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Damage Detection and Condition Assessment of Civil Engineering Structures Using Structural Health Monitoring

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Abstract. Damage identification is critical in evaluating the condition and performance of the existing civil infrastructure. This requires not just routine or critical event-based inspections, but rather a means of continuous monitoring of a structure to provide an assessment of changes as a function of time and an early warning of an unsafe condition using real-time data. Health monitoring plays an important role in the construction and maintenance of the infrastructure. It employs in situ, continuous, or regular measurements and analyses of key structural and environmental parameters under the operating conditions to identify if a damage has occurred, define its location, and estimate its severity, evaluate its consequences on the residual life of the structure also to provide warning of impending abnormal states or accidents to avoid casualties and to inform maintenance and rehabilitation decisions. SHM takes advantage of the new technologies in sensing, instrumentation, communication, and modelling to integrate them into an intelligent system. Structural Health Monitoring for civil structures is becoming increasingly popular in Europe and worldwide because of the opportunities that it offers in the fields of construction management and maintenance. Reduction of inspection costs, research, with the possibility to better understand the behaviour of structures under dynamic loads, seismic protection, observation, in real or near real-time, of the structural response and of evolution of damage, so that it is possible to produce post-earthquake scenarios and support rescue operations, are the main advantages related to the implementation of such techniques.

1 Introduction

Health monitoring of structures is becoming more and more important: its ultimate target is the ability to monitor the structure throughout its working life to reduce maintenance requirements and subsequent downtime. Currently, visual inspection is the standard method used for health assessment of structures, along with non-destructive evaluation techniques. However, most of these techniques require a lot of manual work and a significant downtime. Moreover, all these methods, based on the foreseen damage locations and requiring that the vicinity of the damage is known a priori, and the portion of the structure being inspected is readily accessible (Doebling et al 1998), can hardly detect the in-depth damages or other inaccessible components. Besides, the previous approaches are only validated through simple structures and rarely real structures which are more complicated. Non-destructive evaluation (NDE) is often time consuming and expensive, and access is not always possible. Therefore, both global and local health monitoring techniques are necessary. Thus, currently an increasing interest in optimized and autonomous SHM is rising, because it can provide cost savings by reducing the number of manual inspections (Achenbach, 2007, Lynch et al. 2016). Structural systems often give warning prior to breakdown. Structural problems are almost always accompanied by an increase in vibrational levels that can be measured. The basic principle behind a vibration signature analysis lies in structural vibrations and dynamics. Collectively, these dynamic characteristics form a signature or fingerprint that will not change unless the dynamic parameters are altered.

In the field of damage detection, a lot of algorithms have been proposed on the base of several different mechanical and physical principles. However, they can be classified into two main classes: a first group of techniques, the so-called modal-based algorithms, aims at tracking changes in structural response directly or indirectly related to the mechanical characteristics (such as natural frequencies, etc.) of the structure before and after damage. Conversely, the second approach is based on the post-processing of measurement data to detect anomalies from measurements (ARMAV modelling, wavelet decomposition, etc.). In both cases, the trend is in using methods able to automate the detection process by taking advantage of the recent advances in information technologies (Aktan 2005, Cawley 2018). In this framework, identification of the modal parameters of the structures under operational conditions plays a primary role. Recently, some strategies have been set up to automate identification and tracking of modal parameters (Rainieri et al 2007&2008, Brincker et al 2007, Guan et al 2005, Verboven et al 2001) and allowing a full integration of modal identification within SHM systems.

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Reliable procedures are necessary also towards data reduction and transmission, after an earthquake hazard, when a limited communication bandwidth is available: wavelet-based approach is particularly promising in this field (Li et al 2008, Mizuno and Fujino 2007). However, real-time interpretation of data can fail due their poor quality and in case of sensors failure: therefore, in case of automated applications, verification must be conducted by the data processing system itself. A monitoring system consists of a variety of sensors to monitor the environment and the structural response to loads. A typical architecture of the monitoring systems is based on remote sensors wired directly to a centralized data acquisition system. However, the expensive nature of this architecture, due to high installation and maintenance costs associated with system wires (Lynch 2002, Chen et al. 2017), is causing replacement of wire-based systems with new low-cost wireless sensing units by spreading knowledge over the entire monitoring network. Consequently, a larger effort is currently required to build effective data processing algorithms, considering such a new architecture, another relevant task is related to the strategies to be implemented to manage data and combine information coming from a variety of sensors and, therefore, related to different physical variables.

