DAMAGE IDENTIFICATION OF A BRIDGE COMPONENT USING MODEL UPDATING AND ARTIFICIAL NEURAL NETWORK TECHNIQUES BASED ON FREQUENCY RESPONSE FUNCTIONS

By
Van Vu Nguyen

A thesis submitted in fulfilment
of the requirements of
Doctor of Philosophy

Faculty of Engineering and Information Technology
University of Technology Sydney

February 2018

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Production Note:

Signature of Student: Signature removed prior to publication.

Date: 18/02/2018

This research is supported by an Australian Government Research Training Program Scholarship.

This thesis is the result of a research candidature conducted jointly with the Data61 CSIRO as part of a collaborative Doctoral degree.

Abstract

Many civil engineering structures worldwide are now or will soon be approaching the end of their design lives. In New South Wales (NSW), Australia, a joint study conducted by the Sydney Morning Herald and the University of Technology, Sydney (UTS) suggested that across two-thirds of NSW councils needed more than $340 million to bring their timber and concrete bridges up to a satisfactory condition. The American Society of Civil Engineers reported that 56,007 of the 614,387 bridges in the United States were found to be structurally deficient in 2016. Further, there was a recorded average of 188 million trips across structurally deficient bridges each day. One of the most important factors for budget prioritisation for asset maintenance is the condition assessment of structural assets. Austroads reported that the Roads and Martime Services (RMS) in NSW maintains 5,500 structures in their Bridge Asset Management System. However, they are typically only able to inspect their timber bridges once per year and their other bridges every two years due to budgetary constraints. Further, the most commonly used method for bridge inspection is visual inspection, which is generally unable to identify subsurface damage.

In the past couple of decades, structural health monitoring (SHM) has gained increasing attention as a monitoring system that is able to observe the structural characteristics of a bridge over time. SHM systems have been implemented on in-situ bridges world-wide. However, there are a limited number of publications that show clear and useful interpretations of the information collected from these systems. Meanwhile, damage identification methods that have been proposed and demonstrated in a laboratory environment are often implemented on structures that are much simpler than in-situ bridges.

This thesis aims to reduce the gap between the damage identification methods developed in the laboratory environment and their implementation on in-situ structures by proposing two novel damage identification methods. The first method is based on finite element (FE) model updating, and the second method is based on artificial neural networks (ANNs). Both methods utilise frequency response functions (FRFs), which can be directly measured from the structure and provide an abundance of information. These methods are demonstrated on two jack arch specimens, which are replicates of a structural component of the Sydney Harbour Bridge.

The FRF sensitivity method for model updating is investigated in this thesis to estimate the location and severity of damage in a structure. One of the main challenges in model updating is that a FE model typically contains many more degrees of freedom (DOFs) than the number of DOFs that are measured from a physical structure. One way to address this issue is by reducing the FE model DOFs to the measured DOFs. The drawback of this approach is that important information of the FE mode shapes can be lost. Another approach is to expand the measured DOFs to the FE model DOFs. However, this can significantly increase the computational cost of the model updating procedure. In this study, the FE model is reduced to a linkage model using the System Equivalent Reduction Expansion Process (SEREP). Then, the measured mode shapes are expanded to the linkage model using its mass and stiffness matrices. Based on the expanded mode shapes, interpolated FRFs are synthesised, and the FRF sensitivity method for model updating is applied. The updating parameters are used to form a damage index to estimate the location and severity of damage. The results from the study show that the method is capable of estimating the location and severity of the cracks that are visually identified on the specimen.

