Preface

Structural Health Monitoring (SHM), a process of utilising on-structure or remote sensing systems and/or imaging techniques to monitor the performance of structures and evaluate their health conditions, has rapidly grown worldwide on its research and industrial practices in recent years. Recent disastrous bridge failures, such as the collapses of the Nanfang'ao tied-arch bridge in Taiwan, the Wuxi National Highway 312 overpass in China, and the Pont de Mirepoix suspension bridge in France, all in the year 2019, and the Mexico City Metro overpass collapse in 2021, have further reminded the importance of structural health monitoring for civil infrastructures. During the last three decades, SHM has attracted enormous research efforts around the world because it targets on monitoring structural conditions to prevent catastrophic failure and to provide quantitative data for engineers and infrastructure owners to design reliable and economical asset management plans.

This book showcases the recent advancement in SHM research, especially for civil engineering applications in Australia, covering the state-of-the-art SHM technologies together with its latest developments and successful applications. The book provides a glance on the research outcomes in SHM related areas delivered by some of the experts in Australian universities.

This book is launched to mark the significant milestone of the 10th Anniversary of Australian Network of Structural Health Monitoring (ANSHM) and its contribution to the SHM research and practice over the past 12 years since its inception in 2009. The preparation of this book for an intended completion in 2020 was significantly delayed due to the impact of COVID-19 pandemic. The Network, comprising Australian leading SHM experts, aims to promote and advance SHM application, education, research and development in Australia. Although the title of the book highlights recent SHM advances in Australia, the technologies and approaches described can be applied widely around world.

Dr. Aftab Mufti, the Founding President of the International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII), Member of the Order of Canada, Fellow of Royal Society of Canada, and Professor Emeritus of the University of Manitoba, confirms in his Foreword for the book the ever-increasing importance of SHM implementations in engineering practice. He also provides some inspiring insight into the future directions of smart and intelligent SHM technologies that contribute to the long-term health monitoring of civil infrastructures.

In this book, the eleven chapters are organised in five topic clusters: physical model-based updating and damage detection for bridges and buildings (Chapters 1, 2), smart and mobile sensor networks for bridges and partially submerged structures (Chapters 3, 4), data-driven machine learning based SHM method (Chapters 5 to 8), SHM in railway track maintenance and management (Chapters 9, 10), and finally, digital twin approach for lifecycle management of large-scale civil infrastructure (Chapter 11).

Damage detection and model updating are two important techniques in SHM. Chapter 1 introduces an overview on how these techniques could be used for civil structure monitoring. Both techniques are mainly based on identified dynamic characteristics/signature of a structure at different stages for SHM purposes. Several basic damage detection methods such as the Modal Flexibilities (MF) and Modal Strain Energy (MSE) methods are reviewed in this chapter, followed by more advanced methods such as Correlation-based method using ratio of MSE to eigenvalue (MSEE), deflection-based methods, modal kinetic energy (MKE), plus other advanced modal flexibility and advanced modal strain energy methods. Other developments of applying data analytics to enhance dynamic parametric changes, i.e., machine learning techniques such as artificial neural network, and optimization techniques such as Multi-Layer Genetic Algorithm (ML-GA) optimization and sensitivity-weighted search space (SWSS) are also introduced. In addition, a time domain-based method using Enhanced Auto-Regressive (AR) technique is presented as well. All these methods have been applied successfully to different structures including slab-on-girder bridges, arch bridges, suspension bridges, truss bridges, multi-story buildings, asymmetric buildings and hyperbolic cooling towers. For each of these structures, relative performances of the applied damage detection methods are discussed. Finally, various methods for model updating are presented, including a hybrid deterministic method and an advanced probabilistic method integrating Bayesian approach and Gaussian process.

Followed up from Chapter 1, Chapter 2 presents the model updating of a 380m-main span cable-stayed bridge based on real-time SHM data from on-structure sensors, using weighted least-squares optimisation and parameter sensitivity approaches. The primary challenge of model-based SHM of long-span cable supported bridges is on the development of efficient numerical models that can accurately predict vibration characteristics, which are sensitive to uncertain model parameters and structural modelling assumptions. Using ambient vibration data, which are often recorded over long periods and characterised by levels of noise and randomness, induces unique challenges to the updating process. To address these challenges, sensitivity-based model updating procedure is employed in this chapter taking into account the inherent monitoring data variability. The weighting matrix can be directly defined using the data variability without the need for estimation. While not wholly stochastic, this sensitivity-based updating method maintains the right balance by trading off between the uncertainty and variability in the dataset and parameters in an intuitive way, while avoiding the computational burden of using more complex techniques to gain effectiveness and accessibity for SHM practitioners. The model updating results illustrate that the updated model is in good agreement with the modal properties identified from the monitoring data.