2 State of the Problem

The universe of damage detection scenarios likely to be encountered in realistic civil infrastructure applications is very broad and encompassing. Among the numerous considerations which influence the choice and effectiveness of a suitable method are: variety of materials of construction, level of damage and deterioration of concern, type of sensors used, nature of the instrumentation network, extent of available knowledge concerning the ambient dynamic environment, spatial resolution of the sensors, configuration and topology of the test structure, sophistication of available computing resources, complexity of the detection scheme, degree of a priori information about the condition of the structure, selected threshold level for detecting perturbations in the system condition, and depth of knowledge concerning failure modes of the structure (Elgamal et al 2003). A complete SHM approach consists of four basic steps which are required to be resolved sequentially. These four basic steps involve: (1) identification of damage occurrence in the structure, if any, (2) identification of single or multiple damage locations, (3) quantification of the level of damage, and (4) evaluation of structural performance and its useful remaining life. The idea is to do this reliably and continuously, if possible, in a cost-efficient manner.

3 Motivation of this Research

A recent study by the ASCE of more than 500,000 highway bridges with a span length greater than 25 feet found that over 25 percent are either structurally deficient or functionally obsolete. Timely detection of these bridge defects and accumulated damage enables infrastructure owners and their engineering teams to implement preventive or proactive maintenance and, thereby, avoid bridge collapses and other calamities. Early diagnosis of these problems also ensures that bridges can perform their current and future services effectively. Although bridge testing has been an important tool for evaluating structures for several decades, it has only been within the last decade that specific effort has been given to develop systems that can operate in an autonomous fashion. The economic motivation is stronger, principally for end-users. In effect, for structures with SHM systems, the envisaged benefits are constant maintenance costs and reliability, instead of increasing maintenance costs and decreasing reliability for classical structures without SHM, Fig. 1.

The development of an automatic and low-cost structural health monitoring (SHM) system is in high demand and crucial to reduce the costs associated with manual inspection, effectively monitor the status of bridges, and, therefore, minimize risk associated with bridge infrastructure. Unlike aerospace or automotive structures, civil infrastructures are not built with the same level of precision. In many cases, because of on-site construction constraints and change orders, the structure is not built according to the archived design. Accuracy of implementation is often an issue, and uniformity of material is never guaranteed when concrete is used. On top of these inaccuracies, models based on idealized behavior such as perfect pin or fixed connections can never be achieved. Availability of data to obtain an accurate analytical model is often not possible. This problem makes model-based health monitoring of civil infrastructure a challenge.

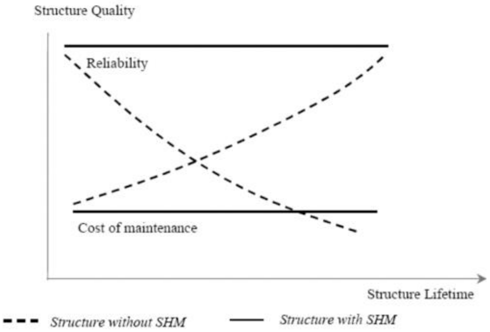

Fig.1 Benefit of SHM for End users (Chang 2002)

The need for effective SHM is clear, with the primary goals of such systems being to enhance safety and reliability and to reduce maintenance and inspection costs. SHM can achieve the goals of an effective infrastructure maintenance by the following outcomes (Büyüköztürk and Yu 2003):

- Knowledge on static and dynamic behaviours of civil infrastructure, Improved understanding of in-situ structural behaviour,
- Verifying and improved understanding of design assumptions (boundary conditions),
- Study of the performance of different design philosophies and construction techniques,
- Development and tuning of the corresponding numerical model (FEM), Clarifying the seismic performance and safety,

- Evaluation of short-term impact due to natural hazardous events (earthquakes), manmade activities (rehabilitation, retrofitting, expansion),
- Determination of actual load carrying capacity and monitoring of long-term deformation due to operational loading, Assurances of a structure's strength and serviceability
- Monitoring of long-term deterioration due to physical aging,
- Investigation of the pattern of environmental variation and influence on the measurements,
- Extending structures' service life by adequate repair and retrofit efforts.
- Early damage detection, Reduction in down time
- Improved maintenance and management strategies for better allocation of resources
- Enables and encourages use of innovative materials

4 Objectives

The current research involves detection and assessment of damage in civil structures. The research projects are highly interdisciplinary in nature and require implementation of concepts in structural design, finite element analysis, vibrations, digital signal processing, digital image processing, data acquisition systems, control systems and extensive knowledge of sensors and statistical methods. The primary objective is to optimize and develop a new Structural Health Monitoring (SHM) system suitable for existing and new civil Engineering structures bridge and high-rise buildings. The objectives of the research are to 1) Detect the presence of damage (surface, subsurface and hidden) in a structure; 2) Determine the location of the damage in the structure; 3) Quantify the damage within the structure; 4) Implement an intelligent decision-making algorithm to classify and predict the damage in terms of severity to the life and performance of the structure.

