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Practicalities of structural health monitoring

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Abstract. Structural Health Monitoring (SHM), particularly remote monitoring, is an emerging field with great potential to help infrastructure owners obtain more and up-to-date knowledge of their structures. The methodology could provide supplemental information to guide the frequency and extent of visual inspections, and the possible need for maintenance. The instrumentation for a SHM system needs to be developed with longevity and the objectives for the system in mind. Sensors need to be selected for reliability and durability, sited where they provide the maximum information for the objectives, and where they can be accessed and replaced should the need arise over the monitoring period. With the rapid changes now occurring with sensors and software, flexibility needs to be in place to allow the system to be upgraded over time. Damage detection needs to be considered in terms of the type of damage that needs to be detected, informing maintenance requirements, and how detection can be achieved. Current vibration analysis techniques appear not yet to have achieved the necessary sensitivity for that purpose. Societal factors will influence the design of a SHM system in terms of the sophistication of the instrumentation and methodology employed.

Keywords: structural health monitoring; performance assessment; infrastructure management; smart structures; structural maintenance; damage detection.

1. Introduction

As infrastructure shows signs of failure, a structural health monitoring (SHM) programme can become a valuable tool for monitoring in-service performance, potentially assessing damage and indicating signs of the progression of failure. Such a programme can also be helpful in the long-term monitoring of new materials and innovative designs used in new construction. In recent years, many owners have seen the benefits to implementing structural monitoring programmes and are using them more and more in lieu of, or in addition to standard inspection procedures. However, the requirements for different projects can be highly diverse: implementation may occur over a large range of structures from historic masonry through pipelines to long-span bridges.

In order to create a successful SHM programme, one should define SHM. Consensus has not been reached on the definition for an SHM programme, which can consequently lead to much debate on the

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relative suitability and applicability of various projects as SHM projects. The most widely accepted definition of SHM is “the use of in-situ, non-destructive sensing and analysis of structural characteristics, including the structural response, for detecting changes that may indicate damage or degradation” (Housner, *et al*. 1997). Others argue that this definition needs to be adjusted to meet the end requirements of the owner of the structure and should represent methods of identifying if damage has occurred, determining the location of damage, estimation of the severity of damage and evaluation of the impact of the damage of the structure (Sikorsky 2000). Yet another definition is “the measurement of the operating and loading environment and the critical responses of a structure to track and evaluate the symptoms of operational incidents, anomalies, and/or deterioration or damage indicators that may affect operation, serviceability or safety reliability” (Aktan, *et al*. 2000). Whichever definition one chooses, the ultimate aim of a SHM programme is knowledge of the integrity of in-service structures on a real-time basis. A clear differentiation must therefore be made between programmes designed to monitor the initial performance of a structure for a set short time period at the beginning of the service life of a structure, an initial performance assessment (IPA), and a SHM programme which is intended for long-term monitoring goals. The shorter time span of an IPA can allow for very different programme designs in comparison to those for SHM. A SHM system should be able to provide, on demand, reliable information pertaining to the safety and integrity of a structure. The information can then be incorporated into management and maintenance strategies for the structure, as well as the adaptation of pertinent design guidelines.

Structural health monitoring is a complex issue and most engineers have little experience setting up monitoring projects. Little is known of the instrumentation and techniques available. In all SHM projects, the instrumentation and results should be assessed against the defined needs. Since a SHM programme is required to obtain specific informational objectives over a long time, the exact requirements for a particular structure (the what, how and where) need to be investigated to define the necessary elements for monitoring. The level of flexibility in the requirements needs to be stipulated very early in the design phase. For example, the simple fact the system needs longevity dictates certain necessities for sensors and data acquisition systems that need to be considered in the design phase and will consequently affect the implementation and operational phases. This said, not all requirements that should be considered are technical. Social and aesthetic requirements are equally important and will influence the design of a SHM programme. Specifically, a careful, well-rounded and well-informed design phase is much more important to a successful SHM than any other single consideration.

