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A review of recent research advances on structural health monitoring in Western Australia

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Abstract. Structural Health Monitoring (SHM) has been attracting numerous research efforts around the world because it targets at monitoring structural conditions and performance to prevent catastrophic failure, and to provide quantitative data for engineers and infrastructure owners to design a reliable and economical asset management strategy. In the past decade, with supports from Australian Research Council (ARC), Cooperative Research Center for Infrastructure and Engineering Asset Management (CIEAM), CSIRO and industry partners, intensive research works have been conducted in the School of Civil, Environmental and Mining Engineering, University of Western Australia and Centre for Infrastructural Monitoring and Protection, Curtin University on various techniques of SHM. The researches include the development of hardware, software and various algorithms, such as various signal processing techniques for operational modal analysis, modal analysis toolbox, non-model based methods for assessing the shear connection in composite bridges and identifying the free spanning and supports conditions of pipelines, vibration based structural damage identification and model updating approaches considering uncertainty and noise effects, structural identification under moving loads, guided wave propagation technique for detecting debonding damage, and relative displacement sensors for SHM in composite and steel truss bridges. This paper aims at summarizing and reviewing the recent research advances on SHM of civil infrastructure in Western Australia.

Keywords: research advances; structural health monitoring; review; Western Australia

1. Introduction

Structural Health Monitoring (SHM) provides practical means to assess and predict the structural performance under operational conditions. SHM is usually referred as 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 deterioration or damage indicators that may affect operation, serviceability, or safety (Aktan *et al.* 2000). The main objectives of SHM are to: (1) validate design assumptions and assess structural performance; (2) identify the possible damages at an early stage to ensure structural and operational safety; (3) provide real-time information for safety assessment immediately after disasters and extreme events; (4) assess the

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current structural conditions, load-carrying capacities and predict the remaining service life of a structure; (5) provide a decision tool for optimum inspection, rehabilitation and maintenance planning; and (6) obtain massive amounts of in situ data for leading-edge research with the benefit of improving design specifications and guidelines (Ko and Ni 2005, Frangopol *et al*. 2008). In the most general terms, damage can be defined as changes introduced into a structure that adversely affect its current or future performance, such as changes in the material and/or geometric properties, changes in the boundary conditions and system connectivity. The process of SHM involves the observation of a structure over time using periodical measurements, and the extraction of damage-sensitive features to determine the current state of structural health. For long-term SHM, the output of this process is periodically updated information regarding the ability of the structure to continue to perform its intended function in light of the inevitable ageing and damage accumulation resulting from the operational environments. Under an extreme event, such as an earthquake or unanticipated blast loading, SHM is used for rapid condition screening. This screening is intended to provide, in near real-time, reliable information about system performance during such extreme events and the subsequent integrity of the structure (Farrar and Worden 2007). Successful implementation and operation of SHM systems, and review of researches on SHM for civil infrastructure have been widely reported in US (Doebling 1998, Pines and Aktan 2002, Farrar and Lieven 2007, Fan and Qiao 2011, Lynch 2007), Europe (Carden and Fanning 2004, Teughels and De Roeck 2005, Brownjohn 2007), Canada (Mufti 2002), Japan (Fujino 2002), Hong Kong (Wong 2004, Yang *et al*. 2007), China (Ou and Li 2010, Li *et al*. 2014a) and Australia (Chan and Thambiratnam 2011). SHM plays a significant role in conducting the in-construction and in-service monitoring of structural dynamic responses and tracking any variations in the structural performance.

Australian Network of Structural Health Monitoring (ANSHM) has been formed in 2009 to promote and advance the awareness, understanding, collaborative research and application of SHM in Australia, to both academic institutions and industry partners, and also increase the involvement and transfer of SHM knowledge and techniques to engineering communities in Australia. The emerging need for SHM and its potential great benefits on the asset management of engineering structures bring all ANSHM members together to present and share their recent researches, achievements, SHM implementations and data mining strategies, and visions in real project applications. Extensive researches have been conducted on various SHM topics. Several typical recent studies include such as, but not limited to, SHM of an iconic building (Nguyen et al. 2015) and Sydney Harbour Bridge (Huynh *et al.* 2015), composite structures (Henderson *et al.* 2015, Ban *et al*. 2015), timber structures (Mahmood *et al*. 2014, Dackermann *et al*. 2014, Samali *et al.* 2010), ultrasonic and guide wave technologies (Sharma and Mukherjee 2015, Ng 2011, Ng 2014, Mustapha *et al.* 2014), signal processing and model updating techniques for structural damage detection (Wahalathantri *et al*. 2015, Alamdari *et al*. 2015, Ay and Wang 2014), artificial intelligence algorithms (Lee et al. 2012, Lee et al. 2014), substructure methods (Li and Hao 2014), climate adaption and reliability analysis (Bastidas-Arteaga and Stewart 2015, Bastidas-Arteaga *et al.* 2013), bridge-vehicle interaction (Zhu and Law 2015, Caprani *et al*. 2008), BIM and GIS techniques (Amirebrahimi *et al*. 2015, Xiong *et al.* 2015), energy harvesting (Lumentut and Howard 2015) and structural retrofitting (Mahini *et al*. 2012), etc. Those publications are only part of studies conducted by ANSHM members, and apologies go to those members whose works are not listed. More information may be referred to ANSHM website: www.anshm.org.au to see more details and ANSHM special issues in various journals.

