical or parametric model of the structure using time-dependent data. This distinguishes it from short term experimental campaigns such as load tests or modal tests that through a combination of system identification and structural analysis seek to identify the state of a structure at a specific time and which are not the subject of this paper.

This time dependence ranges from annual (seasonal) cycles to diurnal variations, to durations of events such as storm or vehicle passage and finally to dynamic response at rates such that inertia properties of a structure are engaged. VBM, which is thus a subset of SHM, focuses on the dynamic part of performance, in several cases constituting the major component of an SHM operation. It provides a rich source of data for structural investigation, but it has often appeared to have an emphasis on a subset of VBM termed 'vibration based damage detection' (VBDD). Hence one specific aim of this paper is shift the emphasis back to proven VBM technologies, usually in simple applications.

The comprehensive 1997 ASCE study of structural control (Housner et al., 1997) covers these topics (SHM, VBM, VBDD) in the same chapter, showing the extent to which they are interlinked and why the terms are often confused as being synonymous. This is rather unfortunate since while the broader area of SHM is now a viable commercial proposition with a number of industrial proponents, extensive research (Doebling et al., 1996), has shown that after initial promise several decades ago (Adams et al., 1978), VBDD effectiveness in *automatically* detecting classical damage i.e. the so called 'level 1' (Rytter, 1993) still apparently remains to be proven for operational civil structures. This is a broad and challenging statement, but it derives from the experience of the authors and other well respected domain experts. For example researchers from Los Alamos laboratories who comprehensively studied this technology in the late 90s (Doebling et al., 1998) elaborated the unimpressive track record applications of this technology to civil structures, while remaining optimistic about the future potential with technology such as operational modal analysis. The very small 'signal to noise ratio' is a major problem with these techniques due to the effect of varying environmental conditions on the modal parameters, masking effects of structural changes (De Roeck, 2003). The scale of the problem is illustrated in Figure 1 for a 355m span suspension bridge (Brownjohn and Carden, 2008); natural frequencies of three major modes show variations due to a number of suspected or mysterious causes. At the coarse detail (left plot) the coefficient of variation of frequencies can be as high as 10%, while the fine detail (right plot) reveals a daily variation that might be linked to structure temperature but is believed to be a combined effect of variability in wind, traffic and temperature loads as well as in parameter identification. Even if there were any structural problems contributing to frequency changes, it would be necessary to 'peel away' the layers of temperature, wind, traffic and identification variability to reveal them.

VBDD methods are not limited to natural frequencies and there are several examples when dynamic performance and modal properties can be used by experienced engineers, for example to diagnose degradation of material properties and loss or change in function of supports and bearings (Wenzel and Veit-Egerer, 2010), or to assist in probabilistic post-earthquake assessment (Naeim et al., 2005), but such methods do not lend themselves to automation.

The failure of 'classical VBDD' (i.e. automated methods based on modal parameter changes) in previous decades has apparently influenced industrial acceptance of the broader VBM and SHM technologies that have extensive and proven capabilities for structural assessment. Indeed there are many success stories for both VBM and SHM, some reported here. Since SHM is now a major research area with a rapidly expanding literature, this paper aims to showcase successful applications of VBM and identify features that contribute to success.

The next sections of this paper describe some early benefits of simple forms of VBM, then describes the significant and promising developments of VBDD in the 1970s. The technology failures and various attempts to enhance VBDD are briefly described before presenting the broader technology of successful VBM through several case studies.

Early VBM and VBDD

Historically the most famous VBM operations have related to long span bridge monitoring. One of the earliest documented systematic bridge vibration monitoring exercises (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 their dynamic behaviour and possible consequences of an earthquake. Carder also studied dynamic behaviour of several buildings and other structures of the era (Carder, 1936a; Carder, 1936b), but the bridge performance studies are most relevant today. Vibrations of the first Tacoma Narrows Bridge during its short life were monitored by University of Washington (1954) before its collapse due to wind-induced instability and helped in the subsequent studies of aero-elastic instability.

