1.1 Advances in Structural Health Monitoring Technology

The structural health monitoring process involves the observation and evaluation of a structure over time using periodically sampled measurements from a sensing system. Structural health monitoring is a popular and growing research field, providing a powerful tool for damage assessment and performance evaluation of engineering structures.

1.1.1 Structural Health in Civil Engineering

Civil infrastructure comprises bridges, buildings, towers, pipelines, tunnels, dams and other types of structures. Their continued safe and economical operation largely depends on proper maintenance and management. In order to evaluate optimal management strategies for existing civil infrastructure, accurate assessment of present and future safety is important and necessary (Ettouney and Alampalli 2012). Maintaining safe and reliable civil infrastructure for daily use is critical to the well-being of the society. Thus, structural health can be stated as its current capacity for providing intended level of service in a safe and cost-effective manner against the expected hazards during its service life.
Despite the necessary design methodology initially used, civil engineering structures deteriorate with time. This deterioration is due to various reasons, including failure caused by cyclic traffic loads, effects of environmental factors (e.g. steel corrosion, concrete carbonation) and aging in the construction materials. Also, the deterioration can be caused by infrequent extreme events such as earthquakes, hurricanes and floods. Therefore, structural health will be affected by operational and environmental factors, including normal load conditions, current and future environments and expected hazards during the lifetime. All these factors are variables with uncertainties, so it is difficult to define the structural health in terms of its age and usage and its level of safety to resist severe natural actions. In order to reliably assess structural health and maintain structural safety, continued in-service monitoring of the structure is essential.

Catastrophic structural failures, such as sudden collapse of the I-35 highway bridge (NTSB 2008), have highlighted problems associated with aging critical civil infrastructure. Severe natural disasters such as earthquakes and typhoons result in demands for quick condition assessment of civil structures (Brownjohn et al. 2011). Currently, the condition assessment of existing civil infrastructure such as bridges largely depends on visual inspection. This subjective and inaccurate condition assessment methodology has been identified as the most critical technical barrier to effective infrastructure management. For example, condition of bridges is typically expressed in terms of subjective indices on the basis of visual inspection alone. Thus, it is difficult to accurately evaluate structural condition from the inaccurate visual inspection data, even when this may be conducted by experts (Aktan et al. 1998). These issues have driven the research and development on the continuous observation and interpretation of full-scale performance of civil engineering structures during their service life.

Health monitoring applications based on advanced sensors and real-time monitoring for civil infrastructure offer great potential for informed and effective infrastructure management. Health monitoring is necessary for civil engineering structures since they may exhibit premature deterioration, structural damage and performance problems, or they may even have aged beyond their expected design life. Health monitoring can be utilised for tracking the responses of a structure along with inputs, if possible, over a sufficient duration to determine anomalies, to detect deterioration and to assess damage for decision making. Damage assessment methods using measured vibration modal data, such as natural frequencies and mode shapes, show promise for the health evaluation of engineering structures (Bicanic and Chen 1997, Chen 1998). Health monitoring can assess the performance of civil structures in a proactive manner using measured data and data interpretation algorithms, in order to correctly evaluate the current condition and to predict the remaining service life.

1.1.2 Aims of Structural Health Monitoring

Structural health monitoring is defined as the process of implementing a damage identification and health evaluation strategy for engineering structures. SHM uses sensing systems and associated hardware and software facilities to monitor the structural performance and operational environments of engineering structures. SHM involves the observation of a structure over time, using periodically sampled structural response and operational environment measurements from an array of sensors and then the evaluation of the current state and future performance of the structure. For long-term
SHM, the output of this process is periodically updated information regarding the capability of the structure to perform its intended function, by considering the inevitable aging and degradation resulting from operational environments (Farrar et al. 2003). Furthermore, SHM is adopted for rapid condition assessment to provide prompt and reliable information regarding the integrity of the structure after extreme events, such as an earthquake or blast loading.

SHM aims to identify structural damage and evaluate the health of the structure using monitored data. Damage is defined here as changes to the material and/or geometric properties of a structure, which affects the current state and future performance of the structure. The objectives of an SHM strategy can be outlined as the following five levels (Farrar et al. 2009).