In the past decade, with supports from Australian Research Council (ARC), Cooperative

Research Center for Infrastructure and Engineering Asset Management (CIEAM), CSIRO and industry partners, intensive research works have been conducted in the School of Civil, Environmental and Mining Engineering, University of Western Australia (UWA) and Centre for Infrastructural Monitoring and Protection, Curtin University on various techniques of SHM. The researches include the development of hardware, software and various algorithms, such as various signal processing techniques for operational modal analysis, modal analysis toolbox, non-model based methods for assessing the shear connection in composite bridges and identifying the free spanning and supports conditions of pipelines, vibration based structural damage identification and model updating approaches considering uncertainty and noise effects, structural identification under moving loads, guided wave propagation technique for detecting debonding damage, and relative displacement sensors for SHM in composite and steel truss bridges. This paper aims at summarizing and reviewing the recent research advances on SHM of civil infrastructure in Western Australia, especially by past and current members in UWA and Curtin University.

2. Signal processing techniques and modal analysis toolbox

An integrated computer software package for data processing and structural vibration properties extraction named Modal Analysis Toolbox has been developed. The programming structure of the toolbox is shown in Fig. 1.

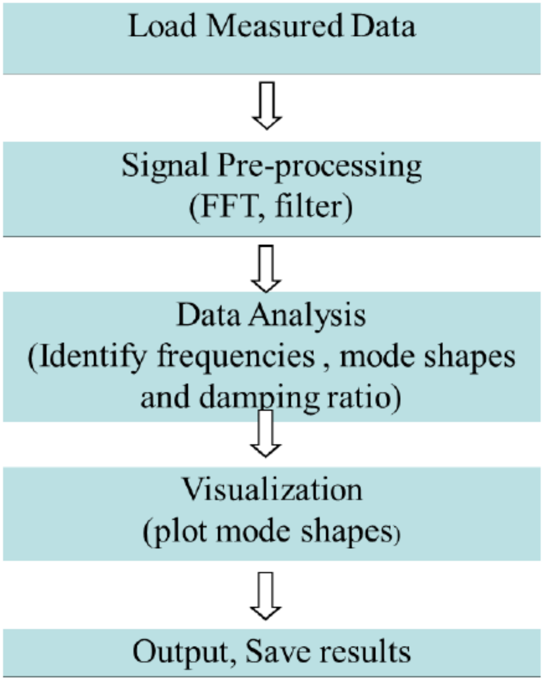
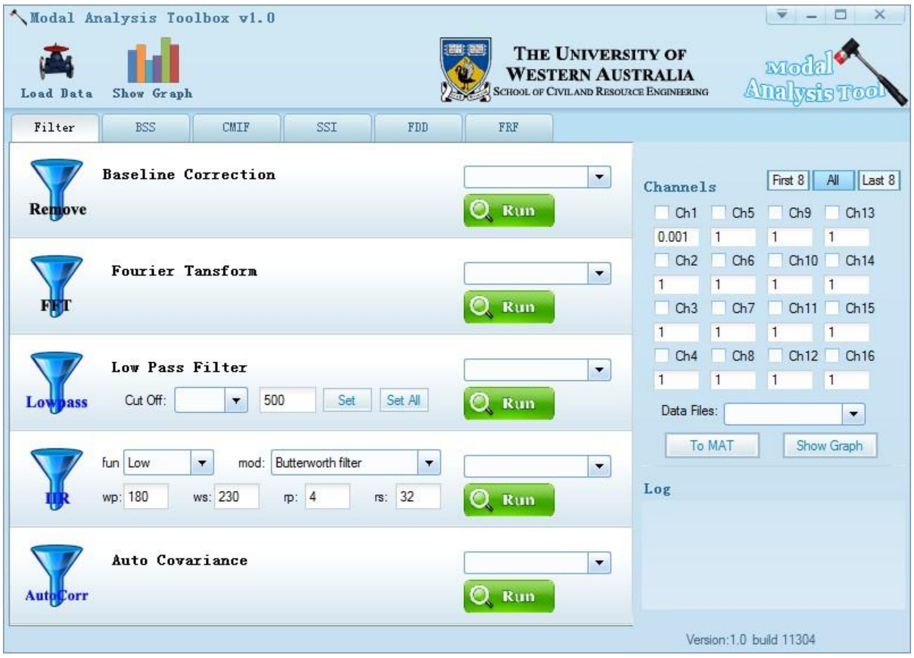


