AUSTRALIAN NETWORK OF STRUCTURAL HEALTH MONITORING

Newsletter

Issue 15, March 2018

Contents

President Message

Tommy Chan

Professor in Civil Engineering, Queensland University of Technology

Dear All,

It is the Chinese custom that we celebrate our New Year until the 15th Day of the first month and a Chinese saying even states that in the 10th month, we still can give New Year's greetings in October, so I consider it is still not too late to wish you all A very Blessed Lunar New Year!

May I also extend our warmest welcome to our new members:

- Dr Zhengyi Wu from Bentley
- Mr Matthew Brunton from Monitor Optics Systems

It's good to be in a multi-cultural country like Australia that we could have all the good things from different cultures. Many of us are celebrating the Lunar New Year in the midst of our normal work schedule. Just like many of us who are in the ANSHM Executive Committee, we had our EC meeting in the early February, one week before the Lunar New Year.

As mentioned in the last monthly updates, for this year we will focus on three Ps:

1. Preparing the ITRP proposal

2. Publishing via Special Issues, Newsletter and other publications to share our development in SHM as well as to help the industry better understand what SHM is and how it could be applied to their asset management
3. Presenting via workshops and short courses for the purposes of Item 2 as well as knowing better how to meet the needs of the industry.

We have been organising workshops and special sessions in international conferences to showcase our SHM developments locally as well as internationally. We have been doing very well on that. In the Industry Forum in the 9th ANSHM Workshop (incorporated in SHMII-8), it was discussed that we should also organise some technical workshops to help local engineers better understand what SHM is. We totally agreed on that. As mentioned in a number of occasions, we as academics should try our best to introduce SHM in our undergraduate engineering courses. I have shared earlier that QUT has already included SHM in its civil engineering courses and I found that students are very interested in this new technology in the so called "classic" engineering courses. Then when they graduate, one batch after the other, there will be more engineers find that SHM is not a stranger but will be helpful in their design, construction, maintenance and management. However, how about the existing engineers? They have heard about SHM but they may have different misconceptions about it, e.g. implementing SHM is very difficult and expensive. All these need to be rectified. Therefore, it is important to organise more technical workshops to help the current engineers realise SHM is more than placing sensors. If we know what information we need to collect, how to collect them effectively and how to make use of information for decision making in asset management, huge amount of maintenance cost will be reduced without any sacrifice of structural or human safety (but even enhancing better safety). Yew-Chin of Vicroads is one of the persons who actively promotes this idea and consider that ANSHM should organise more of this kind of technical workshops and publish technical notes on SHM. As early as last December, he invited us to organise one technical workshop in Melbourne. We responded positively to this idea and invitation, and discussed about it in the last EC meeting. We have set up a task force in organising this kind of workshops with Xinqun being the officer in charge to coordinate this with other members in this task force. I will give more details regarding this later in this President Message.

Below are the updates of the month.

ANSHM Tasks Allocated

In our last EC meeting, we have allocated the tasks we identified in the Industry Forum, ABM and AGM in the 9th ANSHM Workshop. I list below the officers-in-charge for your better understanding of our operation.

- Coordination and Preparation of the ITRP Proposal
  - Jianchun Li (ANSHM Deputy President) will be the Main Coordinator of this Research Collaboration Task Force (RCTF) working with Tuan, Alex and myself
- Continue to help members to establish and strengthen their connections with one another and with industry, and promote the research collaborations
  - Under RCTF led by Jianchun Li
- Coordination of Technical Note publication
  - Xinqun Zhu, Mehri Makki Alamdari, Richard Yang
- Technical Workshop/Short course/Forum
  - Xinqun Zhu, Lei Hou, Richard Yang, Ulrike Dackermann
- Continue to improve ANSHM webpage
  - Hong Guan as ANSHM Web Master
- Continue to establish a platform for regular web forums
  - Lei Hou with the assistance of Xinqun and Richard
- Continue to publish our quarterly newsletter
  - Jun Li, Andy Nguyen and Mehri Makki Alamdari
- Administration of Membership
  - Alex Ng as ANSHM Membership Officer
- SHMII-8 Follow up including preparation of a special issue in CSHM for SHMII-8 and ANSHM External Affairs
  - Saeed Mahini
- Preparation of a special issue in SHM- An International Journal for presentations at the 9th ANSHM workshop
  - Andy Nguyen, Xinqun Zhu and myself
- Organise the 10th ANSHM Annual (hosted by the University of Wollongong)
  - Jun Li as ANSHM representative (since Ulrike is having a sick leave), will be closely working with Tao Yu of University of Wollongong, the Workshop Organiser
- Preparation of ACMSM25 ANSHM mini-symposium
  - Andy Nguyen and myself