Most approaches in bridge SHM measure the vibration responses of an instrumented bridge and extract the structural properties based only on the measured bridge responses under the assumption of white noise traffic excitations. However, it is inadequate to account for the operational variations of excitation on the bridge and ignores the correlation between excitation processes at different spatial points. It is therefore of much research interest to capture the vehicle-bridge interaction (VBI) information from dynamic responses of passing vehicles for bridge monitoring. With the development of the wireless sensor technology, the truck-based mobile sensory system becomes one of the most cost-effective approaches to capture the dynamic interaction between the vehicle and the bridge which has a great potential of application for a quick scan of large stock of highway bridges. Chapter 3 shows an application of drive-by bridge modal identification to an actual cable-stayed bridge using a passenger car equipped with a wireless sensor, which is very important for practical application of bridge SHM.

Chapter 4 focuses on damage detection of partially submerged structures using guided waves, in particular the corrosion damage in metallic plates. Corrosion is one of the major issues for metallic structures, being pervasively used in water storage and distribution systems such as water tanks and water mains. Safety inspections are essential to mitigate the risk of in-service failure. Most of the traditional non-destructive testing (NDT) techniques require the water storage and distribution systems to be emptied and cleaned prior to performing the inspections, which are time-consuming and labor-intensive. Guided waves have been widely recognised as a promising SHM technique for fast and cost-effective inspection of structures under gaseous environments. This chapter presents numerical and experimental investigations on ultrasonic guided waves propagation and scattering at the damage in partially immersed plates. The influence of water on the guided wave propagation is demonstrated by comparing the experimentally measured data from a water-free tank and the same tank partially filled with water. A three-dimensional (3D) finite element (FE) model is also developed to simulate the interaction between the quasi-Scholte (QS) wave and a local area of thickness reduction in the plate loaded with water on a single surface. The 3D FE model verified against experimental measurements is employed in the parametric study, by which the characteristics of the QS wave scattering at the localised thickness reduction are presented in terms of the scattering directivity patterns.

Transportation infrastructure, including roads and bridges, plays a vital role in a nation's economy and quality of life. Unfortunately, there has been plentiful news in the present media about widespread ageing infrastructure that could be issues affecting the transportation network worldwide. In order to ensure structural safety and functionality, conducting regular SHM inspection, maintenance and repair tasks is crucial. In dealing with classification of corrosion in steel bridges, Chapter 5 presents an innovative image processing method to assess the deterioration of this type of infrastructure. The methodology involves two major steps, the first step is to conduct a series of corrosion tests and to acquire steel corrosion images, the second step is to apply the image processing technology, incorporating a Convolutional Neural Network (CNN), to classify the deterioration pattern. It is verified from the evaluation that the accuracy of the innovated CNN classifier is as high as 86.7%, which is promising in infrastructure deterioration diagnosis.

Deep learning-based neural networks, as techniques in artificial intelligence, have received a significant amount of attention and become a central and hottest topic in data science research. Apart from Chapter 5 introducing CNN as a deep learning algorithm for corrosion detection, Chapter 6 presents recent studies on the development and application of deep learning techniques based on three advanced deep learning frameworks for data-driven SHM applications, namely, autoencoders, sparse autoencoders and deep residual networks for structural damage identification with dynamic vibration characteristics. Measured modal information, such as natural frequencies and mode shapes, are used as input to the network models. Both the locations and severities of structural damage can be identified accurately even when the measurement noise and uncertainty effect are presented in the measured data. Two main components, namely, dimensionality reduction and relationship learning with a pre-training scheme, are included in the autoencoders and sparse autoencoders frameworks. Residual neural networks can avoid the problem of vanishing gradients by utilizing skip connections, which allows the information flowing to the next layer through identity mappings. Numerical and experimental studies on various civil engineering structural models are conducted to validate the accuracy and performance of the three network models.

Chapters 7 introduces another deep learning-based method, in which data-driven SHM based on deep transfer learning techniques for crack and fault detection considering uncertainty in hyperparameter tuning and input data are reported. Computer vision techniques can be applied to detect structural defects of concrete structures. In this aspect, deep transfer learning algorithms play a key role in terms of automated crack identification. Selecting appropriate models and tuning them for the classification of crack images, especially in adverse conditions, is a topic that has been neglected until now. Similar to Chapter 5, this chapter presents another image processing technique adopting CNN models for damage detection. To test the robustness and stability of deep transfer learning networks, eight popular pre-trained CNN models with different network architecture complexities were tasked with image classification challenges. This refinement was created by varying a key hyperparameter used for tuning and feeding the networks with two variants of adverse conditions in image data. This chapter provides evidence of the optimal batch sizes that should be used and the best repurposed small and large deep learning networks that can achieve outstanding crack classification capabilities with compromised image data. According to the results, GoogleNet and Xception networks have been challenged and confirmed as high-performing networks on average, particularly when used with reasonable batch sizes. Results from this study can bring large benefits to SHM practitioners, asset and maintenance engineers, especially those with a particular focus on automated crack detection in concrete structures.