Fig. 1 Structure of developed “Modal Analysis Toolbox”



Cut Off: 500

fun: Low mod: Butterworth filter

wp: 180 ws: 230 rp: 4 rs: 32

☐ Ch1	☐ Ch5	☐ Ch9	☐ Ch13
0.001	1	1	1
☐ Ch2	☐ Ch6	☐ Ch10	☐ Ch14
1	1	1	1
☐ Ch3	☐ Ch7	☐ Ch11	☐ Ch15
1	1	1	1
☐ Ch4	☐ Ch8	☐ Ch12	☐ Ch16
1	1	1	1

Version:1.0 build 11304

Fig. 2 Friendly interface of developed “Modal Analysis Toolbox”

The testing data as a .txt file would be loaded into the toolbox for pre-processing and post-processing. The pre-processing module is designed to perform the basic analysis for the measured data, such as, checking the spectrum by using FFT, correcting the original response by using baseline correction, removing the high frequency noise by using low-pass and IIR filters and calculating the auto-covariance. The post-processing module includes several most popular approaches for modal analysis and vibration properties extraction, such as Blind Source Separation (BSS), Complex Mode Index Function (CMIF), Stochastic Subspace Identification (SSI), Frequency Domain Decomposition (FDD) and Damage Identification and Modal Analysis toolbox (DIAMOND, Doebling *et al*. 1997). All the approaches are debugged to make sure they can work compatible to each other. It should be noted that BSS, CMIF, SSI and FDD can be used for operational modal analysis, where only the measured structural responses are required. A user-friendly interface has been designed and developed for engineers and researchers as shown in Fig. 2.

Besides the above most popular modal analysis approaches, Bao *et al*. (2009) proposed an improved Hilbert-Huang Transform (HHT) for identification of time-varying systems and analysis of nonlinear structural responses with closely spaced modes. The auto-correlation of the structural response was taken as the input to the traditional HHT algorithm to significantly reduce the noise effect. Bao *et al*. (2013a) investigated the applicability and reliability of a few popularly used modal identification methods including time-domain, frequency-domain and time-frequency domain methods for system identification of civil structures. The results demonstrate that on average a 2% to 3% error tends to be yielded by using different signal processing techniques for vibration frequencies identification when the signals are not heavily noise contaminated. This should be taken into account when estimating the damage detection results. Various signal processing techniques have been proposed to improve the accuracy and applicability of modal analysis.

3. Structural condition assessment and damage identification

Vibration-based damage detection methods can be classified into non-model based (direct correlation) and model-based (model updating). With non-model based methods, the measured structural dynamic characteristics are directly compared between the undamaged and damaged states of structures. The merits of non-model based methods are that an accurate presentation of the initial finite element model of the structure is not required, and those methods are usually measured data based only. On the other hand, the model based methods require the finite element model of the structure for iterative updating to make the analytical and measured structural vibration properties as closely as possible. One major difficulty of these methods is that an accurate initial finite element model is required for the updating. The notable advantage is that not only the location but also the severity of the damage can be identified.

3.1 Non-model based methods

3.1.1 Bridges

Many bridges are built as the slab-on-girder structures. The concrete slab is supported by the concrete or steel girders, and stirrups are embedded in the girders and cast into the slab as shear connectors to link the slab and girders together. The shear connection between slab and girders in composite structures subjects to the major consequences of stress, overloading and fatigue, especially for large structures such as bridge decks. It follows that damages usually involve a deterioration or break of the shear connection in some regions of the structure, causing a decrease of the overall rigidity of the composite structure and a reduction of its ultimate resistance. Damage of shear connectors will result in shear slippage between the slab and girder, which significantly reduces the load-carrying capacity of the bridge. Condition assessment of shear connectors is of great interest and important to evaluate the structural integrity in health monitoring of slab-on-girder structures.