In the 1950s and early 1960s, driven by demands from the aerospace, automotive and nuclear industries, technologies for dynamic testing and system identification advanced considerably (Bouwkamp and Rea, 1970; Hudson, 1976). Comprehensive reviews of this technology appeared in the 1970s (Hart and Yao, 1976; Ibanez, 1979) when its widespread use began to take off. This was the era of large scale tests using rotating mass shakers to excite dams (Rouse and Bouwkamp, 1967), buildings (Cherry and Topf, 1970) and even bridges (Tezcan et al., 1975), and these devices are still in use for large amplitude testing of structures (Yu et al., 2008). These exercises were usually not VBM, but in fact ‘structural identification’ or St-Id (Aktan and Yao, 1996) which included reconciling mathematical models with experimental observations.

The reconciliation became formalised through ‘model updating’ (Collins et al., 1974) not for civil infrastructure but with the example of the NASA’s Saturn V launch vehicle for the Apollo space program. This sensitivity-based procedure has provided the basis for model updating that has become increasingly used for civil infrastructure in the last decade, although there now exists a range of alternative methods (Friswell and Mottershead, 1995).

One of the early forms of VBDD developed in the 1970s (Cawley and Adams, 1979) in the context of non-destructive testing was based purely on natural frequency changes. This is heavily cited research whose original application was directed at a specific type of aerospace structural component i.e. a composite plate. The method was developed and used successfully for controlled conditions in a civil structure i.e. foundation piles (Lilley et al., 1982) but has been attempted (with very limited success) on a wider range of civil structures, with variations on the technique investigated by many researchers. VBDD has had a more successful track record in aerospace engineering (Manson et al., 2003) where damage detection remains a viable technology. Like successful practical applications to foundation pile integrity testing, VBDD applications in aerospace rely less on modal parameter changes and more on wave transmission and reflection.

Exploration and development of the North Sea and Gulf of Mexico oil and gas reserves in the 1970s resulted in creation of dozens of fixed platform structures operating in water depths of 150m or more and subjected to extreme environmental loads. Needing safe and cost-effective inspection, these structures were ideal candidates for application of the newly developed vibration-based diagnostic systems. These were not limited to VBDD; (Coppolino and Rubin, 1980; Kenley and Dodds, 1980; Shahrivar and Bouwkamp, 1980; Brederode et al., 1986) but also served to identify environmental and platform performance. So called 'Environment and Performance' data (Spidsoe et al., 1980) for Norwegian installations were collected ”*in order to assess the safety of the load carrying structure of the platforms and their foundation*”. The deliverables of this study are one of the tangible benefits of VBM i.e. identification of dynamic characteristics and load-response mechanisms for these critical structures leading to more rational designs.

Most of these studies concluded that detection was only possible under controlled conditions or where severe and usually obvious structural damage had occurred (Kenley and Dodds, 1980), and the technology was abandoned. Offshore installations are highly non-stationary systems: not only are they subject to extreme and variable environmental conditions but also continual changes operational to mass properties through structural modifications, loading or unloading of stores, fluid movements in processing plant and drilling operations that render attempts to decode modal parameter changes practically impossible.

It is now realised that for VBDD based on modal parameter changes to have a chance of working, procedures must incorporate procedures to compensate for or filter out the environmental and noise effects (Peeters et al., 2001; Deraemaeker et al., 2008) and be able to deal with effects of measurement and modelling uncertainties. Without such procedures, classical VBDD appears to be a fallacy for constructed systems (Catbas and Aktan, 2002).

Views of practitioners about viability of VBDD and VBM

The views expressed in the previous section are echoed by quotes from eminent (but anonymous) academics and consultants:

1) *“VBM is hard to be used for a damage detection exercise as vibration characteristics usually represent the global properties but are not sensitive to local damage. So far, the VBM systems we have been*

involved with have not captured failure in real structures, possibly because these structures are very important and have been handled very carefully throughout design, construction and management."

2) *"There is too much information in the data. This is mostly due to spurious causes e.g. lack of excitation, directionality of excitation, gaps in excitation bandwidth, interactions between loosely-coupled sub-systems, electronic interference, imperfect connections, imperfect power, many other sources introducing virtual data. The problem becomes how to identify and differentiate actual structural response from spurious response. This problem is daunting."*

3) *"Critical information about the structure can be missing in the data. This, in our experience, is mainly when best practices are not followed. When an application is framed as a structural identification problem, it is possible to augment excitation, design appropriate sensing and data acquisition, and, leverage advanced signal processing and post-processing to address this problem."*

4) *"I have concluded that the vibration-based approach does not provide adequate resolution (for damage detection) for most SHM applications."*