ITRP Proposal Preparation

We have decided to go ahead for applying Industrial Transform Training Centre (ITTC) under the ARC Industrial Transform Research Program (ITRP) and this will be one of the three areas that we will focus at in 2018. We have some discussion about the ITRP Proposal Preparation in the EC meeting, and also before and after the EC meeting. Jianchun identified the tasks and the corresponding timeline. Based on the successful experience of Tuan, we considered that we need to complete the following by the end of March

i. Finalising the scope and title
ii. Finalising the rule of participation
iii. Preliminary Budget Estimation
iv. Formalising the University Commitment
v. Preparing a flyer/ppt for ITTC invitation
vi. Allocation of Tasks

After finalising the rule of participation (Item ii), we will prepare a document to call for express of interest of participation sending to all ANSHM academic members. We will also call ANSHM members from the industry to participate as the industrial partners of the project. As industrial cash support is crucial to its success, we will prepare a flyer/ppt for ITTC invitation (Item v). Meanwhile we will also identify potential industrial partners (PIP) and allocate person-in-charge approaching PIP. It is expected that negotiation with industrial partners will start in April.

It is expected that chief investigators from different universities will approach the relevant sections to commit some cash amount to support you joining this program, e.g. for research student stipends, travel expenses. It is different from ARC LIEF grant as the amount from each university will not go to the central pool for ARC fund request and yet the amount we secured from our own universities will enhance the chance of success. Therefore Item (iv) is something that we can start to work on. More guidance will be given in due course.

The program will also be beneficial to the ANSHM members from the industry, as it will generate an amount of research funding, for $1 a company invest, we can request as much as $4 from ARC. Such funding could help to enhance your asset management scheme, solving your management and maintenance problems, helping your colleagues understand better SHM to face the challenges like

i. Construction safety and efficiency
ii. Ageing infrastructure (wear, fatigue, corrosion etc.)
iii. High costs and high risk in repair and maintenance
iv. Safety risk and interruption to the public, productivity loss due to failure
v. Uncertainties about structural condition and performance
vi. Many others by considering the question of “What will be the negative impact if we do not use SHM”

Technical Workshops

As mentioned at the start of this message, we intend to organise this kind of Technical Workshops to help the industry to be more familiar with SHM. We intend to regularly organise these workshops in different states. Since we have members in different states, we could organise SHM experts of the states to be speakers of these workshops. This could help reduce the expenses in organising such workshops. Xinqun is the officer in charge of this role and we plan to organise one to two of these workshops in 2018. One will be in Melbourne (because of Yew-chin's invitation). We have prepared a tentative list of topics to be delivered. To follow our practice, we will aim to have the registration being free of charge or just charging a minimal fee to cover the expenses.

10th ANSHM Workshop

It is announced in the 9th ANSHM Workshop that, next ANSHM Annual Workshop will be hosted by University of Wollongong at Wollongong. Thank Dr Tao Yu for initiating this. As mentioned earlier that Jun has kindly agreed to take up this role for Ulrike to act as ANSHM EC representative to assist Tao in organising the 10th ANSHM Workshop. Tao is working on identifying the best dates for the workshop to ensure many of us could be available to attend.

ANSHM Special Issues

ANSHM (2nd) Special Issue in SHMIJ: As mentioned in the last updates that we will have a special issue entitled "Real World Application of SHM in Australia" in the International Journal of Structural Health Monitoring as the special issue generated from the 9th ANSHM Workshop. The preparation for this Special Issue is going well and Andy have just sent out a call for papers. Please refer to that email call for more detail regarding the submission process.