Xia *et al.* (2007) proposed a local detection method by directly comparing the frequency response functions of simultaneously measured vibrations on the slab and girder for detecting the shear connection conditions in composite bridges. It was found that the local method gave better identification results than the global methods, since the global modal information is generally less sensitive to the local damage of shear connectors. The proposed local detection approach was extended to assess the integrity of shear connectors in real slab-on-girder bridges with in-field testing data (Xia *et al.* 2008). The merits and demerits of the proposed non-model based approach over the model updating based method have been discussed. The baseline data and a sophisticated initial finite element model are not required therefore it could be a more practical approach for damage detection with only the measured data from the existing structure. This is a significant merit of the non-model based methods. The merit of model updating method is that it can evaluate the condition of the whole bridge structure and quantify the damage severity. Wavelet packet energy (Ren *et al.* 2008) and the wavelet based Kullback-Leibler distance (Zhu *et al.* 2012) have also been proposed for damage identification of shear connectors following the similar idea in the above studies to compare the vibration characteristics between slab and girder signals, but using a different and sensitive signal feature. Li *et al*. (2014b, 2015a) introduced the transmissibility and power spectral density transmissibility in detecting the damage of shear connectors in composite bridges. The transmissibility is an inherent systematic characteristic, which represents the relationship between two sets of response vectors in frequency domain. Power spectral density transmissibility has been developed between the auto-spectral densities of two response vectors, and used to increase the sensitivity to successfully detect the shear link damage. Both approaches have been applied to analyse the measured data from an in-field bridge, and compared with the previous approach based on relative difference of frequency response functions on the slab and girder.

Nie *et al*. (2012) proposed an innovative technology based on vibration phase space topology changes for structural damage detection. Both numerical simulations and experimental tests with dynamic responses of an example arch structure with different imposed damages were conducted to demonstrate the effectiveness and sensitivity of the proposed approach. Later, experimental studies on a two span reinforced concrete slab were conducted at different damage states, and the damage index based on the geometric changes of the reconstructed multidimensional phase space of vibration signals was calculated to identify structural damage (Nie *et al*. 2013). It has been demonstrated that compared with the traditional modal-based indices for structural damage detection, the phase space based damage index is more sensitive to structural damage and condition change.

Non-model based output only system identification from ambient vibration measurements has been conducted to identify the modal information, such as frequencies, mode shapes and damping ratios (Brownjohn *et al.* 1992, De Roeck *et al.* 2000). The real structures under operational conditions are only excited by random excitations from unregulated traffic, wind, flowing water and ground-transmitted vibrations. Many studies on damage identification methods with ambient vibration measurements have been conducted recently (Lee and Yun 2006, Duan *et al.* 2007). They need both the monitored data from the healthy and unhealthy structures for a comparison with the dynamic system characteristics. Bao *et al.* (2013b) applied an improved HHT method to the SHM of operational civil engineering structures under ambient excitations. A multi-stage damage detection scheme which consists of the detection of damage occurrence, damage location and the estimation of damage severity was developed. Li *et al.* (2014c) proposed a dynamic condition assessment approach based on wavelet packet energy of cross-correlation functions of measured acceleration responses under ambient excitations to identify the damage of shear connectors in composite bridges. The percentage of wavelet packets energy to the total wavelet packet energy, as a function of system's impulse response functions, was used for damage detection. The energy percentage of selected wavelet packets with specific frequency bandwidths in the undamaged and damaged states was used to detect the damage locations of shear connectors.

