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EVALUATION OF EXISTINGTECHNIQUESON STRUCTURAL HEALTH MONITORINGOF BRIDGES

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ABSTRACT

The global higher transportation network operates about 2.5 million bridges all over the world. Current bridge management systems rate them using various methodologies and approaches. Based on studies in the US Federal Highway Agency (FHWA), about 30% of bridges are rated as being deficient, with only a portion of these being deficient for structural reasons. For this reason, it is necessary to focus on bridges that definitely require structural health diagnosis, improvement and monitoring. Structural Health Monitoring (SHM) should be used in a preventive capacity before bridges become deficient. Structural health monitoring is the implementation of a damage identification strategy to the civil engineering infrastructures. Damage is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity. Damage affects the current or future performance of such systems. Structural health monitoring has several techniques, the methods are categorized based on the type of measured data used, and/or the technique used to identify the damage from the measured data. In this paper, first a review of the technical literature concerning the detection, location, and characterization of structural damage via techniques that examine changes in measured structural vibration response are investigated and then recent research and application activities on smart sensing, monitoring, and damage detection for bridges are briefly introduced.

INTRODUCTION

Bridges are complex structures which are made of multiple elements and components that become stressed and interact with one another when exposed to external phenomena. A successful bridge monitoring program requires appropriate planning, design and execution. To fully meet the objectives of such a program, special attention must be given to the specificities of each bridge throughout this process. Structural health monitoring allows rapid assessment of a bridge health, and this approach is recognized as one of the best means available to increase general safety and optimize operational and maintenance activities for bridges. Structural health monitoring is not a new idea. For thousands of years engineers have been examining the ongoing performance of their structures in an effort to prolong structures service lives and ensure public safety (see Figure 1). However, only recently has SHM become a more essential component of a civil engineer’s education. Infrastructure sustainability is an issue that the developed (and developing) world can no longer afford to ignore, and a general awareness of the need for, and implementation of, detailed SHM programs is critical to the success of the next generation of engineers (Bisby 2004).

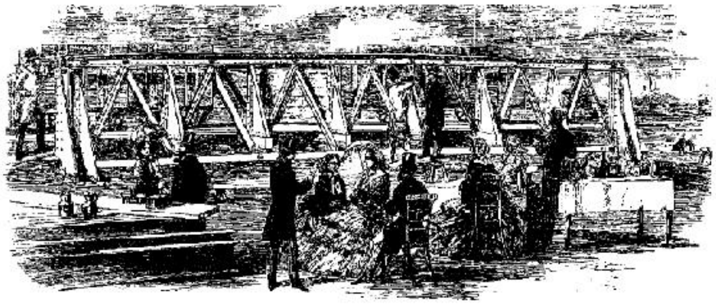

Figure 1.Testing of a steel truss in England for a railway bridge in India in the 19th century

The deterioration of highway infrastructure are attributed to aging, weathering of materials (i.e. corrosion of steel), accidental damage (i.e. natural disasters), and increased traffic and industrial needs as exhibited by the need for higher load ratings of structures and increasing the number of lanes to accommodate traffic flow. (Tajlsten 2002; Karbhari and Seible 2000; Meier 2000). However, deficiencies in structures are not restricted to the effects of aging; poor engineering judgment, inadequate design and changes in code requirements are other factors contributing to deficiencies at any time during the service life of the structure. In order to mitigate deterioration and efficiently manage maintenance efforts on reinforced concrete (RC) bridge structures, two methodologies are needed:

1.A methodology to extend the service life of bridge structures
2.A methodology to monitor performance changes of bridge structures.

In order to maximize the serviceability of civil infrastructure, two specific research areas have experienced significant developments in past decades.

While the use of fiber reinforced polymer (FRP) composites provides an efficient means for repair and strengthening of civil infrastructure (Teng et al. 2003; Bakis et al. 2002; Stallings et al. 2000) methods of structural health monitoring (SHM) of civil infrastructure (Chong et al. 2003; Yuen et al. 2004; Catbas and Aktan 2002; Sikorsky 1999) provide the means of assessing the effectiveness and continued performance of the rehabilitated structure.

In this context, structural health monitoring (SHM) provides the methodology y that evaluates the condition of a structure for a given point in time. A proficient structural health monitoring approach is capable of determining and evaluating serviceability, reliability, and remaining functionality of the structure (Sikorsky 1999).The methodology involves periodic investigation of the structure during service/operation, occasional maintenance, and repair- retrofit or replacement as deemed necessary.