Asset management attempts to monitor and react to asset deterioration to deliver the expected levels of service. However, current road asset management techniques are highly reactive and unable to thoroughly analyse the holistic environment and associated effects. Chapter 8 addresses the issue of impossible task for asset inspectors in checking massive footprints of road networks. The technologies in focus include geographical mapping systems and mobile phones with remote access to cloud databases and image capturing capability. Road inspectors and assessors can automatically detect road faults by integrating these tools coupled with image processing and artificial intelligence (AI). This is possible using image submissions by public members taken from smartphones, enabling a smart and cost-effective automated road fault detection system. The collected road surface images from across an Australian local government area were subjected to classification using deep learning for automated fault detection. Results show that implementing this fault detection procedure into a common engineering software such as MATLAB can achieve a validation accuracy of 95%. This is independent of the technical background or programming knowledge of the road users as data collectors. Additionally, an integration framework to incorporate this smart tool into a standard asset management framework is provided to improve the current road asset maintenance planning and management practices in Australia.

Chapters 9 and 10 present damage evaluation and SHM for railway tracks using non-destructive testing. Railway track failures include broken rails initiated from rail internal flaw or defects, and track buckling/misalignment of Continuous Welded Rails (CWR) that can strengthen railway tracks. However, by eliminating rail joints and gaps between rail sections, high thermal stresses due to temperature changes may occur within welded rails. To ensure stability of CWR tracks, measuring and monitoring the longitudinal neutral thermal stresses via Stress Free Temperature (SFT) is the ultimate goal for CWR track maintenance. Using the three non-destructive technologies being approved by the railway infrastructure authorities for neutral temperature in-field measurement in Australia, namely, the Magnetic Barkhausen Noise method, mechanical method and vibration method, Chapter 9 introduces the ultrasonic testing and provides a review based on in-field measurements, verifications and data comparisons. The advantages and disadvantages of the three methods are compared, by which the technical scope and work instructions for the application are recommended.

Chapter 10 continues to investigate the rail failure detection and monitoring utilising effective ultrasonic testing. As an ultrasonic-testing-based SHM technique deals with huge amounts of testing data, managing ultrasonic testing on rails for better risk management is rather challenging. Rail service failures, initiated from rail internal flaws or defects, constitute a major component of derailment costing. In Australia, considerable efforts were made to minimise such service failures and mitigate risk of derailments, through effective ultrasonic testing. The major Australian railway authorities issued explicit regulations of the schedules for a continuous search for internal rail defects. However, overdue was often happened due to complex rail surface conditions, high costs of ultrasonic testing practices, possession availability or traffic planning as well as capability and/or breakdown of the ultrasonic testing vehicles. The non-compliant rail ultrasonic testing track sections left high risk for rail broken and derailments. This critical issue is addressed in this chapter by presenting three newly developed management and engineering methods, namely, the "Risk Ranking - Prioritisation Matrix" method for risk assessment and prioritisation of non-compliant rail ultrasonic testing track sections; an optimized technical management of the surface affected rail; and an optimised ultrasonic rail test scheduling by the risk-based assessment model. Case studies are also provided to demonstrate the implementation process of these three methods and their outcomes.

The final chapter, Chapter 11, provides a critical review of the existing approaches using the Digital Twin (DT) technology for lifecycle management of large-scale civil infrastructures, such as buildings and bridges. With recent advances in computerisation and digitalisation, the DT approach has gained popularity and has been widely applied in many engineering fields. The DT technology enables an effective transformation from the physical asset to its virtual twin, which allows owners or managers to evaluate its current status and predict potential issues at the early stages of a project, thereby informing correct remedial and timely decisions. DT is a new-cutting edge area, which has been receiving considerable attention from the research community, including civil infrastructure management. The review outcome demonstrates that the DT technology has a wide range of capabilities for creating a digital replica of an infrastructure asset and enabling flexible adjustments, real-time responses and dynamic representations. The literature review conducted in this chapter will support further development and implementation of DT technology for long-term SHM and lifecycle management of large-scale civil infrastructures.

In summary, this book provides a snapshot on wider applications and implementations of SHM in Australia as well as showcase the world the advanced Australian R&D activities in SHM over the last 10 years. It is envisaged that the research and practical contents presented in this book will be beneficial for students, engineers, researchers, asset stakeholders to learn about multidisciplinary SHM concepts, outcomes, and applications and help to achieve cost-efficient maintenance and management of civil infrastructure systems around the world, thereby preventing catastrophic failures of infrastructure assets and networks. We also intend to have this book serving as a prescribed textbook for courses on Structural Health Monitoring.

Professor Hong Guan
Professor Tommy H. T. Chan
Professor Jianchun Li
Editors