- Level I: Damage detection, giving a qualitative indication that damage might be present in the structure
- Level II: Damage localisation, giving information about the probable position of damage
- Level III: Damage classification, giving information about the type of damage
- Level IV: Damage assessment, giving an estimate of the extent of damage
- Level V: Damage prognosis, giving information about the safety of the structure, e.g. estimate of remaining useful life

The level in the order given above represents increasing knowledge of the damage state. A higher level usually requires information available about all lower levels. The first two levels, damage detection and localisation, can be generally achieved using vibration based damage detection methods from structural dynamic response measurements. To identify the type of damage, data from structures with the specific types of damage must be available for correlation with the measured data. Analytical models are usually needed to achieve the fourth and fifth levels, damage assessment and prognosis. In general, these two levels may not be achieved without first identifying the type of damage present. Estimates of the future loading, together with predictive deterioration models, are necessary to accomplish the final level for damage prognosis.

SHM strategies offer useful information for optimising maintenance planning of engineering structures in service. To ensure a reliable operation and to schedule maintenance and repair work in a cost-effective manner, it is necessary to continuously monitor and assess the structural performance and to have an accurate estimation of the remaining useful life. Thus, the SHM strategy integrated with lifecycle management is necessary to calibrate structural assessment and predictions, to enable optimal operation and maintenance of engineering structures and, eventually, to operate the structures beyond their original design life.

1.1.3 Development of SHM Methods

Structural damage identification based on changes in the dynamic response of the structure has been practised in a qualitative manner for a long time. The beginnings of this damage detection method as an area of interest to engineers can be traced back as far as the time when tap-testing (e.g. on train wheels) for fault detection became common. This field, however, did not really become established in research communities until the 1980s, when much interest was generated in the structural condition of offshore platforms, and later in the health of aerospace structures. Recently, the development of
quantifiable SHM methods has been closely linked with the evolution and cost reductions of digital computing hardware and sensing systems. In conjunction with these developments, SHM has received considerable attention in the technical literature. The details of literature surveys on SHM development can be found in comprehensive reviews by Doebling et al. (1996) and Sohn et al. (2004).

The civil engineering community has investigated vibration based damage identification of bridge structures and buildings since the early 1980s. Modal properties, and the associated quantities derived from these properties, such as mode shape curvature and dynamic flexibility matrix indices, were the primary features used to identify damage in the civil engineering structures. Environmental and operational condition variability (e.g. variation of temperature) presents significant challenges to the health monitoring of the civil structures. The physical size of the civil structures, typically in large scale with numerous components, also presents many practical challenges for vibration based damage assessment. Furthermore, the requirement for real-time structural condition assessment after severe discrete events (e.g. aerodynamic gust loads on long span bridges, earthquake loading on civil infrastructure) is also a major challenge for SHM technology. Regulatory requirements in Asian countries such as in China are driving current research and commercial development of SHM systems for large civil engineering structures (Farrar and Worden 2007). Nowadays, SHM is a popular and still growing research field, which is more and more becoming a focus of the civil engineering community.

Recently, advances have been made in various branches of technology, including sensing instrumentation, signal acquisition and transmission, data processing and analysis and numerical simulation and modelling. These technological advancements enable the required current and historical information of the civil structures to be collected and analysed effectively. SHM strategies take advantage of the technological advancements for accurately evaluating the health of civil structures using real-time monitored data.

1.2 Structural Health Monitoring System and Strategy

A health monitoring system for civil structures often includes observation by sensing systems and the evaluation by data interpretation algorithms. In general, both global and local health monitoring strategies are important for effective damage identification and safety assessment of large civil engineering structures.

1.2.1 SHM System and its Components

The development of successful SHM methods generally depends on two key factors: sensing technology and the associated signal analysis and interpretation algorithms. An SHM system generally consists of many key components, including sensors, data acquisition, data transmission, data processing, data management, health evaluation and decision making. Each of these components is equally important in assessing the health state of a civil structure. The sensing component of the SHM system includes the selection of sensor types, their number and location. The data acquisition component involves selecting the excitation methods, signal conditioning and data acquisition hardware. The measured data needs to be transmitted by wired or wireless transmission networks. The data processing component typically includes data validation, normalisation,
cleansing, fusion and compression. This pre-processed monitoring data is then stored and managed properly. From this data, the health of the structure can be evaluated and then a decision will be made on the basis of the health assessment.