The development of methods for accurate identification of modal parameters is quite important as they are, indeed, very good indicators of the structural condition. Many research studies have been conducted to develop accurate modal identification methods, but the perfect reliable approach is yet to be developed. Accurate estimation of parameters from noisy data still seems to be an unsolved problem, especially from real recorded data on structures. It is, therefore, quite necessary that the applicability of various methods be examined on real data recorded in laboratory experiments as well as in the field on real structures; that is, an experimental verification of any proposed identification approach is an absolute necessity before it can be applied in practice. Such a study will also bring out some practical considerations that one might face in the real-life implementation of these methods.

The main objective is to develop a solution to monitor structural health characteristics, including stability, reliability, and liability, in real time by using contemporary computing, sensor, and communication technology. SHM solutions will be designed to capture the vibration signatures of a structure and detect any sudden shifts of structural characteristics.

A design for instrumentation layout for selected key structures with coordination with their owners, (bridges; buildings; offshore, etc..) will be defined, to provide confirmation of seismic capacity, assist in focusing retrofit efforts, detect damage from any cause and provide rapid damage assessment of those structures following a seismic event, will ultimately help improve the safety of future buildings and reduce the number of lives lost from catastrophic events. The objectives of the research proposal could be summarized as follow:

- To develop and implement a real-time seismic structural response system to enable rapid deployment and prioritized inspections of the critical structures; and
- To develop and implement a health monitoring program to address the need for safe and cost-effective operation of structures.
- To develop and implement a cost-effective, reliable Structural Health Monitoring (SHM) technology that makes effective use of sensors and broad band digital communications for remote monitoring of structures subjected to dynamic loads.
- To identify and implement effective algorithms for system identification, model updating and damage detection suitable for remote monitoring of structures subjected to seismic forces and condition changes due to deterioration or impact; and
- To develop an integrated decision-making tool that will speed up prioritization, risk assessment and damage evaluation to assist decision-makers with post-earthquake response and recovery options
- To transform the current practice of inspecting and evaluating all structures after an earthquake to a more rational and effective one that makes effective use of state-of-the-art sensing technology with fast and efficient techniques for data analysis and interpretation. Inspections can then be focused and prioritized to maximize the effectiveness of scarce resources.
- To provide ongoing structural condition monitoring for impact or deterioration to enable timely inspection and intervention.

By accomplishing these objectives, the main objective of the project which is to design and develop a complete smart Structural Health Monitoring (SHM) to monitor the critical infrastructure will be accomplished.

5 Methodology

Vibration-based continuous monitoring systems, already applied successfully to historical buildings, bridges and other types of structures, can also be adopted for precast RC buildings, for their capability of highlighting if they have undergone permanent damage after an earthquake or if they are accumulating damage during a seismic sequence. The vibration-bases structural damage detection is a high technique with widely applied foreground, and it is involved in interaction development among multi-disciplines. Since many key techniques and basic theories in vibration-base structural damage detection still needs to be studied and developed up to its practical application. A new method has been developed for this that involves calibrating the FEM. Possible structural damage is represented with a set of meaningful geometric parameters. The damage detection method is used to search for the damaged elements and the corresponding material attributes so that differences between the modelled and the measured static and modal responses are minimized. The process also helps engineers identify a sound FEM for condition assessment of a structure. Many challenges in detecting damage to bridges are attributed to the complexity of the structures and the presence of noise and environmental interferences.

Finite element model (FEM) calibration is essential to infrastructural health modelling. A calibrated FEM can adequately represent the conditions of existing structures and yield reliable responses under the prescribed dynamic loadings. It is an important tool used by engineers to assess structural conditions and enable condition-based prognostic maintenance. FEM parameters such as material properties and geometric attributes for the built infrastructure are always subject to variations due to material imperfections, manufacturing/construction tolerances, deterioration over time, and ambient effects such as corrosion, temperature, and humidity changes. Identifying models by updating or calibrating the initial FEM with the field data (e.g., natural frequency and mode shapes extracted from the dynamic measurements) is a challenging task due to the large number of elements and uncertain boundary conditions. A FEM calibration method was developed using the optimization technology to facilitate the calibration process. Using the static and dynamic measurements, the FEM calibration is defined to search for a set of the chosen structural parameters so that the difference between the FEM-analysed and field-observed responses (natural frequencies and mode shapes) is minimized. It is an implicit nonlinear optimization problem and solved using Optimization Framework. A methodology for modelling the structural health of a bridge will be developed, and the approach span will be used to critical bridge structures for a pilot study. A finite element model will be created with open FE software detailed design drawings. The FEM will be used to optimize placement of accelerometers on the bridge to record the dynamic responses of the bridge span under normal daytime traffic conditions. The recorded responses will be processed to extract the primary modes and the frequencies used for FEM calibration, facilitated by optimization runs done on a high-performance computing cluster using optimization framework. The calibrated FEM serves as a valuable knowledge tool for bridge maintenance.