5) *"In my opinion, although changes in building dynamic characteristics e.g. period elongation, wavelet indicators, changes in mode shapes and damping etc. may provide indications of possible damage they are not reliable enough on their own to make a judgment whether damage has occurred. Reliance on these measures can result in false alarms because a variety of things other than structural damage can cause permanent or transient changes in dynamic characteristics."*

There is a common consensus here that difficulties with VBDD are fundamentally about poor signal to noise ratio: the 'signal', even if it conveys the relevant information is buried in noise of environmental effects, measurement errors and intrinsic variability of key modal parameters or metrics. Addressing such problems is the aim of current research in VBDD.

Modern VBDD

Despite the past practical failures, VBDD still attracts significant interest among civil structure researchers, aiming to transfer and adapt technologies that have been more successfully applied to aerospace structures. Alas the majority of such studies have been limited to laboratory exercises, although these are still able to provide useful insights for potential full-scale applications.

As a specific example, experimental evidence of effects of scour on bridge pier dynamic performance (Foti and Sabia, 2006) led directly to laboratory studies on structural integrity of a scaled twin-span masonry arch bridge model (Ruocci et al., 2009) in which the central pier has been subjected to progressively increasing settlement steps in order to simulate the development of the scour effect at the foundation base. VBDD studies on natural frequency and mode shape changes showed that transmissibility functions between pairs of accelerometers (Ruocci et al., 2010) were particularly sensitive to the tiniest structural changes, from the earliest stages of degradation. This is a simple method to apply and is planned for real bridges.

Several reviews of VBDD are available, including comprehensive evaluations by the team from Los Alamos Laboratories (Doebling et al., 1998), who reported the potential for techniques based on detecting nonlinear behaviour, along with some more recent contributions (Alvandi and Cremona, 2006; Carden and Fanning, 2004).

These authors found that modal strain energy and a derivative of modal flexibility method worked well on real structures they evaluated; the modal flexibility approach is now one of the more common approaches, and has been applied occasionally to full-scale structures (Catbas et al., 2006; Jaishi et al., 2007) and many times in more controlled laboratory studies e.g. (Catbas et al., 2008).

For buildings instrumented in seismic zones (for example as part of strong motion programs such as http://www.conservation.ca.gov/cgs/smip), as well as inter-storey drift, effects on wave propagation have been identified as useful damage indicators (Trifunac et al., 2003). Finally, damage identification is not in fact a deterministic exercise, but considers variability of parameters and probabilities of identification (Xia et al., 2002; Naeim et al., 2005).

In all of these exercises there are certain types of structural change to which modal parameters are more sensitive (with enhanced signal to noise ratio) and for which VBDD should be relatively effective, for example bearings and boundary conditions, along with general degradation of materials (Siringoringo and Fujino, 2008).

One significant technology enhancement that improves the potential of VBDD is the use of automated real time operational modal analysis (OMA). Although restricted to identifying frequency, damping and mode shape, there is significant potential for future developments in VBDD and VBM, with a few applications so far (Magalhaes et al., 2009; Brownjohn et al., 2010) proving capability and in the latter case demonstrating genuine capability for identifying significant changes in dynamic properties caused a major changes in the (thermal) loading regime and signalling a structural investigation.

More recent developments in OMA have addressed the statistical properties of the OMA-derived modal parameter (Reynders et al., 2008; Au, 2011) that relate to the reliability of the parameters used for vibration-based structural diagnosis. Together with machine learning techniques for identifying and compensating for effects of environmental and loading conditions on modal parameters (Cross E.J. et al., 2010), genuine automated VBDD, at least in the form of identifying genuine anomalies (level 1) is now feasible in real world (i.e. commercial) applications.

Long term dynamic monitoring, management of and interpreting of performance data

Extended monitoring generates large quantities of data, particularly for dynamic response, so that data reduction and data mining have become a major concern of continuous monitoring. Rationalisation of changes in performance parameters, a form of continuous VBDD, is a major research challenge, and more realistic short term aims relate to the ‘level 1 SHM’ (Rytter, 1993) where changes or anomalies in structural performance are identified and could indicate ‘damage’.