In general, damage identification methods can be categorized as local or global techniques. Some examples of local techniques are acoustic emissions or ultrasonic methods, magnetic field methods, radiography, eddy current techniques, thermal field methods, dye penetrant, fibre optic sensors of various kinds. Successful implementation of the local damage identification methods usually requires former knowledge of the damage location and at the same time, ready access for physical inspection. Subject to such limitations, these local methods can detect damage on or near the surface of the structure. In addition, these methods are generally costly, time consuming and ineffective for large and complex structural systems such as bridges. Global structural damage identification methods, on the other hand, are based on global structural response measurements, namely dynamic and static responses, at certain points of a structure so as to inversely determine its damage condition state (Chang and Liu 2003). provides a schematic of a structural health monitoring paradigm that uses an estimate of the remaining service life as a means of decision making.

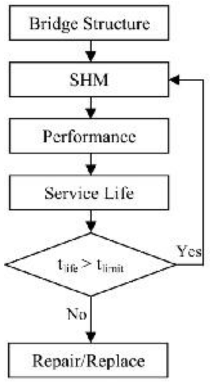

Figure 2.Schematic showing application of SHM

BENEFITS OF MONITORING BRIDGES?

Monitoring is usually carried out in order to achieve one or several goals. They are presented and discussed in this section.

Structural Management

The most safe and durable structures are usually those that are well managed. Measurement and monitoring have an essential role in structural management. The data resulting from the monitoring program is used to optimize the operation, maintenance, repair and replacing of the structure based on reliable and objective data. Detection of ongoing damage can be used to detect deviations from the design performance. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information.

Many structures are in much better conditions than expected. In these cases, monitoring allows to increase the safety margins without any intervention on the structure. Taking advantage of better material properties, over-design and synergetic effects, it is possible to extend the lifetime or load-bearing capacity of structures. A small investment at the beginning of a project can lead to considerable savings by eliminating or reducing over-designed structural elements. A few structures might present deficiencies, which cannot be identified by visual inspection or modeling. In these cases it is possible increase safety and to decrease managing costs by taking actions before it is too late. Repair will be cheaper and will cause less disruption to the use of the structure if it is done in time. Monitoring can also reduce insurance costs. The economic impact of structural deficiency is twofold: direct and indirect. The direct impact is reflected by costs of reconstruction while the indirect impact involves losses in the other branches of the economy. Fully collapse of damaged historical monuments, such as old stone bridges and cathedrals, represent an irretrievable cultural loss for society.

Increase of safety

Malfunctioning of civil structures often has serious consequences. The most serious is an accident involving human victims. Even when there is no loss of life, populations suffer if infrastructure is partially or completely out of service. Collapse of certain structures, such as nuclear power plants, may provoke serious ecological pollution.

Having permanent and reliable monitoring data from a structure, can help to guarantee the safety of the structure and its users.

Knowledge improvement

Learning how a structure performs in real or laboratory conditions will help to design better structures for the future. This canleadto cheaper, safer and more durable structures with increased reliability and performance. Structural diversity due to factors such as geographical region, environmental influences, soil properties, loads etc. makes absolute behavioral knowledge impossible: there are no two identical structures.

A good way to enlarge knowledge of structural performance is to monitor their behavior. That's why monitoring during the complete lives of structures, from construction to the end of service, is of interest from the theoretical point of view as well as from the point of view of structure management. Theories need to be tested, and an excellent method to test theories describing the civil structures is monitoring. For structures built of unusual materials (e.g. roofs composed of thin plastic membranes or tensegrity structures) monitoring is an effective way to comprehend the real behavior and to refine behavioral theories.

CLASSIFICATION OF SHM SYSTEMS

SHM systems can be classified both in terms of their level of sophistication and by the types of information (and decision making algorithms) which they are capable of providing. These classifications of SHM systems can be summarized as follows (Sikorsky 1999).

- Level I: Determination that damage is present in the structure.

- Level II: Determination of the geometric location of the damage.
- Level III: Quantification of the severity of the damage.
- Level IV: Prediction of the remaining service life of the structure.

DAMAGE INDICATORS AND SIMULATION OF DAMAGE

The definition of damage is difficult to conceptualize in a general and widely accepted manner. Most of the time, the sources of damages are unknown and the range of probable causes makes it difficult to generalize damage. However, it is often accepted (with certain limitations) that damage affects the behaviourof structures (e.g. vibration characteristics), which is described by the structural properties of stiffness, damping and mass. In general, after damage has occurred, the member stiffness is affected as well as the damping characteristics of the structure. Altering the mass only, in comparison, may or may not be considered damage (Liszkai 2003).

For a linear finite element model, stiffness reduction can be accomplished in several ways, including alteration of section properties (cross sectional area, second moment of area, plate thickness Young's modulus, etc). Probably the easiest but most effective way to alter member stiffness is to change the Young's modulus. By altering the Young's modulus, all DOF's stiffness properties are reduced or increased by the same proportions in the same element. There are several kinds of mechanisms for damage simulation according to the study objectives of interest. By reviewing the numerical or experimental studies in damage detection or assessment, the simulations of bridges damage are classified into the following categories.