Bridges are major applications of SHM systems due to their large-scale and structural complexity. In general, bridge health monitoring process involves the collection and analysis of data for the execution of the following four categories of works:

- **Observation**, e.g. collection, processing, analysis and reporting of all observed (measured and derived) data from the sensory systems
- **Evaluation**, e.g. real-time or near real-time performance analysis of the structure under monitoring, and off-time diagnostic and prognostic analyses of the structure under normal operations or after extreme events
- **Rating**, e.g. ranking and prioritisation of structural components for planning and scheduling of inspection and/or maintenance activities
- **Management**, e.g. systematic storage and fast retrieval of all observation, evaluation and rating data for subsequent interfacing analysis and display

The SHM system architecture of a bridge is generally composed of four key subsystems, as demonstrated in the applications to long-span bridges (Wong and Ni 2009) and as shown in Figure 1.1:

- **Structural health observation system** (SHOS), devised as an on-structure instrumentation system including sensory system and equipped with appropriate data processing, analysis and reporting software tools

![Figure 1.1 System architecture and operation diagram of a SHM system for a bridge.](image-url)
- **Structural health evaluation system** (SHES), devised as a computation system equipped with relevant pre-constructed analytical models to carry load demand analysis and load resistance analysis
- **Structural health rating system** (SHRS), devised as an analytic database system equipped with relevant customised software tools and databases for evaluating the condition ratings of the structure and its components
- **Structural health data management system** (SHDMS), devised as a data and information management system for systematic storage and fast retrieval of all data by means of data warehouse platform and data warehouse

### 1.2.2 SHM Strategy and Method

SHM strategies can broadly be categorised into two groups: global and local. In general, both global and local monitoring strategies provide different types of information, and support different types of analysis. Figure 1.2 shows global and local monitoring strategies, the types of information collected and the associated measurement types (Frangopol and Messervey 2009).

Selecting an appropriate monitoring strategy largely depends on the structure concerned, the type of analysis, or both. For example, a global monitoring approach has to be chosen when accessibility to specific parts of the structure is impossible. For a global monitoring system, accelerometers would be an appropriate instrument for measuring the dynamic response (i.e. accelerations) of the structure subjected to forced or ambient vibration. The measured acceleration data can be used for extracting modal parameters such as natural frequencies and mode shapes. This extracted modal data then can be

![Figure 1.2](figure.png)

**Figure 1.2** Structural health monitoring strategies for civil engineering structures (after Frangopol and Messervey 2009).
used for updating the structural parameters of the analytical model, or for identifying structural damage using global SHM techniques. However, in the cases when analysing a specific structural failure mechanism at local area such as crack or fatigue, information on the local material and geometrical properties as well as stress state may be needed to assess the structural condition at the local level. Typically, non-destructive testing techniques such as ultrasound could be used to identify the local damage in the structure.

Global monitoring strategies have been the traditional tool used to assess the safety of large civil engineering structures such as bridges. Ideally, by use of measured parameters, health monitoring of civil structures has the ability to identify the location and severity of damage in the structures when damage occurs. However, existing global SHM methods, such as some vibration based damage detection methods, may only determine whether or not damage is present somewhere in the entire structure. These global methods are important for checking if damage has occurred in the structure. Once damage presence is detected, further examination of the structure to determine the exact location and severity of the damage can be undertaken. Then, local SHM methods, such as guided waves to measure the state of stress or eddy current techniques to locate cracks, are adopted to determine the exact location and extent of the damage. Non-destructive testing, used here as a local SHM method, is often time-consuming and expensive, and access is not always possible (Chang et al. 2003). Therefore, both global and local SHM strategies are necessary in health monitoring of large civil structures.

1.3 Potential Benefits of SHM in Civil Engineering

Civil engineering structures are typically large and are constructed with uncertainties. Their in-service behaviour is often affected by environmental factors. These issues make SHM strategies in civil engineering a challenge. However, the application of SHM strategies to civil structures will bring many benefits, such as structural safety and cost savings.