We aim here to discuss the basic elements necessary in a structural monitoring programme as determined through our experiences, critically analyse the pitfalls that are often encountered and suggest methods for ensuring the successful implementation of a SHM programme. Thus we discuss what we see as important considerations for a SHM system. Our comments are influenced by critical analysis of a bridge project originally designed as an IPA and evaluated for conversion into a SHM. With hindsight, the project was found not to be sufficient to meet the requirements for a SHM programme. Our comments highlight many obstacles which we understand from discussions with colleagues are commonly encountered and potentially not considered as issues at the start of a project. However, many of the “errors” which arise from these issues are preventable through education, dissemination of the discussions of the experiences of others in trying to create successful SHMs. By relating these experiences, we hope to ensure that others will have some background for creating a successful SHM programme and provide important items for consideration in the design phase.

2. SHM is long-term

The key to any good structural health monitoring system is the ability of that system to be working when the events happen for which the monitoring was implemented - for example an event such as the failure of a post-tensioning wire in a post-tensioning cable. In some cases, this will mean the sensors and data acquisition must function continuously for many years and in other cases perhaps periodic monitoring will suffice. In either case, the longevity of the structural heath monitoring system must be established in the planning stages.

In the bridge project, a monitoring programme was designed to compare the performance of two reinforcement types used in a suspended lower deck of a two-deck bridge (Fig. 1) for the first few years after construction. The owner wished to know if a fibre reinforced polymer reinforcing system was performing similarly or otherwise to standard mild steel reinforcing (Shrive, *et al*. 2002, 2003). The system implemented used sensors and acquisition methods to meet this end and was not designed for survivability: the instrumentation and initial results are provided in Shrive, *et al*. (2008). It will probably be more than twenty years before the bridge begins to show signs of damage and deterioration, i.e. changes in its "health". Thus, the monitoring system implemented cannot accurately be called a SHM programme as it was, in essence, only an initial performance assessment programme (IPA).

2.1. Sensor type and location

In general, sensor type and location should be carefully considered in regards to the desired outcome. The best sensor type will be that which can indicate the desired information or expected potential damage for that particular structure. It may be that the desired information can be acquired through inexpensive sensors and periodic readings; or a more complex system may be required with readings taken on a continuous basis.

For example, considering that the desired goal of the bridge project was to compare the reinforcing materials of the lower deck, there was a commitment to place strain gauges on the reinforcement (Fig. 2). However, placing the gauges on the reinforcement was actually not the best choice. Analysis of the

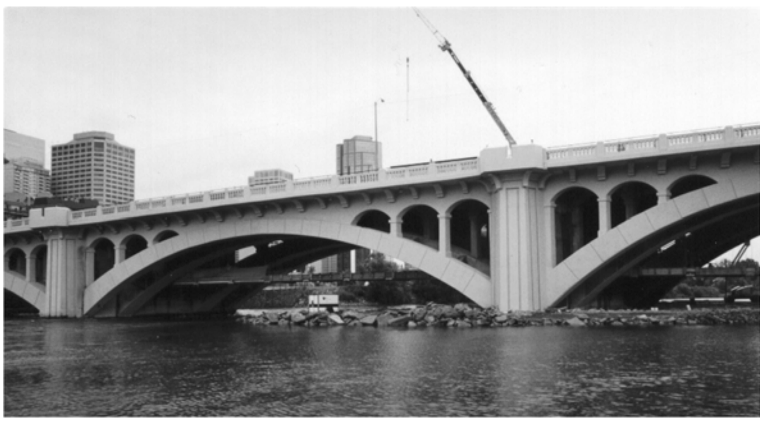


Fig. 1 The Centre Street Bridge, Calgary, showing the lower deck (the deck that was monitored) under re-construction