For beam like or bridge structures:

- Decreasing the stiffness of the element numerically
- Reducing the thickness or cross section of the selected elements
- Support failure and/ or crack degradation (the process of deteriorations of structures with time)

For truss bridge:

- Reducing the cross section or Young's modulus of the bars to simulate the axial stiffness failure
- Loss of stiffness and mass of members

DAMAGE IDENTIFICATION METHODS

Damage identification methods could be summarized as:

- Methods Based on Natural Frequency Changes
- Methods Based on Mode Shape Changes
  - Direct mode shape based methods
  - Mode Shape Curvature Based Methods
  - Methods Based on Dynamically Measured Flexibility
- Genetic Algorithm based method
- Frequency Response Function Based Methods
- Artificial Neural Network Based Methods
- Signal processing method

Methods Based on Natural Frequency Changes

The most common and earliest approaches for vibration based damage detection implement either the natural or the resonant frequencies of the structure to evaluate the existence of damage. The presence of damage or deterioration in a structure causes changes in the natural frequencies of the structure. An extensive review on using natural frequency data to identify structural damage was provided by Salawu (1997). The advantages of using natural frequencies are easy implementation and relatively low cost. It should be noted that frequency shifts have significant practical limitations for applications to the type of bridges, although ongoing and future work may help resolve these difficulties. Hearn and Testa (1991) developed a damage detection method that examines the ratio of changes in natural frequency for various modes. Assuming that the mass doesn't change as a result of damage and neglecting second-order terms, the change in the ith natural frequency that results from damage can be related to a change in global stiffness as

$$\Delta\mu_i^2 = \frac{\{\text{¤}_i\}^2[\Delta K]\{\text{¤}_i\}}{\{\text{¤}_i\}^2[M]\{\text{¤}_i\}} \qquad (1)$$

That ω_i is ith modal frequency (rad/s, Hz), $\{\varphi\}_i$ is ith mass-normalized mode shape vector, $[\Delta K]$ is global stiffness matrix perturbation and $[M]$ is global mass matrix

Methods Based on Mode Shape Changes

Mode shapes are inherent properties of a structure. They do not depend on the forces or loads acting on the structure. Changes in mode shapes are much more sensitive to local damage when compared to changes in natural frequencies and damping ratios. However, mode shapes are difficult to measure and a large number of measurement locations may be required to accurately characterize mode shape vectors and to provide sufficient resolution for determining the damage location. A large number of damage identification methods have been developed, based on directly measured mode shapes or the properties of mode shapes such as curvature or modal strain energy.

Direct Mode shape based methods

A comparison between two sets of mode shape data (either direct mode shape data or their derivatives) can be used to identify damage as mode shapes can provide much more information and are much more sensitive to local damage when compared to natural frequencies. There are two common methods available to compare two sets of mode shapes; the Modal Assurance Criterion (MAC) and the Coordinate Modal Assurance Criterion (COMAC).

Kim et al. (2006) formulated a vibration based damage evaluation method to detect, locate and size damage using the lower frequency ranged mode shapes. Their proposed method intended to resolve the mode selection problem, the singularity problem, the axial force problem, and the absolute severity estimation problem. The proposed method provided a single representative damage index using more than one mode. Furthermore, the proposed method did not require any special knowledge about mass density, applied axial force or foundation stiffness. However, in order to obtain good damage accuracy results, a dense measurement of grid and the accurate extraction of the mode shapes were prerequisite.

Mode Shape Curvature Based Methods

An alternative to using mode shapes to obtain spatial information about sources of vibration changes is using mode shape derivatives, such as mode shape curvature. Derivatives of mode shapes are sensitive to small damages, so they can be used to detect damage. If a structure is locally damaged, mode shape changes will occur in the vicinity of that damage. The reduction in stiffness caused by damage alters the mode shapes of the structure. In theory, changes in the mode shapes could be used to detect damage; however, the changes are usually so small that detection of damage is difficult. The correlation between the local loss of stiffness and change in mode shape curvature was shown by Pandey et al. (1991) with assumption that the structural damage only affects the stiffness matrix and not the mass matrix. While modal displacements often hardly change for realistic damages with respect to the initial mode shapes of the intact structure, modal curvatures are more sensitive to damage.

Methods Based on Dynamically Measured Flexibility

During the last decade, researchers have found that the modal flexibility can be a more sensitive parameter than natural frequencies or mode shapes alone for structural damage detection (Salehiet al., 2011). Pandey et al.(1994) proposed a method of detecting damage that is based on the difference between the flexibility matrices of the damaged and healthy structure.

Genetic Algorithm Based Method

The genetic algorithm is one of the artificial intelligence-based optimization algorithms, which has been extensively developed for structural damage detection. Genetic algorithms have much stronger global optimization performance than gradient-based traditional algorithms, because these algorithms can calculate the values of objective function without the requirement for the continuity of the objective function. Besides, parallel clues in the searching process make it not only avoid falling into local minima, but also prove more efficient and effective (Liu et al., 2011).