Data mining of time series is a relatively new aspect of VBMM that embodies ‘data driven’ technologies where physics-based relationships are not considered, rather the performance data are studied to reveal patterns, trends, relationships and anomalies. Examples are found in research studies of bridges of the Lantau Fixed Crossing in Hong Kong (Ko and Ni, 2005) and other bridges in Mainland China (Zhou et al., 2008). Procedures used include wavelets, neural networks, support vector machines, principal component analysis etc..

It is hard to find any cases where these methods have migrated from the research domain to practice, but this continuous VBM employing ‘level 1’ data mining techniques will increasingly be used to signal more detailed investigations and remedial action.

Views on present status of VBM

With advances in computing power, system identification, management of uncertainty and compensation for multiple influences, there is now a capability for reliable dynamics-based performance diagnosis of civil infrastructure. Automated real-time interpretation capabilities now range from threshold crossing to modal parameter identification, which with filtering of environmental effects can provide effective structural identification, potentially even of certain forms of structural degradation.

By demonstrating the benefits of VBM technology to stakeholders (infrastructure owners, operators and instrumentation/monitoring specialists) we hope to generate a more receptive attitude and motivation to consider the technology. This requires better communication between researchers and end users: compared to cutting edge research developments, convincing stakeholders and selling even part of the technology is at least an equal challenge.

Hence the second part of this paper provides a number of case studies that highlight successful real-world implementations, some of them commercial. The aim is to draw out the factors that lead to success as well as to advertise the technological achievements. Typically success is not purely a result of technology, it is achieved through a rational examination of the problem, having reasonable expectations and good project management. Another aim here is to identify what the reasonable expectations are and what it 'off limits' far beyond present capabilities.

Case studies in VBM

With the aim to showcase examples where VBM has been used successfully in practice, Table 1 summarises results of a survey on case studies provided by a number of leading research groups around the world. The studies are heavily biased towards bridges, with a few exercises on tall buildings and chimneys plus a few special structures.

Case study overview

Survey respondents were asked to provide:

- Structure name (optional)
- Structure type (e.g. suspension bridge, span >1000m)

- Reference (many examples have further information available from www.ishmii.org)
- One sentence statement about how the vibration measurements benefited the operator/designer/any other stakeholder, or how the measurements didn't quite measure up (e.g. failed attempts in vibration based damage detection or where noise/signal ratio defeated everything)

Of particular interest for this study is the purpose and benefit to the 'stakeholders'. Benefits reported include:

Direct assessment of the structure itself:

- Performance evaluation prior to and to assist retrofit
- Evaluation of construction process
- Conformation of retrofit effectiveness
- Structural condition assessment
- Direct measurement of cable forces

Direct assessment of quasi-structural attributes:

- Identification of load/response mechanisms
- Identification of aero-elastic effects
- Damping estimation for extreme performance evaluation

Assessment of effects of and control of response levels (serviceability):

- Evaluation of occupant comfort or fatigue
- Extreme load/performance evaluation
- Verification of vibration control system

Long term benefits for the wider engineering community:

- Evaluation of loading code provisions
- Calibration of software for use in other applications
- Evaluation of structural identification/model updating technology

- Feedback to structure designers for successive structures

Among these, there are no reported cases of ‘damage detection’ of operational civil structures. There are numerous cases where various aspects of the structural condition are revealed, e.g. example identification of stay cable forces features in several case studies. Performance evaluation of vibration mitigation measures is also a frequent outcome along with direct evidence supporting and subsequently assessing retrofit.

There are several cases of indirect benefits e.g. through loading code assessment/improvement, evaluation of structural/system identification technologies and providing information for future designs.

The case studies deliberately focused on real-world applications of continuous monitoring. This mostly ruled out the very large number of short ‘field test campaigns’ e.g. forced or ambient vibration tests that feed directly into structural identification (St-Id), although a few examples are included, as well as one relevant laboratory study. Realistically some of the long-term St-Id exercises are extended versions of these requiring longer duration due to the difficulties in controlling the experimental situation, such as management and measurement of the loading function. Hence the VBM activities for the purpose of St-Id typically relate to larger or taller structures responding to environmental loads such as wind.