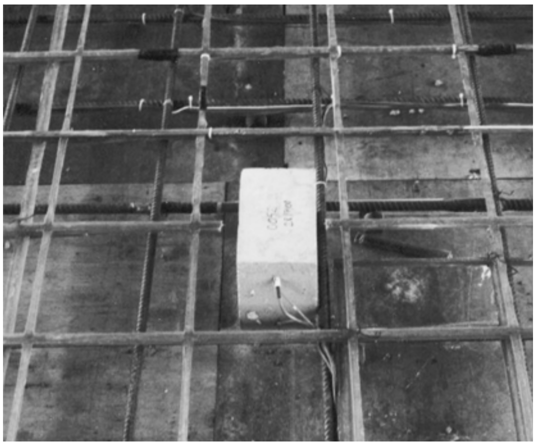


Fig. 2 View of part of the deck with glass fibre reinforced polymer (GFRP) in the upper reinforcement mat, prior to pouring of the concrete. The steel reinforcement of the lower mat is also visible. A concrete block containing an embedded concrete gauge is in the centre of the picture, while in the upper half, gauges on the GFRP are wrapped in tape. Wires from other gauges are tied to the reinforcing bars

final transformed deck section (designed after the commitment to place strain gauges on the reinforcement had been made) revealed that the reinforcement was extremely close to the neutral axis of the deck when the structural steel rigidly attached to the deck with studs was taken into account. Consequently, readings from the strain gauges were extremely small and it was hard to isolate strain response to live loads. The sensitivity of the gauges (15 $\mu\varepsilon$) was a significant proportion of the readings recorded - about 70 $\mu\varepsilon$ for a 7 ^{o}C temperature change. Gauges could have been better placed in locations with greater strain activity; in places closer to concrete surfaces or on the top surfaces of beams and stringers.

2.2. Data acquisition, transmission and analysis

On this bridge project, data were acquired with a prototype system which used Cellular Digital Packet Data (CDPD) to transfer files to the University on demand. A total of 10 data units were used at the bridge; each unit was downloaded on an individual prompt from the user.

Data were acquired every 15 minutes and then stored on the data unit CPU. However, due to limited space, the CPU filled with data in four months, at which point the older data would start to get overwritten. Originally data were acquired every 5 minutes but that rate of data acquisition was found to fill the unit capacity too quickly and there was little gain in information at this rate compared to every 15 minutes. Even with the reduced the rate, over 10 GB of data could be generated in a few months and the bulk of these data was not of much value. Designing a filter tree to delete valueless data and buffering the data for a specific time period could have eliminated some of these issues.

The CDPD transmission method was unreliable. The units seemed to have trouble in cold weather. In addition, CDPD is becoming a less used method of transmission and maintenance of the system has become more infrequent. Consequently, interference issues were a big problem; connections with the system on the bridge were hard to establish long enough for complete transfer of the data. This problem was exacerbated with large file sizes. A consistent downloading schedule, over a reliable system, would have eased these issues. Other data transmission methods such as GPRS (ground packet radio service) do exist and are in higher demand, i.e. better maintained, than CDPD and could be a much better choice.

An alternate power source for the data acquisition system is also a must. The bridge project employed a battery back-up to the data units in the event of a power failure. This power back-up allowed the continual collection of data and no data would be lost due to power problems. The back-up system can be designed for shorter or longer periods depending on the expected lengths of outages or the import of ensuring all data are recorded. The ability to bridge power surges or power outages should be designed into a SHM system and in this regard, the bridge system worked well.

Long term operation of a project can incur ongoing costs and consequently continuity of budget is also an issue that needs to be accounted for. For example, on the bridge project, monthly bills for the phone line and finances to pay someone to download and analyse data continuously over the months, would become prohibitive for a single structure over a longer time span. Recent research indicates that sensor networks can be set up to be more power efficient, in that some sensors can be assigned to a “sleep” mode when they are unlikely to capture events of interest (Farinelli, *et al.* 2008). The distribution of sensors can also be optimized so as neither to over-monitor nor under-monitor a particular area, and account for the loss of some sensors (Rahman and Hussain 2007). These refinements could help produce an efficient network and reduce the cost of operating the monitoring system without losing efficacy.