The research will address integration of material characterization, computational modelling, sensor instrumentation, information management, damage detection and laboratory / in-situ experiments. This overall goal will be pursued using a multidisciplinary approach including the following primary items: Physically based Multi-scale Modelling; Methods for In Situ Interrogation and Detection; Prognosis via State-awareness and Life Models; Testing, Validation and Application (Focus Problems); Extensions of Research into Next-Generation Smart Structures

This research comprehend five main phases: (i) numerical modelling and ambient vibration test to characterize the dynamic behavior of the bridge and better design the monitoring system, (ii) installation of the monitoring equipment, (iii) development of software to retrieve the continuously generated data series from the bridge and perform the on-line automatic identification of the bridge modal parameters, (iv) study of the modal parameters variations to build numerical models suitable to eliminate the effect of environmental and operational variables and finally, (v) evaluation of the capability of the installed monitoring system to detect realistic damages. Although model updating based on the lower modal parameters is feasible because the energy of lower order modes is higher for long-span bridges, sometimes local detection must be reflected by higher order modes of structure, and it is very difficult for higher order modes test. So accurate model updating is still a challenging task for full scale bridge in terms of the field test results. Many practical issues such as boundary condition simulating, operational vibration measurements, parameters identification, environmental effects, damage detection and durability, etc. need to be explored and solved.

6 Limitations associated with vibration-based damage assessment.

6.1 Low sensitivity to damage

Vibration characteristics are global properties of the structure, and although they are affected by local damage, they may not be very sensitive to such damage. As a result, the change in global properties may be difficult to identify unless the damage is very severe, or the measurements are very accurate and made with extra care. Accurate vibration measurements on civil structures are difficult because such structures are large, so that controlled force excitation is often impractical. As a result, reliance must be placed on the measurement of vibrations induced by ambient forces. Such vibrations are of low amplitude, so that noise in the data makes determination of the vibration characteristics difficult.

6.2 Incomplete measurements of vibration characteristics

A real structure will normally possess a large number of degrees of freedom and hence a large number of frequencies and mode shapes. However, the higher frequencies and mode shapes can rarely be measured with sufficient accuracy. Vibration-based damage detection must therefore depend on the measurements of a limited number of the lowest vibration frequencies, or such frequencies and the associated mode shapes. In general, the measurement of mode shapes is more difficult than the measurement of frequencies. On the other hand, frequencies alone may not be sufficient for a reasonably accurate assessment of the location and severity of the damage. It is often very difficult or impracticable to measure the response along all of the DOF. necessary for the complete definition of a given mode shape, hence one must work with incomplete mode shapes. Measurement errors as well as mode truncation and incomplete mode shapes introduce errors in damage prediction and may make such a prediction unreliable.

6.3 Complexity of the damage identification algorithms

The identification of a possible damage site and the severity of damage on the basis of a change in global properties derived from measurements at a limited number of sensor locations is a problem that has a non-unique solution. Sophisticated and complex mathematical techniques including non-linear programming need to be employed to obtain the most probable solution. In fact, this is at present an area of ongoing research. The methods that are currently available cannot deal with situations where the damage introduces nonlinearity in the structure. Such nonlinearity may, for example, result from the presence of cracks. Closing and opening of the cracks alters the stiffness of the structure, introducing nonlinearity in its behaviour. Nonlinearity may also result from loose connections that slip under load.