Bridges

No less than 24 of the case studies concern bridges and of these eight (4, 10, 14-17, 26, 29) are long span cable-stayed or suspension bridges. Of these all the Asian bridges (14, 15, 26, 29) feature permanent monitoring systems which capture vibration data, others either have had temporary monitoring systems or were the subject of extensive vibration measurement campaigns. The remainder are a miscellaneous set of unusual bridges, including a footbridge (21), a railway bridge (31), two highway bridges deliberately damaged as part of research projects (23, 28) and one short span highway bridge (30) studied before and after retofit. Only for the 23 and 28 does it appear that the motive (and hence funding) was purely on a research basis.

In several of these bridge examples (4, 7, 8, 14, 18, 21, 24, 26, 29) a major motive was to learn how the bridge behaved under operational loading, often in relation to wind, occasionally in relation to seismic loads, twice in relation to vehicular traffic and twice concerning pedestrian-induced dynamic issues. In three cases (4, 14, 26) a specific aim of the monitoring was to provide knowledge useful for future bridge designs, and in several cases, various forms of vibration monitoring were commissioned to investigate the condition of the bridge or its components, in many cases focussing on behaviour of stay-cables (10, 16, 18, 22, 25).

As well as (23) and (28), the closest approaches to damage evaluation are a case of fatigue life estimation (30) and of evaluation after ship impact (14).

The Stonecutters Bridge example (29) is now influencing design of VBM technology in major new long span bridge projects, with an emphasis on combining advanced computer simulation with effective data interpretation.

Buildings

VBM is more traditionally applied to buildings, particularly in seismic areas where the practice is in some sense routine, yet there are only three (3, 6, 12) building case studies provided. However numerous case studies can also be found in (Naeim et al., 2005). The main interest here has been in recording and understanding in-service performance.

Others

Two chimneys (1, 2) and a TV tower (13) have employed long-term monitoring systems providing in-wind performance data through vibration response. The odd structure out is the JETPACS frame (5), included to represent structures such as the IASC-ASCE benchmark structure (Bernal and Beck, 2004) where thorough evaluations have provided useful results applicable to full-scale structures.

Case study conclusions

The case studies reported cover a range of applications, with the majority related to bridges. Of these, it is the long span bridges that usually have VBM considered as a component of an SHM system, although there are several examples where ‘static’ strain monitoring systems have been built in at the start (Brownjohn and Moyo, 2001; Barr et al., 1987).

There are also several examples where short term monitoring of strain has been used to capture dynamic effects of vehicles or assess load carrying capacity and performance reserves (Heywood et al., 2001; Moyo et al., 2004; Moyo, 2007).

In all the examples of commercial applications VBM technology has been a success. While we might not hear about the failures, it is telling that none of these exercises related to damage detection.

Some of the examples have been research-driven exercises to investigate the potential of VBM procedures, but the majority have been well planned exercises driven by clear objectives.

The main lesson is that VBM (but not VBDD) has an excellent track record and powerful capabilities for structural performance assessment and structural assessment. While VBM may not be used in commercial applications to identify damage it can clearly identify poor performance and provide evidence to support structural intervention to mitigate failure at either serviceability or ultimate limits states.

Recommendations

Considering the discussions, and the applications reviewed in this paper, the authors have the following recommendations and suggestions relating to VBM systems.

1. The most successful implementations are likely to be the simplest ones with clear deliverables and clear system specifications.

2. Cases where data only are provided by the VBM system and post-processing is carried out by the client or a third party are likely to result in unusable data due to poor choice of sensors, locations and acquisition parameters, hence analysis specialist/engineer should be involved in developing the specification.

3. Clients need to be aware that new technology needs to be evaluated in field conditions and as each implementation is in effect a prototype, they should have realistic expectations and a willingness to allow for lessons to be learnt on the job about applications of new technology or processes. This way the specialist learns better techniques and the client gets more than he bargained for.

4. In the spirit of this paper, learning from successes and failures requires clients to allow publication (with provisos) of case histories such as reported here.