Moslem et al. (2002) and Chou et al.(2001) reported some research works on structural damage detection using GAs, and they were successful in determining the severity and locations of structural damage. However, GAs-based structural damage detection requires repeatedly searching from numerous damage parameters so as to find the optimal solution of the objective function (measured data). When the measured data and the structural damage parameters to be determined are multitudinous, the efficiency of this method is often not feasible to online damage detection of in-service structures.

Frequency Response Function Based Methods

Frequency response function-based methods have certain advantages compared with modal analysis data for damage identification. As a result, there are many advantages of using a frequency response method in a SHM system. They can be implemented cheaply and FRFs can provide good insight as to the global condition of the system (Kessler et al., 2002). One of the limitations of the FRFs-based methods is that these methods provide little information about the local damage area unless large quantities of sensors are used.

Artificial Neural Network Based Methods

In recent years there has been increasing interest in using artificial neural networks to estimate and predict the extent and location of damage in complex structures. Neural networks have been promoted as universal function approximations for functions of arbitrary complexity. A general overview of neural networks can be found in Bishop (1994).

Mehrjoo et al.(2008) presented a method for estimating the damage intensities of joints for truss bridge structures using a back-propagation based neural network. A sub-structural identification technique was employed to overcome the issues associated with many unknown parameters in a large structural system. The natural frequencies and mode shapes were used as input parameters to the neural network for damage identification, particularly for the case with incomplete measurements of the mode shapes. Numerical example analyses on truss bridges are presented to demonstrate the accuracy and efficiency of the proposed method. In the proposed approach, the location and severity of damages in joints location of truss bridges could be found with precision. The sub-structuring technique was found to be very efficient in reducing the number of unknown damage parameters to be estimated. Multi-Layer Perceptron network architecture was sufficient for the identification of damage location and severity in truss bridges. Furthermore, research outcomes showed the applicability of the present method for the identification of large structural systems.

Signal processing method

How to identify damage using the information already obtained from structures under inspection is significant to health monitoring and damage detection. Various signal processing methods have been explored and applied for this target. Staszewski (2002) discussed the importance of signal processing for damage detection in composite materials and concluded that many of the recent advances in damage detection can be attributed to the development of advanced signal processing techniques. The major elements of signal processing for damage detection include: data pre-processing, feature extraction and selection, pattern recognition and data/information fusion. For a multi-sensor architecture, it is also important to establish the optimal type, number and location of sensors. It is not only important to obtain features related to damage and to overcome different boundary and environmental conditions,

but also to develop automated damage detection system. Kim and Melhem (2004) has done a significant literature review on damage detection of structures by wavelet analysis. Al-khalidy et al. (1997) published numerous papers about damage detection using wavelet analysis. Robertson, et al. (1991)

presented a wavelet-based method for the extraction of impulse response functions (Markov parameters) from measured input and output data. Kitada (1998) proposed a method of identifying nonlinear structural dynamic systems using wavelets. Other research studies aimed at determining modal parameters using wavelets can be found by Hans, et al. (2000), Lamarque et al. (2000) and Ruzzene et al. (1997). Hou et al. (2000) provided numerical simulation data from a simple structural model with breakage springs. Hou and Hera (2001) proposed pseudo-wavelets to identify system parameters, and the associated

pseudowavelet transform was developed. Amaravadi et al. (2001) proposed a new technique that combines these two methods for enhancing the sensitivity and accuracy in damage location. Farrar, et al. (2001) discussed the construction of integrated structural health monitoring system.

CONCLUSION

This paper presented a review of literature related to damage detection of bridges over the past three decades. It is clear that a wide range of dynamic based parameters have been used by researchers for damage identification and condition assessment of structures. From the review, it is found that damage fingerprints derived from natural frequency and mode shape of the structure are the most popular parameters to identify the damage as these two quantities are easy to determine, with a relatively high level of confidence and relatively low cost. However, the frequency based method is limited because of many reasons. Damage which creates low frequency requires very precise measurements. Significant damage may cause very small changes in natural frequencies particularly for larger structures; these small changes may be undetected due to measurement errors. Also, these methods cannot distinguish damage at symmetrical locations in a symmetric structure. Changes in mode shapes are much more sensitive to local damage when compared to changes in natural frequencies.

Due to complexity of large structures and susceptibility of measured modal data to signal noise, damage detection algorithms in the form of optimization problems and decision making programs have evolved, employing machine learning techniques, namely genetic algorithms and artificial neural networks. Further, artificial neural networks (ANNs), have pattern recognition and classification capability and also they can effectively deal with qualitative, uncertain, and incomplete information, making it highly promising for detecting structural damage.

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