ANSHM 3rd Special Issue in CSHM: 9 papers have been accepted and published, one article was just submitted and has been sent for review. We are about to close the submission for this special issue.

ANSHM Special Sessions

ACMSM25: In our last EC meeting, we have decided to organize an ANSHM special session in the 25th Australasian Conference on the Mechanics of Structures and Materials (https://acmsm25.com.au/) to be held on 4-7 December 2018 at the Brisbane Convention and Exhibition Centre and Andy has sent out the call for abstracts on the 12th of Feb. If you plan to attend ACMSM25 and participate in this session, please submit your abstract to us by 1 April. Please contact Andy (Andy.Nguyen@usq.edu.au) for any query.

7WCSCM: Special session **SS01: Recent Research Advances on Structural Control and Health Monitoring in Australia** has attracted 14 abstracts. The full conference paper submission is due 31 March 2018. The authors and interested participants are welcome to submit the full papers through the conference website at: http://www.7wcscm.com/Data/List/Submission

IABMAS 2018: 18 abstracts and possible full papers have been accepted. The early bird registration closes on 2 March 2018 (http://iabmas2018.org/).

ANSHM Website (www.ANSHM.org.au)

Thank Hong Guan and her team for their continued hard work in updating and maintaining the site. Web updates have been done, specifically:

1) Home
2) Contact Us
3) Member Institutions (still waiting for the latest list from Alex)
4) Advisory Board
5) Executive Committee
6) Current Projects
7) Completed Projects

Please have a look and inform Hong Guan (h.guan@griffith.edu.au) for any correction and suggested improvement.

SHMII-8 Follow Up Work

Prof Farhad Ansari, Editor-in-Chief of CSHM has agreed to have a special issue for papers presented in SHMII-8. We are considering to invite the best paper awardees to modify their papers for submission to this Special Issue and Saeed is working on it. A proceedings specialist company has approached me exploring the possibility of indexing the proceedings and publishing it as hard copies (publish on demand). I am working on that.

In this issue, we have two interesting articles. Alamdari et al. presented an interesting work on SHM of a full-scale cable-stayed bridge and shared the results of damage identification, damage localisation, operational modal analysis and traffic monitoring on this bridge. In the second report, Nguyen et al. proposed an optimization-based forward method using correlation of ratio of modal strain energy to eigenvalue (MSEE). Results for a planar truss model have demonstrated its superior performance compared to the traditional MSE correlation method.

With kind regards,

Tommy Chan

President, ANSHM

www.ANSHM.org.au

AUSTRALIAN NETWORK OF STRUCTURAL HEALTH MONITORING
Newsletter

Structural Health Monitoring of a Cable-Stayed Bridge

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Abstract

This paper aims at presenting some of the research activities on a cable-stayed bridge instrumented by Data61|CSIRO. A dense array of accelerometers and strain gauges has been mounted on this bridge to monitor the dynamic behavior of the bridge. Control tests have been done for calibration purpose and several mathematical and analytical tools and algorithms have been developed and implemented. They include machine learning (ML) to identify any change in the bridge behavior, fully-automated operational modal analysis (OMA) to capture the modal features of the structure, Bridge Weigh in Motion (BWIM) to characterize the traffic loading and to identify any overloading traffic and fatigue life analysis to count the load cycles and to estimate the remaining life of the structures.

Introduction

Every bridge structure is degrading over time and many are subjected to high loads and harsh environments. The current practice of monitoring is visual inspection with simple testing which is expensive and time consuming, qualitative, subjective, and only capable of assessing suspicious problems (Li J. and Hao, 2016). In addition, due to the increase in traffic loading and structural degradation, many of the bridges may not meet the current Australian standard or may even lack safety requirements. To ensure long term quality of aging infrastructure, it is critically important to develop and implement ongoing structural health monitoring (SHM) (Farrar & Worden, 2007). A vast amount of research work has been done along this line; however, limited real-world implementation of the technique has been demonstrated, in particular for small bridges which form a large population of the bridge structures. This work presents a case study of a fully instrumented small bridge structure and the ongoing research activities. Data61 is currently collaborating with University of New South Wales (UNSW) and Western Sydney University (WSU) on several research activities on this bridge.