In the context of vibration-based damage identification, researchers have used ANNs to detect damage in a structure. In some of these studies, principal component analysis (PCA) was used to reduce the dimensionality of FRFs, turning them into principal component (PC) scores and making them more practical to be used as inputs into ANNs. These researchers demonstrated that ANNs are capable of identifying trained and non-trained damage cases. However, few of these studies elaborated on how the PC scores of the non-trained cases can be obtained when they have no involvement in the calculation of the PCs that are used to transform the FRFs into PC scores. This important feature is explored, as the non-trained cases should have no involvement in the calculation of the PCs or in the ANN learning process. Further this methodology is applied to the jack arch specimen, which simulates a realistic structural component of a bridge where the inflicted damage is small, resulting in minimal changes in the FRF. The results from this study show that the PCs calculated from the FRFs of the trained cases can be used to calculate the PC scores of the non-trained cases, and that these PC scores are compatible with the ANNs that are learned with the trained cases. Further, this method is applicable to the jack arch specimen, and should be tested on in-situ structures in future works.

The main contributions to the body of knowledge in this thesis revolve around applying damage identification methods that have been demonstrated on simplified laboratory models in the past to more realistic applications. The jack arch specimens used in this study replicate a structural component of the Sydney Harbour Bridge. The complex geometry of the jack arch specimens means that these structures require solid elements to be modelled accurately. This will invariably mean that the FE model will contain far more DOFs than the DOFs that can realistically be measured from the physical structure. The proposed linkage modelling technique is able to mitigate this issue. Additionally, when training ANNs to identify damage, it is impractical for all possible damage scenarios to be incorporated in the calculation of the PCs that are used to transform the FRFs into PC scores. Hence, this study investigates techniques to obtain PC scores of damage cases that have no involvement in the calculation of the PCs.

Acknowledgements

This PhD project could not have been possible without the support provided by numerous people. In particular, I would like to express my deepest appreciation and gratitude to:

- My supervisor, Professor Jianchun Li, for providing countless discussions and advice on how to move forward in my PhD when I had run into problems. Not only was he my mentor in research, he was also my supervisor for the subject that I have enjoyed teaching over the years, Engineering Computations. I strongly believe that the experiences that I have gained in research and teaching over the past couple of years have helped me to develop my character and I am greatly thankful for that.
- My co-supervisor, Dr Ulrike Dackermann, for her strong guidance in the early stages of my PhD while research was new to me. She introduced me to modal testing and artificial neural networks, which helped form my early understanding of damage identification. She was also comprehensive in reviewing my work, and provided me with the invaluable experience of travelling to Berlin, Germany to gain experience in non-destructive testing at the Federal Institute for Materials Research and Testing.
- My external supervisor, Dr Mehrisadat Makki Alamdari, for providing me with guidance and criticism of my work on model updating. She was also a colleague for Engineering Computations in the early stages of my PhD, and has always made herself available to provide advice when I needed it.
- My previous external supervisor, Dr Samir Mustapha, Mehri's predecessor, for providing me with guidance in the early stages of my PhD. He reinforced the importance of conducting comprehensive literature review, and made himself available when I was unable to contact my other supervisors.
- Peter Runcie from CSIRO for giving me the opportunity to work with the structural health monitoring research team at Data61. He and Samir, gave me the opportunity to present at the 9th Austroads Bridge Conference, which was the first conference that I had attended.