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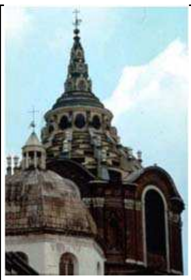
Table 1: The case studies

#	Structure and photo		Structure details and reference	How VBM benefitted the stakeholder
1	Rugeley Chimney		183m chimney: reinforced concrete windshield with inner refractory lining sleeves (Brownjohn et al., 2010)	Performance tracking of TMD, evaluation and confirmation of safety and serviceability, live condition assessment.
2	Smokestack ŠKO-ENERGO		200m reinforced chimney in Czech Republic (Veit-Egerer et al., 2009b)	One year of monitoring during which several storms were experienced provided evidence of unsatisfactory structural performance, leading to a retrofit program.
3	Republic Plaza		280m concrete shear core, steel frame office tower, 1995 (Brownjohn and Pan, 2008)	Provided evaluation of wind and seismic loads relevant to code development, assessment of structural design, foundation rigidity, vibration serviceability etc..
4	Humber Bridge 		1410m suspension bridge, 1981 (Brownjohn et al., 1994)	Calibration of software used by Politecnico di Milano for design studies of Stretto di Messina Bridge, identification of loading mechanisms, identification of aero-elastic performance of box deck.

5	JETPACS 	Scaled (2:3) 2-storey 1-bay steel frame building structure, with concrete slab floors. Floors' width: 4m x 3m. Inter-storey height: 2m (Matta et al., 2009)	Identifying significant contribution of secondary structural member to dynamic performance.
6	The Holy Shroud Chapel in Turin 	Heritage masonry structure (De Stefano et al., 2008)	Dynamic testing and model updating exercise, providing models as the starting point for the following phase of damage detection and structural health assessment. The updated models supplied by the multi-model approach represent a useful resource in order to estimate the health condition of the building.
7	Brooklyn Bridge 	486m span suspension bridge, 1883 (Grimmelsman and Aktan, 2005)	Dynamic characterization of towers by ambient vibration measurements for seismic evaluation and retrofit investigation of the bridge.
8	Henry Hudson Bridge 	Steel arch and viaduct spans, 1936 (Grimmelsman et al., 2007)	Dynamic characterization of towers by ambient vibration measurements for seismic evaluation and retrofit investigation of the bridge.
9	Clifton suspension bridge 	214m span cable-stayed bridge, designed by IK Brunel, completed 1864 (Macdonald, 2008)	Measurement of severity of crowd-induced vibrations.

10	Second Severn Crossing 	456m main span cable-stayed bridge, 1996 (Macdonald, 2002; Macdonald et al., 2002)	Estimation of damping of cable stays, in particular the effect of corrosion protection wax on damping (found to be insignificant), in relation to mitigating rain-wind induced cable vibrations. Cross-ties were subsequently fixed to the cables. Measurement of large amplitude vortex-induced vibrations of the deck and estimation of structural damping and wind turbulence intensity, which were important parameters in the behaviour. Data were used for validation of wind tunnel tests, leading to an aerodynamic solution, proven by full-scale measurements after installation of baffles.
11	Bridges over Gariep Dam spillways 	Short span RC bridges (13m span) (Moyo et al., 2009)	Vibration measurements helped engineers understand how the bridges behaved before and after retrofitting interventions, in particular how the bearings functioned and regarding transverse behaviour.
12	Di Wang Tower, Shenzhen 	384m tall building, RC core, steel columns and beams (Xu and Zhan, 2001)	A vibration measurement system and wind measurement system were installed in 1999, just before Typhoon Sam and Typhoon York attacked the area (Typhoon York wind speeds were equivalent to 50-year return period). This provided a rare opportunity to examine wind-induced vibration and human comfort of the skyscraper under the standard design loading
13	Guangzhou New TV Tower 	612m twisted lattice outer structure, RC core, 2009 (Ni et al., 2009)	A comprehensive structural health monitoring system has been installed on the tower. The vibration monitoring system not only provides the client the vibration level of the structure under extreme loadings (wind and earthquake), but also verifies the effectiveness of the structural form. The effectiveness of active/passive sway damping solutions can be checked.
14	Tsing Ma Bridge 	1377m main span suspension bridge, road and rail traffic (Wong, 2007)	The monitoring system of the bridge has been operating for more than 10 years. It has provided huge amount of data to the operator and researchers to verify some new theories and technologies employed in the structure which carries both highway and railway traffic. These data and technologies have been applied to the design activities of other bridges in Hong Kong and have strongly influenced design of other monitoring systems e.g. for Forth Replacement Crossing.