From the above, it would appear sensible to do most data processing on-site. This could involve the use of an artificial intelligence algorithm that is trained over time to recognize normal behaviour of the structure. Anything abnormal can be sent to the engineer responsible for interpretation and a decision with respect to action. “Normal” data could be held temporarily in a buffer so that the engineer could download them if desired to build a record over time of the behaviour of the structure. An alternative would be to use the internet to move data from the remote site to a central processing facility where any abnormal data could be flagged and inspected. In this sort of arrangement, a number of structures could be compared in real time. The data processor (a person) could also alter the filtering algorithms to account for activity on a particular structure (e.g. repairs and construction) or fine-tune the filters. In either instance a computer is required on-site, meeting the definition of Spuler, *et al*. (2008) for remote monitoring. This computer will need a power source. If there is no electricity supply easily available nearby, then batteries need to be considered, and some form of recharging them - solar panels for example.

2.3. Reliability, durability and accessibility

In the bridge project, installation and placement of the reinforcing and pouring of the concrete created many opportunities for gauges and their wiring to be damaged. Care was taken to try to minimize this damage but nevertheless when the gauges were connected after construction, many gauges were already non-functioning. Since the gauges’ placement on the internal reinforcing of the deck left them inaccessible, no subsequent repairs could be made to either gauge or wiring. Sensors should therefore be placed in accessible locations where they can be repaired or upgraded over the monitoring period, as technology and the parameters of the system change.

A further problem arose from the temperature exposure of the gauges. Specialized equipment was used to make an initial assessment of some fibre optic gauges. Only 7 of 16 gauges appeared to survive construction. A month later, after a few really cold days, a test was performed and readings from the fibre optic gauges were again taken: by this point only 1 of the 16 gauges was readable. Such high failure rates can be attributed to a lack of gauge durability to weather extremes or poor installation quality control. However, again, due to the inaccessibility of the gauges, no remedial action could be taken nor the reasons for failure confirmed. This problem was not confined to the fibre optic sensors:

throughout the two year monitoring period, some electric foil gauges also failed either due to mechanical failure or debonding. In contrast, in other projects, provided the gauges make it through installation and are adequately protected from alkaline attack, that strain gauges can have a high survival rate and are quite durable (Damson 2001).

Other projects involving other sensor types, such as monitoring the lean of the Leaning Tower of Pisa show how changing technology has been implemented to measure the lean more accurately over the years with simple yet consistent methodology. Much of the instrumentation on the Confederation Bridge between Prince Edward Island and the mainland can be replaced if damaged (Brown 2007). Externally applied acoustic sensors can also be replaced or upgraded, as can the data acquisition technology and software (Paulson 1999).

2.4. Documentation

The continuous data obtained through monitoring need to be verified as still reasonable. In many cases, the occurrence of damage or changes to the structure will occur long after the installation process and long after the personnel who installed the system have stopped working with it. Documentation needs not only to indicate the sensors throughout the years, but also to examine the data: the changes that occur over time are often the purpose of implementing the system in the first place. The installers will know what changes were made to the originally planned system during installation, and the problems encountered. These individuals were probably also responsible for developing the initial "healthy" picture of the behaviour of the structure. Continuity of the knowledge is important. The knowledge possessed by the first analysts needs to be archived for future analysts.

On the bridge project, the installation of the sensors became pressured due to the time constraints of construction objectives (completion of formwork, steel layout, pouring of concrete) and complications that reduced the allotted times in contractor schedules. The first major issue was that during installation of the instrumented bars, the contractor imposed a site decision that the location of the data acquisition system had to be moved. This forced a flipping of the layout of the gauges which meant that cable lead lengths were wrong, and additional connections were required. The sensor numbering system required on-site revision. The consequence of these changes, the on-site mark-up to the plans, the incapability to return and check the mark-ups, in addition to the pressure to complete the installation for progression of construction and a timely bridge re-opening, resulted in quality control being jeopardized.