3.1.2 Pipelines

Subsea pipelines provide a vital transportation service to transport natural oil or gas from offshore wells to an onshore location. Free-spanning damage is one of very common problems both in the design phase and during operation of pipelines. Most vibration-based damage detection methods require the modal properties obtained from measured signals through the system identification techniques. Peng *et al.* (2012) proposed a damage index called the average wavelet packet energy change rate based on the covariance of output signals to identify the free-spanning damage in a scaled pipe model excited by ambient wave force. To further verify the above proposed approach, two scaled pipe models with different boundary conditions were designed and tested subject to random wave forces in a large wave tank (Peng *et al.* 2013). Different damage scenarios were simulated by removing soil underneath the pipe models with different lengths. Waterproof accelerometers were used to collect pipeline responses which were subsequently analyzed for pipeline condition monitoring. The results show that using output-only dynamic responses of pipeline subject to random ambient wave excitations can accurately identify free span locations and length. Bao *et al.* (2013c) proposed an integrated method based on Autoregressive Moving Average (ARMA) algorithm to realize the structural health monitoring of the subsea pipeline system. Measured acceleration signals were used for analysis, and Partial Auto-correlation Function (PAF) was employed to estimate the optimal AR model order. A damage indicator with the Mahalanobis distance calculated based on the generated AR coefficients was defined for damage detection. Numerical studies were conducted and later followed with experimental studies (Bao *et al.* 2013d). The results demonstrated that the proposed method is sensitive to damage and insensitive to noise. It provides very good results for the detection and localization of damages in subsea pipeline system with a high efficiency and reliability.

3.2 Model based methods

Hao and Xia (2002) proposed a structural damage detection approach by using Genetic Algorithm (GA), which compares the measured vibration data before and after damage and updates the finite element model so that the changes of its vibration data are equal to the changes in the measured vibration data due to structural damage as closely as possible. To the authors' knowledge, this could be one of the several pioneer studies by using GA in structural health monitoring and damage identification. Peng and Hao (2012) developed a finite element model considering fluid-pipe-soil interaction for submarine pipeline system. The ambient hydrodynamic force in the marine environment was simulated based on the Joint North Sea Wave Observation Project (JONS-WAP) spectrum. The calculated dynamic responses were assumed as measured ambient vibration responses for condition monitoring to extract the pipeline vibration properties, which were used in the finite element model updating to identify the pipeline conditions. Wang *et al.* (2013) proposed a damage identification method based on the calibrated Auto Regressive Moving Average Exogenous (ARMAX) model. The calibrated ARMAX model was used to identify different damage scenarios through model updating process using Clonal Selection Algorithm (CSA). Numerical and experimental studies on a steel pipe laid on the soil with and without soil support were conducted to verify the effectiveness and performance of the proposed approach. Wang and Hao (2014) proposed a new damage identification scheme based on sparse representation of time domain structural responses and compressive sensing techniques. The structural damage identification problem was transferred into a sparse representation based pattern classification problem. Compared with traditional methods, the proposed approach requires less information, i.e. vibration time history of one point on the structure can yield good identification results. Later, a new concept termed as power spectral density transmissibility (PSDT) has been used for structural damage identification with numerical and experimental verifications (Li *et al.* 2015b). Damage identification was conducted by minimizing the difference between the measured and the reconstructed power spectral density functions. The dynamic response sensitivity based model updating was used to identify the damage location and severity. Li *et al.* (2015c) presented a structural damage identification approach based on the extracted time domain impulse response functions (IRF) from the measured dynamic responses with the input available. IRF sensitivity based optimal sensor placement strategy was employed to investigate the best sensor locations for identification. Numerical studies were conducted to demonstrate the effectiveness of the proposed approach with and without optimally selected sensor locations.

An important issue in the area of structural health monitoring and damage detection is to detect the local damage using measured responses from the structure under moving vehicular loads which serve as excitations to the structure. This topic has been receiving increasing attention since it is desirable to conduct the system identification based only on the system output (vibration responses of the bridge) with the system input (traffic excitations) difficult to measure. Li *et al.* (2013) proposed a damage identification approach for bridge structures subjected to moving vehicular loads without knowledge of the vehicle properties and the time histories of moving interaction forces. Experimental studies on a Tee-section pre-stressed concrete beam subjected to a moving vehicle were preformed to validate the proposed approach. Identification results from the experimental test data demonstrated that the damage locations can be identified with a reasonable estimate of the damage extent. Later a damage identification and optimal sensor placement approach for structures under unknown traffic-induced vibrations, has been presented with numerical investigations (Li *et al.* 2015d). Damage identification was conducted based on the initial finite-element model of the structure and the measured responses from the damaged structure under traffic-induced ground vibrations. With the use of optimal sensor locations, the introduced damages have been identified effectively and accurately with nearly exact damage severity estimation and very small false positives and false negatives under a 5% noise effect.