- The staff of the Structures Laboratory deserve some special thanks. They needed to put up with my lack of knowledge in modal testing and the equipment practices associated with it in the early stages of my PhD. A special thanks to Peter Brown for explaining how the equipment works, how things get done in the lab, who I needed to talk to when certain things needed to be done, and so on. I'd also like to thank Rami Haddad for reinforcing the importance of keeping to the time schedule. He needed to ensure that other projects ran on schedule and when my project was delayed due to unexpected circumstances, he was not happy, but he was understanding. David Dicker was always very helpful when it came to moving or lifting the extremely heavy specimen. Richard was also helpful in ensuring that the sensors worked and in uplifting the mood with his jokes.
- The administrative and support staff at the UTS Faculty of Engineering and IT for reminding me when something was due and being very responsive to my enquiries. They include Van Le, Elaine Parica, Trish Dimasi, Phyllis Agius, Matt Gaston and many more.
- My friends from UTS for providing me with minibreaks, John Phung, Navid Yeg, William Scuderi, Kavin Miranda, Bella Basaglia, Kirsten Lewis, Hannah Sun, Jennie Wang, Kireesan Sornalingam, Lingxiang Wu, Josh Tapas, and Rainnie.
- My unisex basketball crew at Bankstown Basketball for helping me maintain a hobby that I enjoyed, including Philip Chan, Roxanna Lam, Song Nguyen, Humphrey Luong, Cindy Ly, Katie Nguyen, Jim Liu, Paige Ly, Sheng Zheng, Peter Ngo, Lynda Lam, Phalla Sem and Alan Tran. Ball is life.
- My usual hang out group including Vuong Nguyen, Christine Le, Andy Tran, Danny Nguyen, Annie Phan and Jacqueline Iskov.
- A special thanks to my family for supporting me through my journey, including my parents, Van and Van (yes... there are three Vans in our household), and my sisters Nhung and Lannhi. You all supported me and reminded me that I need to move forward with my life.

Van Vu Nguyen

Sydney, February 2018

List of Publications Based on This Research

Journal Articles

1. Nguyen, V.V., Dackermann, U., Li, J., Alamdari, M.M., Mustapha, S., Runcie, P. and Ye, L., 2015. Damage identification of a concrete arch beam based on frequency response functions and artificial neural networks. *Electronic Journal of Structural Engineering*, *14*(1), pp.75-84. *
2. Nguyen, V.V., Li, J., Erkmen, E., Alamdari, M.M., Dackermann, U., 2017. FRF sensitivity-based damage identification using linkage modelling for limited sensor arrays. *International Journal of Structural Stability and Dynamics*, Accepted for publication. *
3. Mustapha, S., Hu, Y., Nguyen, K., Alamdari, M.M., Runcie, P., Dackermann, U., Nguyen, V.V., Li, J. and Ye, L., 2015. Pattern recognition based on time series analysis using vibration data for structural health monitoring in civil structures. *Electronic Journal of Structural Engineering*, *14*(1), pp.106-115. *

Conference Papers

1. Nguyen, V.V., Li, J., Dackermann, U., Mustapha, S., Runcie, P. and Ye, L., 2014, December. Damage identification of concrete arch beam utilising residual frequency response function. In *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*. Southern Cross university. *
2. Nguyen, V.V., Li, J., Yu, Y., Dackermann, U. and Alamdari, M.M., 2016, December. Simulation of various damage scenarios using finite element modelling for structural health monitoring systems. In *24th Australasian Conference on the Mechanics of Structures and Materials (ACMSM24)*. Curtin University. *
3. Nguyen, V.V., Li, J., Erkmen, E., 2017, December. Numerical investigation of a linkage modelling technique for damage identification using FRF-based model updating. In *The 8th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII8)*. Queensland University of Technology. *

4. Mustapha, S., Nguyen, K., Runcie, P., Hu, Y., Dackermann, U., Nguyen, V.V., Li, J. and Ye, L., 2014, October. Structural health monitoring in civil structures based on the time series analysis. In *Austroads Bridge Conference, 9th, 2014, Sydney, New South Wales, Australia* (No. 3.3). *
5. Alamdari, M., Nguyen, V.V., Runcie, P. and Mustapha, S., 2015, September. Damage characterization in concrete jack arch bridges using symbolic time series analysis. *Structural Health Monitoring 2015*. *
6. Alamdari, M.M., Khoa, N.L.D., Runcie, P., Mustapha, S., Dackermann, U., Li, J., Nguyen, V.V. and Gu, X., 2015, December. Application of unsupervised support vector machine for condition assessment of concrete structures. In *International Conference on Performance-based and Life-cycle Structural Engineering* (pp. 182-189). School of Civil Engineering, The University of Queensland. *

(* indicates peer-reviewed publications)

Table of Contents

List of Figures

List of Tables