Test Structure: A Cable-Stayed Bridge

A short-span cable-stayed bridge over the Great Western Highway in the state of New South Wales, Australia (33°45'50.49"S, 150°44'31.14"E) has been intensively instrumented. Figure 1 shows an illustration of the bridge. The cable-stayed bridge has a single A-shaped steel tower with a composite steel-concrete deck. The bridge is composed of 16 stay cables with semi-fan arrangement. The bridge span and the tower height are 46 m and 33 m, respectively. This bridge provides a connection between two Western Sydney University campuses over the Great Western highway and carries one traffic lane and one sidewalk. The deck has a thickness of 0.16 m and a width of 6.3 m and it is supported by four I-beam steel girders. These girders are internally attached by a set of equally-spaced floor beams as depicted in Figure 1.

(a) (b) (c)

Figure 1. A cable stayed bridge over the Great Western Highway NSW Australia (Ref. Google Earth), (a) side view, (b) top view, (c) Illustration of deck, steel girders and floor beams.

Sensor Array

A dense array of accelerometers and strain gauges along with environmental sensors has been installed on this bridge. The measurement grid for the dynamic test consists of 29 synchronized accelerometers to measure the acceleration responses of the deck, cables and the mast. These sensors were permanently installed on the bridge in order to monitor the dynamic behavior of the bridge and to identify the modal parameters. 24 uni-axial sensors were placed under the deck at the intersection of the girders and floor beams to measure the vertical acceleration of the bridge, (see Figure 2). These sensors are low noise accelerometers with model number 2210-002 manufactured by Silicon Design, Inc (2010). The 2210-002 is a sensor that incorporates a 1210L micro-machined capacitive accelerometer. This model can detect accelerations within the range of ± 2 g with an output noise of 10 μg/√Hz and sensitivity of 2,000 mV/g. Another four 2210-002 uni-axial accelerometers were mounted on the cables on the eastern side of the bridge. These sensors measure the acceleration response of the cables in the vertical plane orthogonal to the line of the stay. In addition, one tri-axial accelerometer (Silicon Designs 2460-002) was installed on top of the mast to measure the vertical, lateral and longitudinal acceleration responses of the tower.

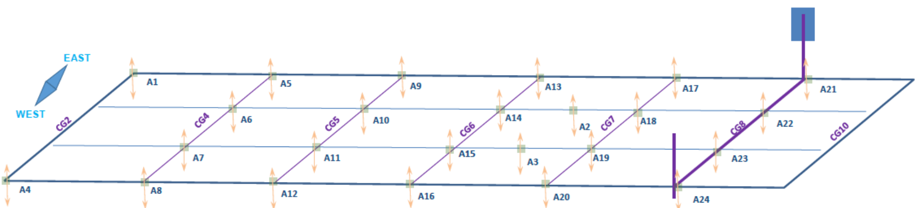


Figure 2. The accelerometer array on the deck.

The bridge has been instrumented with an array of strain gauge sensors. The location of the sensors has been elaborated in Figure 3 where most of the sensors are located in between CG6 and CG7. All 8 cables have been instrumented with uniaxial strain gauges as denoted by SAi (i=23 to 30) in Figure 3. Uniaxial strain gauges SUi (i=17 to 22) have been mounted under the deck in either longitudinal or transverse directions between cross girders CG6 and CG7. The longitudinal distance between SU19 and SU22 is almost 4 m which is appropriate for calculation of speed. Strain gauges SUi (i=13 to 16) have been installed under the flange of the longitudinal girders at middle of the span between CG6 and CG7 to measure bending strain. These strain gauges are also located close to mid-span of the bridge, where large strains are expected. Shear rosettes have been mounted at three different longitudinal locations along the bridge; north end of the span near cross girder CG2, (north end-span of the entire bridge), bridge mid-span close to cross girder CG6 (this is also located at the north end of the span between CG6 and CG7), mid-span close to cross girder CG6, and half-way between cross girders CG6 and CG7. Figure 4 illustrates the sensor placements on different structural members in the bridge.