1.3.1 Character of SHM in Civil Engineering

Unlike aerospace or automotive structures, civil structures are not built with the same level of precision. In many cases, because of on-site construction constraints and varying ground conditions, the structure may not be constructed according to the archived design. Accuracy of implementation and uncertainty of workmanship are often an issue. Total uniformity of material can never be achieved when concrete materials are used. Furthermore, the behaviour of civil structures is usually affected by environmental factors such as temperature and moisture. For example, the natural frequencies of a bridge are often related to the temperature variation around the bridge due to thermal effects. For health evaluation of civil structures, physical models based on idealised behaviour such as perfect pin or rigid connections can never reflect what is achieved in practice. It is often not possible to obtain the data necessary for building an accurate physical model (Chang et al. 2003). These problems make the health monitoring and evaluation of civil infrastructure a challenge, in particular for model-based (physics-based) SHM techniques.

Civil structures deteriorate with time due to operational loads and environmental effects. Structural damage such as fatigue caused by repetitive traffic loads often occurs in the structure. Meanwhile, large-scale discrete events such as earthquakes and
hurricanes can cause serious structural damage. Typical examples are aerodynamic gust loads on long span bridges and earthquake loading on all types of civil infrastructure. Thus, the following assessment through an SHM strategy would typically be necessary (Karbhari 2009): (a) damage to the structure and changes in the structural resistance, (b) probability of failure or of the structure’s performance falling below a certain threshold, (c) evaluation of the severity of damage and the remaining service life.

Vibration based damage identification methods show promise for global damage assessment of large civil structures (Chen and Maung 2014). These damage identification methods can be broadly divided into two groups: data-based and model-based techniques. Data-based techniques adopt measurements directly to assess the current state, but may only be able to detect the existence of damage. Model-based techniques require a validated initial physical model of the structure (baseline) for locating and assessing damage in the structure (Chen and Bicanic 2000, Chen 2008). Their dependence on baseline data can be an issue in global damage assessment, since environmental effects such as temperature can change the vibration measurements from an undamaged structure. Thus, the environmental effects need to be treated properly in the damage identification process.

Although the field of SHM as applied to civil structures is still in its infancy, it is already demonstrating significant advantages not only in the safety assessment of existing structures but also in paving the way for both a better understanding of structural response and the development of design codes. It is expected that the further development of SHM systems in civil engineering will lead to the establishment of a comprehensive methodology for automated health monitoring of civil structures, so that true condition based inspection and maintenance would become a reality (Karbhari 2009). The integration of advanced sensing networks with the development of effective tools for real-time data analysis provides useful tools for current condition assessment, remaining life prediction and optimal repair planning of civil structures, as illustrated in Figure 1.3. In addition, the use of an appropriately designed SHM system would

![Figure 1.3 Integrated framework for health monitoring and evaluation of civil structures.](image-url)
enable further understanding of structural response through data analysis and interpretation. This would also lead to better and more refined methods of structural design. As a result, all of these would generate innovations in the design and maintenance of civil structures, leading to the development of a modern field of smart civil infrastructure.

1.3.2 Potential Benefits of SHM

Structural health monitoring technologies have the potential to improve the design and management of civil structures in several ways (Frangopol and Messervey 2009, Ko and Ni 2005):

- performance based design can be undertaken by recording site-specific environmental conditions such as wind, load demands or temperature
- design assumptions and parameters can be validated with the potential benefit of improving design specifications and guidelines for future similar structures
- inspections can be scheduled on an “as needed” basis informed by structure-specific data when indicated by monitoring data
- performance thresholds can be established to provide warning when prescribed limits are violated, such as for anomalies in loading and response
- real-time safety assessment can be carried out during normal operations or immediately after disasters and extreme events
- accuracy of structural assessments can be improved by analysing recorded structural response data
- more accurate information can be used for optimally scheduling maintenance and repair activities, leading to cost savings.

Among these potential benefits, the first and most obvious benefit is increased human safety. Unsurprisingly, the majority of the research on SHM strategies has been motivated by disasters such as bridge collapses. Even at the lowest level of SHM strategies, e.g. detection of damage existence or strength degradation, they can be hugely beneficial if used to provide an early warning for safety issues (Cross et al. 2013). In addition, with an automated SHM system, any inaccessible areas of a structure can be assessed to increase safety, while these areas may have been neglected in a visual inspection routine.