3.3 Performance evaluation

Ding et al. (2009) developed an evolutionary spectral method to evaluate the dynamic vehicle loads on bridges due to the passage of a vehicle along a rough bridge surface at a constant speed. The effects of the road surface roughness, bridge length, vehicle speed and axle space on the dynamic vehicle loads on bridges were studied. The results demonstrate that the road surface roughness has a significant influence on the dynamic vehicle-bridge interaction. The dynamic amplification factor and dynamic load coefficient depend on the road surface roughness condition. Zanardo *et al.* (2006) assessed a Main Roads Western Australia's bridge (No. 3014) to evaluate its condition before and after strengthening works with carbon-fiber-reinforce-polymers (CFRP). Vibration based structural condition assessment was conducted before and after the completion of the upgrading works. The changes in the structural vibration properties and stiffness based on the updated models of the bridge were presented and discussed. It has been demonstrated the dynamic assessment method coupled analytical results with field observations and dynamic testing of the structure is effective to assess the bridge condition and identify the stiffness of bridge structures retrofitted with CFRP. This may be the first reported investigation where the assessment of the effects of deck strengthening by CFRP on the performance of reinforced concrete bridge structures has been performed thorough the analysis of dynamic measurements. Ding *et al.* (2012) evaluated the bridge load carrying capacity using updated finite element model and nonlinear analysis. The original finite element model based on the design drawings was updated by modifying the stiffness parameters of the various bridge components to match the analytical vibration properties of the finite element modal well with the experimentally measured ones. The load carrying capacity of the bridge was then calculated with the updated finite element model considering the nonlinear material properties. The influence of the shear connectors on the load carrying capacity was specially investigated. This study significantly demonstrates that the updated model can represent the actual condition of the bridge better and the load carrying capacity calculated based on the updated model can provide a more realistic condition of the bridge.

4. Environmental and uncertainty effect

Many sources of uncertainties that are introduced into the structure during their construction and service stages make it not easy to perform a reliable structural condition assessment or achieve an accurate finite element model for updating. Finite element modelling errors and noise effect in the measurement data are two of the most significant uncertainties. Different signal processing techniques may yield different structural parameters from the same measured data, and different damage index definitions may result in different structural damage identification results. Environmental factors are also kinds of uncertainty in the system, such as temperature and humidity that affect structural vibration properties and lead to false identifications. If the effect of these uncertainties on structural vibration properties is larger than or comparable to the effect of structural damage on the vibration properties, structural damage is difficult to be reliably identified.

4.1 Environmental effect

Xia et al. (2006) performed the long term vibration monitoring of a reinforced concrete slab subjected to changes in environmental conditions such as temperature and humidity effect. The variation of frequencies, mode shapes and damping with respect to temperature and humidity changes has been investigated. It has been found that the frequencies have a negative correlation with temperature and humidity, damping ratios have a positive correlation, but no clear correlation of mode shapes with temperature and humidity changes can be observed. Linear regression models between modal properties and environmental factors were built.

4.2 Uncertainty effect and propagation in structural health monitoring

Xia and Hao (2003) proposed a statistical damage identification algorithm based on frequency changes to account for the uncertainties in the structural model and measured vibration data. The statistics of the parameters were estimated by the perturbation method and verified by Monte Carlo Simulation technique. Random errors in material properties and measured vibration signals were considered. The Probability of Damage Existence (PDE) was estimated based on the probability density functions of the parameters in the undamaged and damaged states. Xia *et al.* (2002) combined uncertain frequency and mode shape data for statistical structural damage identification. The effects of uncertainties in both the measured vibration data and finite element model were considered as random variables in model updating. Discussions were also made on the applicability of the method when no measurement data of intact structure was available. The confidence level of false damage identification is reduced, but most damaged members still can be confidently identified. Zhu *et al.* (2008) applied the above technique for statistical damage detection of underwater pipeline systems via vibration measurements. Laboratory tests of a scaled pipeline model were conducted in a towing tank. The model includes a plastic pipe and some removable springs which were designed and fabricated to link the pipe and the steel base to simulate the bedding conditions. Different damage scenarios, in terms of location and severity of scouring under the pipe, were simulated by removing one or several springs. Considering the uncertainties in both the finite element modelling and measured data, free spans and damage in the pipe can be reliably identified by using statistical model updating.