15	Jiangyin Yangtze River Bridge	1385m main span suspension bridge (Zhou et al., 2008)	The online vibration monitoring system has captured the vibration of the bridge under a ship-collision event. This rare and precious data enable the researchers to evaluate the condition of the long-span bridge (1385m main span) under this extreme loading. Response to ship impact is a major concern for such bridges.
16	Øresund Bridge	Cable stayed highway/railway bridge (Larsen and Andersen, 2007)	The vibration monitoring in combination with weather records provided proof of the cable vibration mechanism (ice/wind induced galloping). The combined vibration/strain monitoring of cable supporting outriggers provided decision basis for initiating retrofit of the outrigger as measurements showed too short fatigue lifetime due to cable vibrations.
17	Great Belt East Bridge	1624m main span suspension bridge, 1998 (Andersen and Fustinoni, 2006; Frandsen, 2001; Larsen et al., 2000)	Early measurements studied the vortex-shedding induced response and helped design the mitigation strategy. The vibration monitoring in combination with weather records provided prove for the cable vibration mechanism (ice/wind induced galloping).
18	Alamillo Bridge, Seville 	200m main span cable-stayed bridge with raked pylon, 1992 (Casas and Aparicio, 1998; Casas, 1994; Casas and Aparicio, 2010)	First measurements were made to verify the dynamic characteristics of the bridge to assess the good performance to wind vibration. That was important since a cable-stayed bridge with such structural configuration was never built before. Later measurements were used to estimate the actual forces in the cables after bridge completion and their evolution in time as a health monitoring tool 12 years later, the cable measurements were repeated and also the problems related to rain-wind induced vibration solved thanks to a vibration analysis of the cables.
19	Huelva Bridge	Pre-stressed concrete highway bridge with a total length of 20220m (typical span length of 40 m) (Casas, 1997)	The main outcome of the vibration analysis for the owner was to know the correct behaviour of the bridge when subject to forces in the horizontal plane. This issue was of high importance as the bridge was founded in a very heterogeneous and soft soil.

20	Europa-Gate bridge, Barcelona 	242m span bascule steel bridge, Barcelona Port, 2000 No publication	The dynamic test allowed to check the correct behaviour of the lifting mechanisms and also to check the correct continuity and clamping between the two half parts when the bridge was closed and in operation mode.
21	Coimbra footbridge 	Two half-steel arches supporting composite deck, designed by Adão da Fonseca and Cecil Balmond, (Moutinho et al., 2008)	Assessment of serviceability and confirmation of TMD performance
22	Infante D Henrique Bridge 	Pre-stressed concrete arch bridge, main span 280m, 2002 (Magalhaes et al., 2008)	Assisting construction process through tracking of temporary stay cable forces.
23	Z24 bridge 	Three-span (14/30/14m) skew concrete box girder bridge, 1963 (Maeck et al., 2001)	Used in a benchmark study for evaluation of vibration-based damage detection methodology and of procedures for correcting for temperature changes.
24	Europabrucke 	Mutli-span steel box-girder bridge with tall concrete columns, Innsbruck (Veit-Egerer et al., 2009a)	The Europa Bridge near Innsbruck - Austria, opened in 1963, is one of the main Alpine north-south routes for urban and freight traffic. Currently the bridge is stressed by more than 40000 motor vehicles per day. The combination of measuring and analytical calculation over the past years has led to a detailed system identification. Due to the requirement to assess the prevailing vibration intensities with regard to fatigue problems and possible damage, a permanent measuring system has been installed in 2003. Extensive lifetime studies including the influence of mitigation measures have been performed.

25	Taichung Cable stayed bridge 	Double 89.5m span arch/cable-stayed bridge, Taiwan (Wenzel and Veit-Egerer, 2007)	Assessment of cable forces and pylon behaviour. Unfortunately the comprehensive monitoring system did not provide a follow up contract for data evaluation.
26	Ting Kau Bridge 	Cable-stayed bridge with 448m and 475m main spans, 1998 (Wong, 2004)	Verifying design assumptions for future bridges, with similar benefits as for the Tsing Ma bridge. Also provided check on in-wind performance and validation of wind tunnel predictions.
27	Westend Bridge 	Multi span pre-stressed RC box girder bridge, Berlin (Rohrmann et al., 2000)	The Westend bridge is a structure studied by BAM over a long period with several investigations to develop dynamic approaches for the inspection of bridges including SHM. Many of the questions bridge owners have, like actual acting static traffic loads, dynamic amplification factors or combined loadings due to traffic and temperature or condition monitoring and the automatic detection of damage cannot be answered without SHM.
28	Bridge Object S101 Reibersdorf, Austria 	Short span concrete overpass (Wenzel et al., 2009)	Demonstration of ability to determine and localise problem zones in a short span bridge. Comprehensive damage identification has been validated by this destructive test campaign. A rare example of practical VBDD, but not for operational structure.
29	Stonecutters Bridge 	1018m span cable-stayed bridge, 2009 (Wong, 2010)	Real time modal analysis coupled with finite element analysis provides validated finite element model used for computing stress histories, correlation of stresses and forces/moments against temperature, wind. Accelerometers represent only a fraction of the 1500 sensors on this bridge.