Other arising benefits will come from the policy change that sophisticated SHM systems could generate. Currently, most civil structures undergo routine inspection and maintenance at specific time intervals. For example, bridge inspections in the USA are scheduled every two years. A time based approach to management of civil structures has the implication that any unexpected faults occurring in between scheduled inspections may be ignored and cause danger to life. On the other hand, the set timescales for inspections of civil structures may be unreasonably conservative. If a structure continues to be in good health, the costs of thorough inspections could have been saved. In the case of routine maintenance, where structural components may be replaced even if they are in excellent condition, the economic impact may be even greater. SHM strategies have the ability to solve both sides of this issue, since structural monitoring has the potential to become continuous, and maintenance could become condition based (Cross et al. 2013). Use of condition based maintenance could also reduce the downtime that a structure may undergo for routine and emergency maintenance. This, in turn, would be of economic and environmental benefit.
SHM is an emerging technology that will allow existing time based maintenance policies to evolve into potentially more cost-effective condition based maintenance strategies. The concept of condition based maintenance is based on the philosophy that SHM on a structure will monitor the structural response and notify the operator that damage has been detected. Life safety and economic benefits associated with such a philosophy will only be realised if the SHM system provides sufficient warning, so that corrective actions can be taken before the damage evolves to a failure level (Farrar and Worden 2007). The trade-off associated with implementing an SHM system is that it requires a more sophisticated monitoring system to be deployed on the structure and a more robust data analysis procedure to be used for interpreting the measured data.

1.4 Challenges and Further Work of SHM

The development of SHM methods for structural damage identification has now achieved some degree of maturity. However, the application of SHM methods for practical structural health evaluation and condition based maintenance is still in its infancy. Further work is needed to ensure that infrastructure managers benefit from the emerging SHM strategies.

1.4.1 Challenges of SHM in Civil Engineering

Although SHM technology has advanced significantly over the past decade, there are still many significant barriers to the general implementation of SHM systems. The common technical challenges to the adaptation of SHM systems in practice are discussed by Farrar and Lieven (2007) and Farrar et al. (2009), and are summarised as follows.

- The philosophy of vibration based SHM methods is that damage will alter structural parameters such as stiffness of a system, which in turn will alter the measured global dynamic response properties of the system. Although vibration based methods appear promising, their actual application in civil engineering raises many significant technical challenges. The most fundamental challenge for vibration based methods is the fact that damage is typically a local phenomenon. Damage may not significantly influence the lower frequency global structural dynamic response, which is normally measured during system operation.

- Another fundamental challenge for SHM methods is that in many situations feature selection and damage detection must be performed when data from damaged systems is not available. Moreover, the selected feature must be sensitive to small damage sizes, e.g. a fatigue crack at a structural component. Large complex civil structures are usually made up of numerous components, and they may have multiple damage present. An SHM system that is suitable for detecting one type of damage may not be useful for detecting other damage types.

- A significant challenge for SHM systems is to choose properly the required sensing system before field deployment, and to ensure that the sensing system itself will not be damaged in service. The number and location of the sensors need to be optimally determined, and a certain amount of redundancy must be implemented into the
sensor network. Sensors need to be inexpensive and easy to implement, so that they can be attached to existing civil structures with little effort.

- Civil structures in their service life are usually subjected to changing operational and environmental conditions, e.g. temperature and moisture. The varying conditions will generate changes in structural response measurements, which should not be interpreted as indications of damage. For example, temperature variation can affect the stiffness of a civil structure, and moisture variation can influence the mass of concrete and pavements. Thus, these changing operational and environmental conditions must be accounted for during the damage identification process.

- Damage in civil structures can accumulate over a long timescale, which poses significant challenges for an SHM sensing system. This problem generates many practical issues for accurate and repeatable measurements from the sensing system over long periods of time. The sensing system is usually expected to operate for the life of the civil structure, which may be as long as 50 or 100 years. Thus, robust sensing system is needed to perform reliably for lifetime of the structure.

- Finally, there are other non-technical issues in the applications of SHM technology to actual practice. For example, SHM technology has to provide asset managers with an economic benefit over current maintenance approaches. In the meantime, this technology has to provide regulatory agencies with a significant life-safety benefit. Furthermore, SHM systems need more effort to be undertaken, owing to its multi-disciplinary nature. It requires people with diverse technical expertise and a significant amount of technology integration and validation.