Bakhary *et al*. (2007) proposed a statistical approach to take into account the effect of uncertainties in developing an Artificial Neural Network (ANN) model. The influence of uncertainty on damage identification using a combination of frequency and mode shapes as the input variables was investigated. A statistical ANN model was trained with vibration data generated from the finite element model, but smeared with random variations and noises. The input data consisted of natural frequencies and mode shapes, and the output layer consisted of Young's modulus to represent the stiffness parameter. The statistics of the stiffness parameters were estimated by applying Rosenblueth's point estimate method, and verified by Monte Carlo Simulation. Numerical and experimental results demonstrated that, compared with the normal ANN approach, the statistical ANN approach gave a more reliable identification of structural damage. Bakhary *et al*. (2010a) proposed an approach to detect structural damage using substructure technique along with a multi-stage ANN. The full structure was divided into several substructures, and each substructure can be represented by one ANN model, which was trained separately. The number of unknowns in one ANN model was substantially reduced and the training quality and time were improved. Two-stage ANN system was designed with the first stage used to detect the specific substructures that have suffered damage, while the second stage defined to identify the damage location and severity. The frequencies and mode shapes of the full structure were used as the inputs to the first stage ANN model, and the outputs were the frequencies of every substructure. The output of the first stage ANN model, together with the mode shape values of the full structure at nodal points corresponding to the substructure, were used as the input variables to the second stage ANN model. The proposed approach is effective in reducing the size of the required ANN models, and as a result the computational effort can be reduced substantially. It can also be reliably and efficiently used to identify multiple damages in multiple substructures, overcoming the difficulties presented in previous investigations and avoiding visual inspections to approximately locate the damage before applying ANN. Later, this approach was extended to a statistical approach to not only tackle the measurement noise and modelling error in the multi-stage ANN model, but also reduce the influence of duplication error and mode shape error associated with the multi-stage substructuring ANN model (Bakhary 2010b). The uncertainties were considered in both the training and testing data in this study. Numerical and experimental results demonstrated that, compared with the deterministic multi-stage ANN approach, the statistical multi-stage ANN approach gave a more reliable prediction of structural damage. PDE was given. The proposed approach can also be reliably used to identify damage in a single substructure and in multiple substructures.

5. New sensing technology

In this section, the recent developments and applications of the developed guided wave propagation techniques for detecting the debonding in reinforcements and the designed relative displacement sensor for detecting the shear slip between two structural interfaces will be reviewed.

5.1 Guided wave propagation for debonding detection

Wang *et al*. (2009) developed a concrete-steel spectral element to investigate the guide wave propagation along the steel rebar in the concrete. Scalar damage parameters characterizing changes of the interface conditions were incorporated into the formulation of the spectral finite element. The changes in the wave propagation properties were used to detect and assess debonding damages along the rebar and concrete interface. Numerical and experimental studies have been conducted to verify the developed spectral finite element method for modelling wave propagations. The results demonstrated that the model can be used to predict the wave propagation along the steel bar in concrete with a complex interaction between the steel rebar and concrete. Wang *et al*. (2011) later applied the spectral elements to model the local damage (cracks in the reinforcement bar) and global damage (debonding between reinforcement bar and concrete) in one-dimensional homogeneous and composite waveguide, respectively. Clonal Selection Algorithm (CSA) was used for the spectral element model updating. Numerical results showed that local damage was easy to be identified by using any considered objective function with the proposed method, while only using the wavelet energy-based objective function output a reliable identification of global damage. Experimental studies on the wave propagation in a rectangular steel bar before and after damage demonstrated that the updating with CSA can be used efficiently for damage identification, and identifying cracks in steel bars based on measured wave propagation data. Wang and Hao (2012) proposed an integrated structural condition monitoring strategy using local and global methods. Global methods using low frequency structural vibration properties may not be sensitive enough to minor damages in a structure, while local methods could be very sensitive but their detection range is usually limited. The integrated system has been developed to take advantage of both methods. Vibration and guided wave tests were conducted, and CSA is adopted for model updating calculations. Using wave propagation data in the first-stage model updating to identify the damage location, and combining wave propagation and vibration data in the second-stage to identify the damage severity successfully and efficiently. Wang *et al*. (2012) proposed to use imaginary spectral elements combining with the real structural elements to model wave reflections at structural boundaries. The proposed approach was applied to model wave propagation in a steel bar with not only boundary reflection, but also reflections from single and multiple cracks. Zhu *et al*. (2013) presented a novel technique based on wavelet transform and wavelet packet energy to detect the delamination between the steel bars and concrete in the reinforced concrete structures. The piezoelectric components were mounted on reinforcing bars embedded in reinforced concrete structures as sensors and actuators to receive and generate the signals. Experimental studies on two reinforced concrete slabs with different debonds between rebars and concrete were conducted to verify the proposed approach and investigate the effectiveness of the used damage indices.