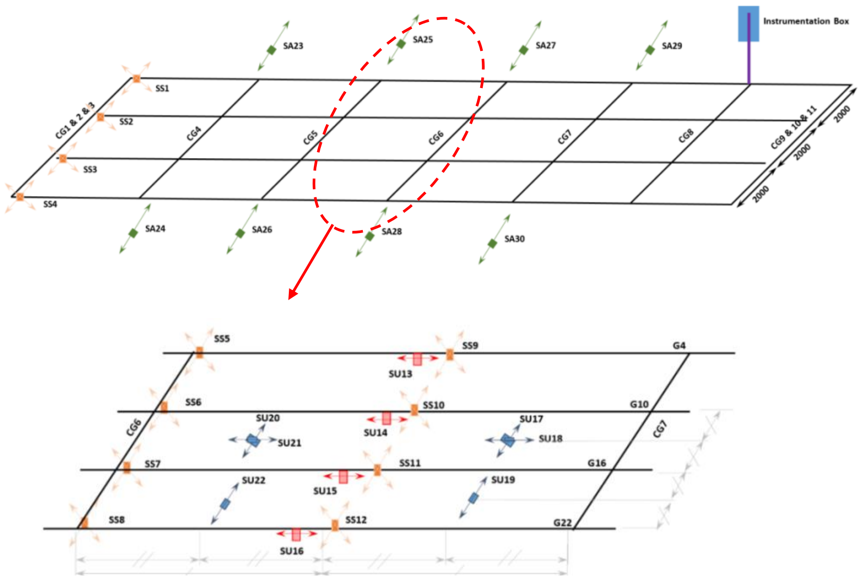


Figure 3. Illustration of dense array of strain gauges installed on the bridge.

(a)

(b) (c) (d)

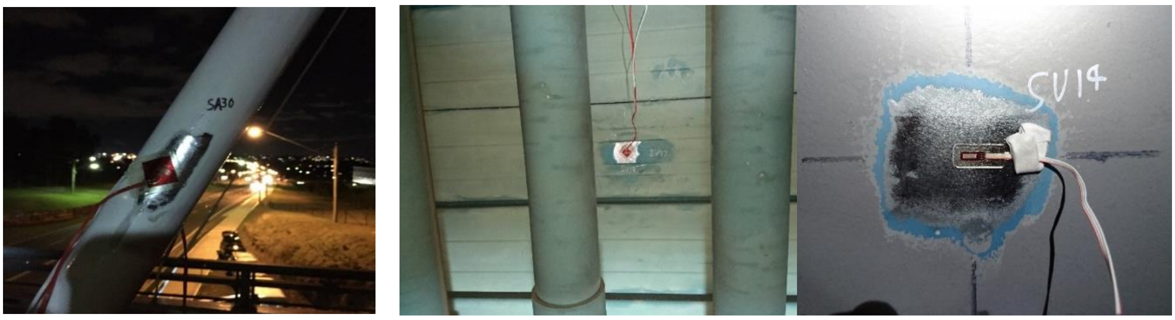


Figure 4. Sensor placements, (a) shear strain gauge on the web of the girder and magnified view of the shear sensor, (b) uniaxial strain gauge in the cable, (c) uniaxial gauges in longitudinal and transverse directions under the deck, (d) uniaxial gauge under the flange of the girder.

Data Acquisition

The signal conditioning and data logging software consist of an embedded PC and HBM QuantumX data logger to record data. This system provides an integrated and reliable device to log high quality data with 24bit resolution with bandwidth capability of 0 to 3 kHz. This hardware combines instrument excitation, voltage regulation, digitization, anti- aliasing filters and data logging. The logging software is Catman. The software collects all channels at a default sample rate of 600 Hz with an anti-aliasing filter. The 3 dB cut-off frequency of the filter is 100 Hz and it is a fourth order Bessel low-pass filter.

RESEARCH ACTIVITIES

Collection of real data from this bridge provides valuable opportunity to undertake several research activities. This section provides a summary of some of our ongoing research activities and obtained results on this bridge.