As SHM technology evolves, it is anticipated that the SHM strategies in civil engineering will be used for many purposes, such as to assess structural integrity to normal and extreme loading conditions, to estimate the reliability of the structural system and its components over its lifetime, to predict the remaining service life and to determine the optimal times for inspections and repairs. SHM strategies in actual engineering applications will become a huge challenge for engineers in the coming decades, because of their multi-disciplinary and complex nature.

1.4.2 Further Work on SHM for Practical Applications

Although extensive efforts have been made in research on SHM technology, this technology is still in its current embryonic stages of development. For real applications of an SHM strategy, more studies are needed for the health evaluation and maintenance planning of civil structures over their lifetime, as illustrated in Figure 1.4. Further works for the development of effective SHM strategies are discussed in Miyamoto (2009) and Farrar and Lieven (2007), and summarised as follows.

- Advance of sensing systems with optimised placement of networkable sensors. More efforts are needed to develop large-scale, self-organising and embedded sensing networks for a wide variety of applications. Investigations should focus on developing cost-effective dense sensing arrays and novel approaches to powering the sensing systems. The number and location of sensors must be optimally determined. Sensors must be properly selected and be sensitive to changes in structural condition caused by damage. The sensing system itself must be more reliable than the structure and its components under monitoring.
Advanced signal processing techniques for robust damage identification. The accurate definition of damage and novel sensitive features (e.g. damage indices) should be developed. These features could be able to distinguish not only the location and the extent of damage but also the types of damage in a structure.

Predictive modelling for future loading estimates. A successful damage prognosis requires the current state assessment and the strength deterioration prediction when subjected to future loading. Future loading should be forecast from the analysis of previous loading histories and reliable predictive modelling techniques.

Verification and validation of initial and damage models of a structure. Reliable identification of the location and extent of damage in a structure largely depends on the quality of the initial physical model of the undamaged structure. Accurate future performance predictions are based on the predictive deterioration model of the structure subjected to cumulative damage over time. Thus, the initial physical model and the predictive damage model must be verified and validated.

Reliability analysis for infrastructure management decision making. From the future loading estimate and the predictive deterioration model, the probability of failure over lifetime can be determined using time-dependent reliability analysis. As a result, the remaining useful life can be estimated, and the optimal maintenance strategy can be determined using lifecycle cost analysis.

Need for long-term proof-of-concept studies on SHM systems. There are very limited long-term SHM investigations performed on actual civil structures. These investigations are difficult to undertake due to their costs and the rapid evolution of sensor technology. However, such investigations are necessary to deal with the environmental and operational variability issues and to develop a methodology for condition based maintenance.

These topics for further work are currently the main focus of various research efforts by many industries, including civil infrastructure, defence, instrumentation and communication, where multi-disciplinary approaches are adopted to advance the current capabilities of SHM strategies.
1.5 Concluding Remarks

The development of robust SHM technology for cost-effective infrastructure management has become a major challenge for the engineering community. For a civil structure, it is important and necessary to identify damage in the structure at the earliest possible time. Obviously, SHM technology has the potential to offer tremendous economic and life-safety benefits. However, there are still limited examples of where SHM technology has made the successful transition from research to practice.

Currently, extensive techniques exist for structural damage assessment, including local non-destructive testing techniques and global vibration based damage identification methods. Since all the techniques have their own advantages and disadvantages, there is no general approach that can be used for tackling all kinds of problems in various structures. In general, only damage above a certain size can be detected. It should be noted that a reduction in stiffness does not necessarily mean that there is a decrease in structural strength. The quantification of damage and the prediction of the remaining useful lifetime are definitely the most challenging problems in SHM strategies (Montalvão et al. 2006). Other major challenges of SHM strategies include developing and integrating advanced sensing networks, robust monitoring systems and powerful data processing and analysis algorithms.

Significant future development of an SHM strategy requires multi-disciplinary research efforts involving fields such as sensor, signal processing, data telemetry, data interpretation, numerical modelling, probabilistic analysis and computational hardware. In general, these topics are the focus of significant discipline-specific research efforts. Thus, these technologies must be advanced and integrated with the specific focus of developing SHM strategies. Finally, the problem of global SHM methods is very complex and diverse, and it is difficult to see it being solved in the immediate future. Advancements in SHM will be made in increments, requiring focused and integrated research efforts over long periods of time.

References