5.2 Relative displacement sensors

Wang and Hao (2013) validated that the natural frequencies are not sensitive to the shear connector damage. In the conducted static loading tests, laser displacement sensors were placed horizontally to monitor the relative displacement between the concrete slab and steel girder. This study pointed out the relative displacement between slab and girder at the beam end could be a promising indicator for shear connector damage detection. Li *et al*. (2015e) proposed the development and application of an innovative relative displacement sensor to measure directly the relative slip between slab and girder in composite bridges for assessing the health condition of shear connections. The structure, design principle, features, and calibration of the developed relative displacement sensor were presented. The accuracy of the developed sensor has been verified by comparing the measured relative displacement with that derived from laser displacement sensors. The developed relative displacement sensor does not require a fixed reference point and can be directly installed on the target structure that is easy to setup. Another advantage is that the sensor is cost effective, reliable, and capable of performing various structural health monitoring purposes. It has been demonstrated to have a good performance for the structural health monitoring of composite bridges, i.e., damage detection under ambient vibrations and crack detection. Later, Li and Hao (2015) investigated the applicability, effectiveness and performance of using the developed relative displacement sensor for identifying the damage of shear connectors in composite bridges under moving loads with time-frequency analysis techniques. Continuous Wavelet Transform and HHT were applied to analyse the measured relative displacement measurements. Comparative studies by using the relative displacement, acceleration and displacement measurements respectively for the damage detection were conducted. Numerical and experimental studies demonstrated that both relative displacement and acceleration measurements can identify the location and the instant of damage occurrence in shear connectors when the bridge was under moving loads, but the relative displacement was a better and sensitive response quantity for structural health monitoring of composite bridges. The relative displacement sensor has also been successfully applied for the structural health monitoring of joint conditions in steel truss bridges (Li and Hao, online). The dynamic relative displacement measurements were analysed with a time-frequency analysis method to identify the structural condition change, namely the loosen bolt damage in the joint connection of steel truss bridges under ambient vibrations. Relative displacement measurements of the steel truss bridge models under free vibration tests from both undamaged and damaged states were also analyzed, and a damage index based on the change in the percentages of a specific wavelet packet component to the total wavelet packet energy between the undamaged and damaged states was used to detect the existence of the loosen bolt damage in steel truss bridges. Experimental studies demonstrated that the developed relative displacement sensor has a sensitive performance to identify and assess the joint conditions in steel truss bridges. The relative displacement sensor is very sensitive to the damage which could introduce any relative displacement change, for example, the shear connection damage in composite bridges and the bolt connection loosen in the gusset plate of the truss bridges. The developed relative displacement sensor has many potential applications in various civil engineering structures.

6. Challenges

Vibration based SHM techniques rely on that structural damage or condition change significantly alters the structural properties, such as stiffness, mass and damping, which in turn changes the structural vibration properties extracted from the measured data. Damage-sensitive feature selection is extremely important to perform an effective and economic SHM. New sensing techniques with specific purposes to monitoring structures with particular types of damage or adverse effects may attract more attention and new developments. The long term SHM strategy integrating new technology developments, new sensing device/materials, networking techniques and data mining algorithms could be a continuous research focus. Accurate interpretation of a large amount of measured data under operation conditions and various environmental conditions is significant to guarantee a successful structural condition assessment and performance prediction. The accuracy of structural condition identification depends on the reliability of structural response measurements, signal processing techniques to extract the required structural parameters, damage index to define and quantify structural condition, a high fidelity finite element model of the structure, and a model updating technique to locate the damage and quantify its severity. All these steps are associated with uncertainties, such as finite element modelling errors and measurement noises. Uncertainty quantification and investigation of uncertainty propagation in the operational modal analysis, performance assessment, model updating, reserve capacity estimation and remaining service life prediction is attracting more and more attention, which is also of great interest to asset managers and owners to understand the real performance and capacity of structures after a long service life or under extreme events. This would be good demonstrations to industry regarding the benefits and values of SHM technology. Those challenges are not intended to be an exhaustive list in this filed, but only based on authors' experiences.

7. Conclusions

This paper reviews the recent research advances on structural health monitoring in Western Australia, including signal processing techniques for operational modal analysis, a graphical user-friendly modal analysis toolbox, non-model based methods for assessing the shear connection in composite bridges and identifying the free spanning and supports conditions of pipelines, vibration based structural damage identification and model updating approaches considering uncertainty and noise effects, structural identification under moving loads, guided wave propagation technique for detecting debonding damage, and newly developed relative displacement sensor for SHM in composite and steel truss bridges.

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