30	Pioneer Bridge 	18.2m span comprising precast pre-tensioned inverted T-beams supporting a RC slab (Brownjohn et al., 2003)	Monitoring of dynamic strains over a period of several weeks before and after upgrading showed changes in extreme values of strain for given return periods, confirming effectiveness of upgrade (and that it was perhaps unnecessary)
31	Kalbaskraal Bridge 	2x32m span wrought iron truss (Moyo, 2007)	Dynamic testing and model updating followed by dynamic response monitoring characterised strain regime in order to predict fatigue life for a range of increased loading conditions.

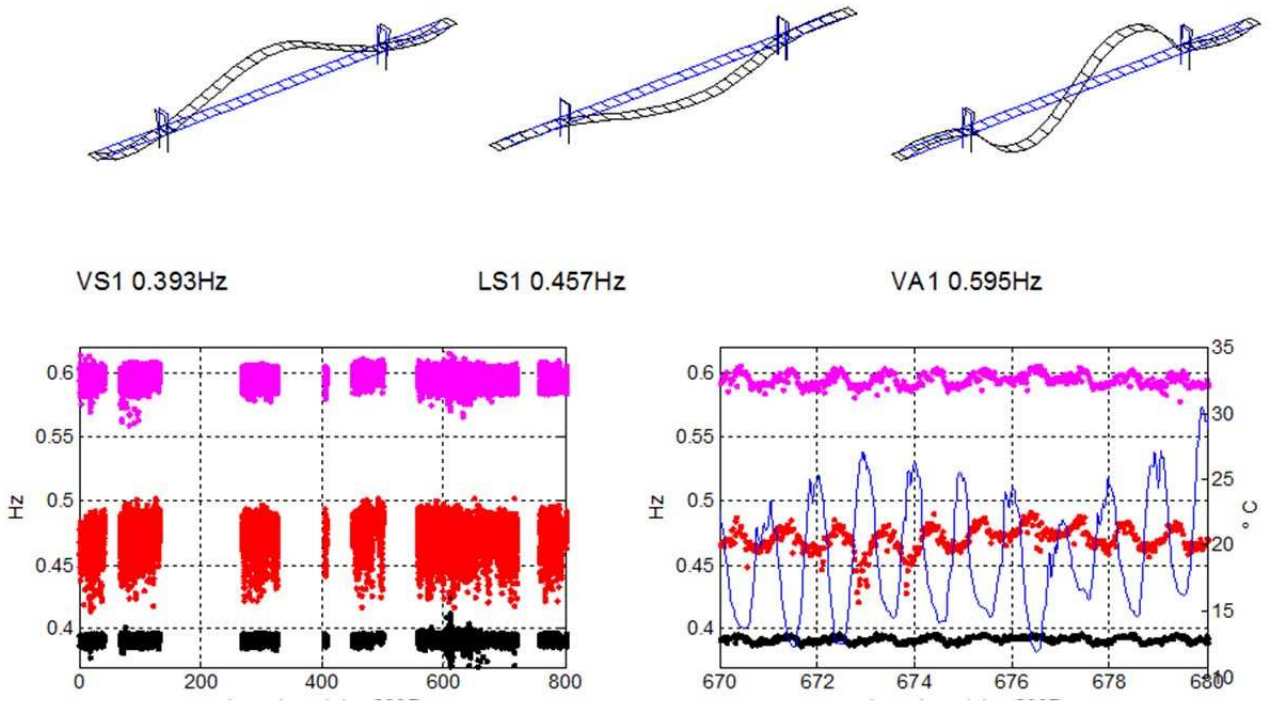


Figure 1: Variation of estimates for first three natural frequencies of Tamar Bridge from continuous monitoring. Specific values were identified during modal test in April 2006.