Anomaly Detection

Application of statistical-based learning methods, e.g. machine learning (ML) for SHM is quite advantageous. These techniques do not require a numerical model and can be performed in unsupervised manner which does not require data associated with damaged state of the structure. The idea is to build a model based on the measured data from the current state of the bridge. When new data come in, they will be compared against the model to see if any deviation has occurred. Figure 5 shows a flow chart of ML-based damage identification approach. Data fusion can be used to aggregate information from multiple sensors at different locations in order to localize damage. Damage severity assessment can be achieved by comparing the scores returned by the classifier to show the progress of damage.

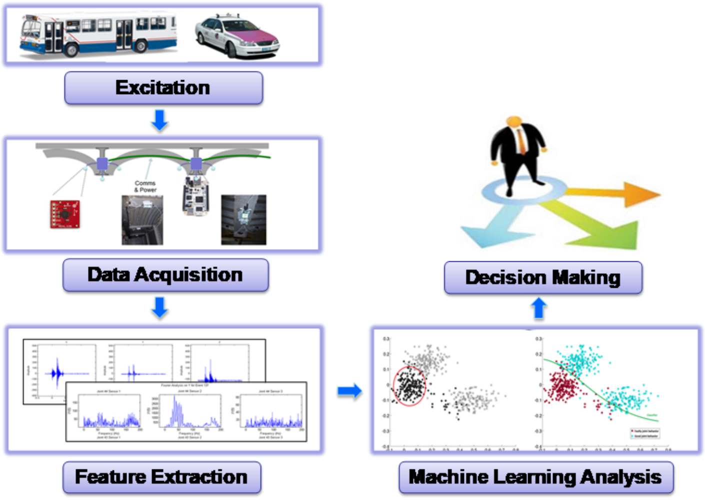


Figure 5. A ML flow chart for damage identification.

Several approaches have been investigated in the past on this bridge to detect the emulated damage. Three scenarios have been considered, which includes: no vehicle is placed on the bridge (healthy state), a light vehicle with approximate mass of 3 t is placed on the bridge at different locations ("Car-Damage") and a bus with approximate mass of 12.5 t is located on the bridge at mid-span ("Bus-Damage"). This emulates a series of several independent damage points, which were used in our evaluation. The fundamental frequency of the structure for these three cases is, respectively, 2.04 Hz, 1.98 Hz and 1.80 Hz which indicate a drop of 2.94% and 11.76% as a result of damage occurrence. A novel data fusion technique using tensor analysis was integrated with ML to investigate this dataset (Anaissi et al, 2018). Figure 6 shows the ML scores for these three scenarios. As expected, positive scores were obtained for the healthy state whereas the scores for the damaged states are negative with an increasing trend from the "Car Damage" to "Bus Damage" which indicates the progress of damage in the structure.

Figure 6. Damage identification results using tensor feature (Anaissi et al, 2018).

Traffic Monitoring and Characterization

Reliable live traffic data collection is crucial for effective pavement life prediction, fatigue estimation, vibration control, maintenance, and condition assessment of the bridge structures. Bridge weigh-in-motion (BWIM) is an approach through which the axle and gross weight of trucks travelling at normal highway speed are identified using the response of an instrumented bridge. The vehicle speed, the number of axles, and the axle spacing are crucial parameters, and are required to be determined in the majority of BWIM algorithms. Nothing-On-the-Road (NOR) strategy suggests using the strain signals measured at some particular positions underneath the deck or girders of a bridge to obtain this information. Figure 7 represents schematic of a BWIM system (Kalhori et al, 2017).

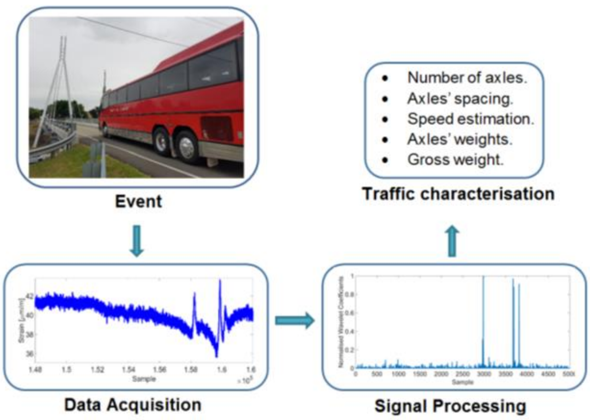


Figure 7. A schematic of a BWIM system (Kalhori et al, 2017).