As any good electrician knows, good labelling is imperative. Labels need to be concise, durably attached and durably legible. Plan mark-ups should be generic enough that anyone can understand and yet specific enough that the intent is never confused. Documentation should be kept up-to-date and accurate; maintained by a single person, stored and backed-up. It is also advisable to make daily back-ups of all the information obtained that day and stored in a separate location to the operating file. Neat, labelled and organized installations will reduce confusion when returning for maintenance checks. Many of these issues are related to good project management and good communication between the parties involved. The priority placed on getting the SHM system in-place needs to be sufficiently high such that sufficient time is allotted in the project schedule to ensure careful implementation.

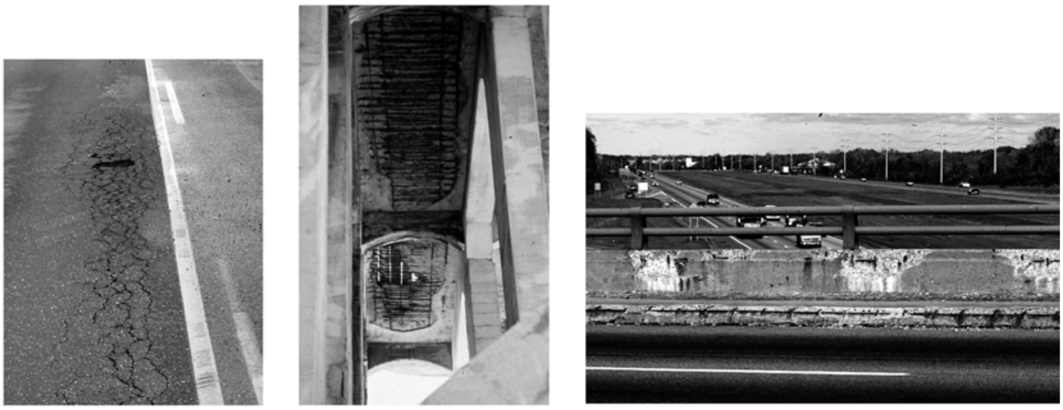
3. Damage detection, if possible, requires careful planning

Many researchers have argued that damage detection is theoretically possible (e.g. Casas and Aparicio

1994, Chen, *et al*. 1995, Hjelmstad and Shin 1997, Khattak and Cheng 2002, Shi, *et al*. 2000, Zhou, *et al*. 2002). However, results from our project demonstrated just how difficult this might be in practice. The argument is that by comparing data of the "healthy" structure to data from the structure when damaged, that the damage can be located and the extent of the damage determined. Both static and dynamic tests were performed in the bridge project to verify the daily recorded strains from the continuous acquisition system. A finite element model was also created and used to generate a set of healthy data. The concept was that in the future these healthy data would be available for comparison and analyzing the effects of time and damage to the structure. Due to sensor placement, the static test strain data gave very low readings, within the sensitivity of the gauges, thus making the strains that could be expected from the bridge indeterminate; healthy or damaged. The dynamic test, performed with accelerometers, produced very noisy data, which had too many uncontrollable sources of error and did not give an adequate enough picture of the bridge to determine healthy data with any degree of confidence.

In addition, the most likely form of damage to the bridge is cracking of the deck, loosening of a bolt in a structural steel connection (which is still attached to the deck through studs) or most drastically, the breaking of a suspension hanger. None of these damage types would be noticeable through the data being obtained by the sensors because the sensors would be insensitive to changes in behaviour that such damage would cause. Had the system initially been intended for damage detection rather than reinforcement comparison as designed, other sensor locations and/or types would have been used. A retroactive objective change is very hard to accommodate with a fully designed system. Additionally, many factors on site such as temperature, humidity, shrinkage, creep and settlement can cause behavioural changes in the structure. Attributing shifts in readings only to damage and not to any other factor that may have changed, is tenuous. One possibility would be to develop and incorporate a probabilistic model or uncertainty threshold when examining variations in sensor readings, to indicate the probability of the variation in reading being caused by damage. Nevertheless, the responsibility for data interpretation must lie with the appointed individual. Alternatively, or in addition, extra sensors to manage such factors could be included in the monitoring programme to minimize potential misinterpretation of reading shifts; however, this adds new cost, data acquisition and analysis issues. Consequently, damage detection has to be carefully planned and the sensors located such that they will be sensitive to the changes that damage is most likely to cause.