6.4 Effect of factors other than damage

Global vibration characteristics are often affected by phenomena other than damage, including environmental effects, such as change of mass caused by water waves and snow accumulation, thermal effects caused by temperature variation, and change in boundary conditions. Whenever the structural system is constrained or indeterminate, thermal effects introduce axial stresses in the structural elements. The presence of such axial stresses changes the stiffness of the structure and may alter its vibration characteristics. The boundary conditions in a structure can have a significant effect on its stiffness, and if these boundary conditions, such as at bridge bearings, are prone to change with the age of the structure, they may lead to a change in the vibration characteristics even when there is no damage in the structure. A large number of research studies are currently being carried out to address the difficulties associated with the practical application of vibration-based damage detection. The current study presents a survey of some of the damage identification algorithms reported in the literature and carries out a critical evaluation of their success, or lack thereof, in identifying damage in the face of practical limitations imposed by the many factors described earlier. The evaluation is based on computer simulation. It cannot therefore assess the impact of pronounced nonlinearity in the structure or of factors other than damage that may cause a change in the vibration characteristics. Nevertheless, the study is important because it helps in identifying methods that are unlikely to work in practice and need not be pursued, and others that have the potential for success.

7 Challenges for SHM

The basic premise of SHM feature selection is that damage will significantly alter the stiffness, mass, or energy dissipation properties of a system, which, in turn, alter the measured dynamic response of that system. Although the basis for feature selection appears intuitive, its actual application poses many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the lower-frequency global response of structures that is normally measured during system operation. Stated another way, this fundamental challenge is similar to that in many engineering fields where the ability to capture the system response on widely varying length- and timescales, as is needed to model/develop phenomenological models of energy dissipation, has proven difficult.

Another fundamental challenge is that in many situations feature selection and damage identification must be performed in an unsupervised learning mode. That is, data from un-damaged systems are not available. Damage can accumulate over widely varying timescales, which poses significant challenges for the SHM sensing system. This challenge is supplemented by many practical issues associated with making accurate and repeatable measurements over long periods of time at a limited number of locations on complex structures often operating in adverse environments. Finally, a significant challenge for SHM is to develop the capability to define the required sensing system properties before field deployment and, if possible, to demonstrate that the sensor system itself will not be damaged when deployed in the field. If the possibility of sensor damage exists, it will be necessary to monitor the sensors themselves. This monitoring can be accomplished either by developing appropriate self-validating sensors or by using the sensors to report on each other’s condition. Sensor networks should also be ‘fail-safe’. If a sensor fails, the damage identification algorithms must be able to adapt to the new network. This adaptive capability implies that a certain amount of redundancy must be built into the sensor network.

8 Outcomes and Impact

The research will provide novel diagnostic SHM techniques through theoretical, and Laboratory/in-situ experimental investigations and new algorithm modelling. The research offers improved monitoring systems for detecting damage of existing civil engineering structures, potentially introduce cost efficiencies to facilities maintenance programs. SHM innovation can contribute to the sustainability of infrastructure, ensuring proper performance, safety, and integrity. The outcomes of research proposal will help transform the current practice of inspecting and evaluating all structures after an earthquake to a more rational and effective one that makes effective use of state-of-the-art sensing technology with fast and efficient techniques for data analysis and interpretation. Inspections can then be focused and prioritized to maximize the effectiveness of scarce resources. These outcomes will further provide ongoing structural condition monitoring for impact or deterioration to enable timely inspection and intervention. The following items identify the research proposal's current goals, the anticipated outcomes and expected key findings:

- Provide technical support on the design, installation, and operations of SHM systems and equipment
- Support for data acquisition, transfer, and management of data
- Develop techniques for efficient data collection, maintenance, presentation and archival
- Support for integrating SHM systems to the Internet for remote monitoring
- Provide field training, site visit, and develop training and design manuals of SHM systems.
- Interact with industry, evaluate, and validate SHM equipment and sensors under various field and laboratory environments
- Build laboratory demonstration facilities to understand and teach SHM technologies and systems
- Integration of vibration-based measurements into current damage-detection algorithms
- Evaluation and development of energy-harvesting techniques suitable for wireless sensor networks
- The baseline updating methods based on vibration measurement and stiffness identification developed in this study can also be applied to existing bridges in the following two ways; one is for establishing the current baseline of the bridge for its future damage detection and deterioration assessment, and the other is for Research
- All findings presented in this research contribute to the development of a design tool for research engineers, to assist the implementation of structural health monitoring technology in safety-critical structures.

9 Summary and Conclusions

First, this work highlights the structural damage detection methods as a step of structural health monitoring (SHM) via discussing limitations of the traditional damage inspection, and the differences between global and local damage detection techniques and the merits of each technique. Furthermore, the state-of-the-art of different global damage detection methods and their applications are presented. Thus, vibration-based methods, static and dynamic response-based methods, model based and model free methods, as well as implementation of long term SHM to critical civil structures are discussed. Finally, the state of the art and the future of different types of response measurements and their applications in SHM of civil structures are reviewed. General conclusions as well as recommendations for future research are presented.

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