It has been argued that damage to a bridge can be detected from changes to the frequencies of vibration. However, the modal frequencies will vary slightly with ambient conditions (temperature, humidity, number of vehicles on the bridge). Once the normal range of variation for a particular mode of vibration has been established, one has to consider whether any damage might make a difference that can be detected as being outside of this normal range. For example, for a reinforced concrete bridge girder, all the cover concrete below the flexural tension reinforcement could fall off. This would make no difference to the stiffness of the girder, as it is likely cracked in the first place, and thus would not change the flexural stiffness of the beam. There would be a slight drop in the mass of the beam, which would make a small change in the flexural vibration frequency, but would that change be big enough to detect as being significant? The damage described should certainly be repaired to prevent more drastic damage. Humar, *et al*. (2006) argue that no vibration based techniques for detecting structural damage were robust or sensitive enough to be reliable. Similarly Park, *et al*. (2002) indicated that for a large structure, the effects of what they defined as low levels of damage were in the noise of the measurement data. Yet it is these levels that need to be detected and repaired. Typically the engineer responsible will not wish substantial damage to have occurred before being alerted and instituting repair and maintenance



(a) (b) (c)

Fig. 3 Superficial damage that requires repair before structural damage develops, and that is unlikely to cause a change in the dynamic response of a structure. (a) Cracks and a pot-hole in a bridge running surface; (b) Spalling of concrete from the underside of a bridge beam; and (c) Spalling and staining of a bridge parapet

measures. The examples of damage shown in Fig. 3 are at levels where repair needs to be instituted, yet the damage is unlikely to have had a detectable structural effect. Further developments in damage detection techniques through vibration analysis are therefore needed for the level of damage that needs to be detected to be identified with confidence. In the mean time damage needs to be detected by some other means.

A different approach to damage detection from comparing the healthy and damaged states is acoustic monitoring (Tozser and Elliott 2000). This method is applicable to high tension cables where fracture of a single wire in a cable can be detected (heard), Assessment of the rate at which such events are heard gives an indication of the general state of the structure, and can be used to estimate when a more thorough examination needs to occur. Tozser and Elliott (2000) describe applications to a post-tensioned parking garage, a post-tensioned bridge, a suspension bridge and a cable-stayed bridge.

4. Societal issues

The bridge which we instrumented is one of the oldest bridges in the City and is considered a historical landmark. Not only is it a heritage structure but it is also one of a few routes across the river for daily traffic and very heavily used. When the bridge was under repair, the City was responsible for restoring it to its original state as much as possible with supposedly no change to its external appearance. The lower deck was added to the bridge some while after the original single deck construction. Many of the features of the original structure, that are hard to preserve and match, are not present on the lower deck. Nevertheless, since the lower deck has constituted part of the overall bridge appearance for many years, all designs for elements of the monitoring system had to blend into the bridge and be as inconspicuous as possible. The colour of all conduits, junction boxes and acquisition boxes had to blend with the concrete and be inconspicuous and unobtrusive. Concrete grey was easy to match, but on other projects, restraints of this kind could be costly and difficult to implement with ease. Depending on the age of the structure to be monitored, the building layout and design, these constraints could be much stricter and require a lot more ingenuity.

Another possible constraint to design is the degree to which the structure is in the public eye. For some owners, alerting the public to the fact that the structure is being monitored could cause alarm amongst members of the lay population. For this reason, discretion with placement of the sensors and the monitoring equipment could be needed. This could affect the overall appearance of the system, the routes cables can or cannot be run and the method of data transmission. System design choices need to accommodate these public issues, yet maintain the value of the information that will be obtained, accessibility and budgets.

In the same vein, another concern is the degree to which the system may be susceptible to tampering and vandalism. Again, this reduces the design choices available for the system and the possible locations at which various elements can be placed and connected. On the bridge project, the data acquisition system was placed 20 feet above ground level on an abutment to avoid possible tampering from pedestrians on the city pathway below. However, this made access to the data acquisition system difficult for installation as well as research and maintenance staff. Component sizes in any system may be constrained by the physical size of protective boxes and space available.

The style and design of a feasible SHM programme will be reflected in the available budget and the budget, in turn, reflects the thinking of the people and interest in the structure, be it preservation, innovation or risk management. A public or government that is interested in evaluating new ideas, reducing operating costs to structures through real-time maintenance indicators or even monitoring of rapidly deteriorating historic structures to reduce future damage impacts, would be more likely to provide adequate funding for SHM projects. This would increase the capability of designers to implement more comprehensive SHM programmes in a particular project. The bridge project was a reflection of an open-minded, forward-thinking City administration with many groups interested in supporting and investigating new ideas. This attitude is shared by some infrastructure owners and by citizens of some cities. However, in other locales there is not the same interest in innovation or in maintenance of current or heritage structures.

5. Evaluation for best practice

Once a SHM programme has been designed, implemented and is functioning, it is important to provide summaries for other future designers. Most projects will not run smoothly, encounter issues during implementation and operation and will usually have “lessons learned” worth passing on. Many of the lessons from the bridge project are basic and could easily be overlooked by a first-time SHM designer. Practical experience is often the best teacher and since SHM programmes are often not a common occurrence for engineering practitioners around the world, many obstacles are encountered that have been encountered before but are not common knowledge.

Some obstacles and concerns were avoided through discussions with other individuals who had been involved in other SHM programmes and with experts and technicians who had previous exposure to the equipment. In a large part, each participant in the project only had a small piece of information to include in the overall design and functioning of the monitoring programme. However, each part was valuable and many more obstacles would have been encountered without the input from so many knowledgeable people.

Each SHM programme needs to be custom designed for each project and usually the design process will start by outlining the goals and objectives of the programme. How best to achieve these goals will depend on budget, available technology and expertise and the physical constraints of the site. The transfer of the constraints to a system that functions and meets the SHM objectives in the field is complex but can be eased if discussions of the practicalities of SHM programmes were more readily available as background material. SHM is not a precise science and the technologies used in SHM are changing rapidly, but the basic principles and the steps needed to ensure that one can create, manage and maintain an effective structural monitoring system, for the required design life, are the same for every project.

6. Conclusions

Structural health monitoring is a long-term activity and the system must be designed with longevity in mind. Sensors need to be located where they can be replaced and/or upgraded if they fail. Sensor durability is a primary concern. Sensors also need to be placed where the most sensitive response is expected for the information sought from the monitoring programme. Data acquisition and assessment needs to be thought through so that large volumes of valueless data are neither transmitted nor processed at great cost. The methodologies employed for interrogating data to alert the user of an event of interest should be adaptable to changing circumstances over time - notably in hardware and software. Installation needs to be well-documented and labelled. Time needs to be allotted to these activities to ensure the quality of the project.

If one of the objectives of the programme is to detect damage, a suitable technique must be used. Current techniques based on vibration analysis do not appear to be sensitive enough to be able to detect the level of damage at which maintenance should be implemented. Acoustic methods appear to be satisfactory for certain types of structure. Remote, continuous monitoring should be used only as a supplement to guide visual inspection of the structure itself.

Societal issues will influence what resources are assigned for monitoring, and what will be seen as an acceptable intervention on a structure. No matter what is implemented, practicing engineers need to report more on the successes and failures of what has been done, so that the community at large can be more effective in this emerging activity.

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