Several tests with vehicle with different axle configuration were conducted to investigate which arrangement of strain gauge sensors is more sensitive to identify the individual axle in presence of closely-space axles. It was realized only the shear response of the bridge at either end of the span can reliably identify the presence of each axle. Figure 8 illustrates the time history of shear strain at the end of the bridge when vehicle with different axle configurations are passing over the bridge. All the other strain gauge sensors fail to identify the individual axles.

(a) (b) (c)

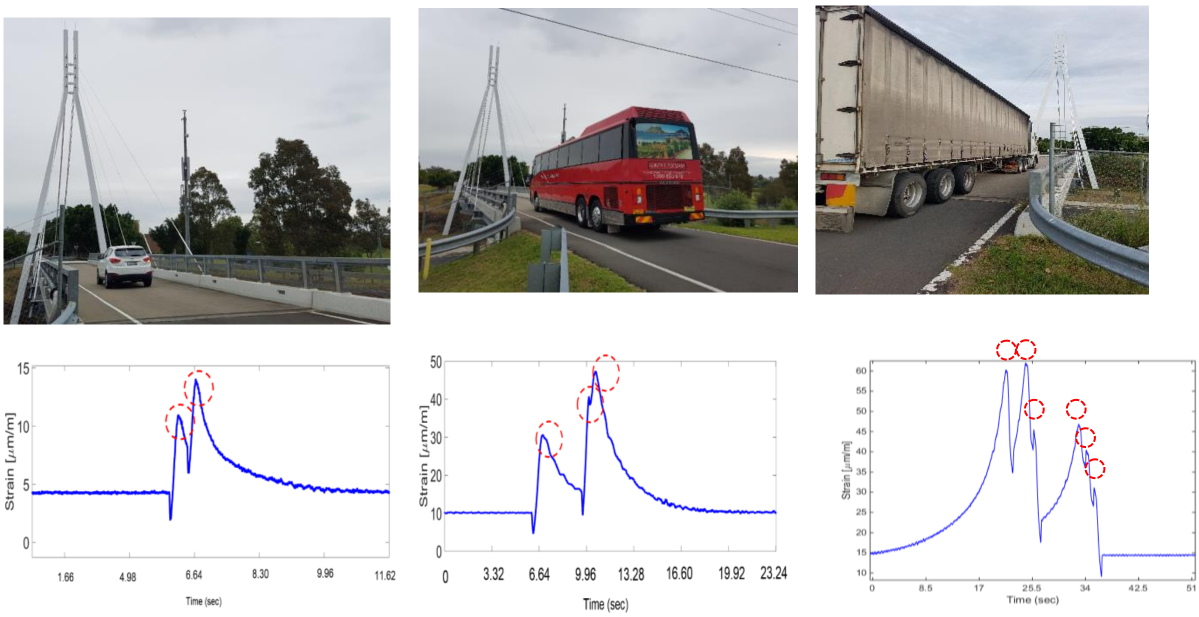


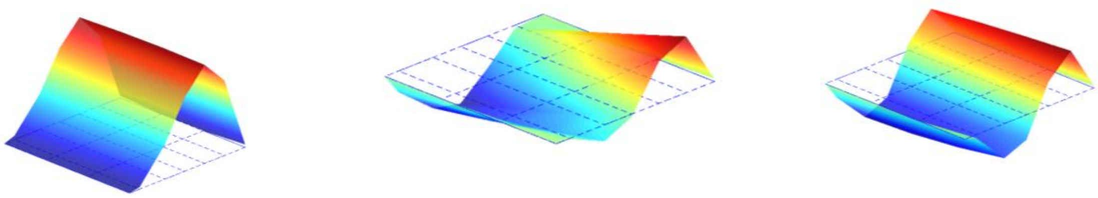
Figure 8. Illustration of the testing vehicles and corresponding strain response, (a) a light two-axle vehicle, (b) a three-axle bus including a tandem-axle, (b) a six-axle truck including two tridem-axle.

Operational Modal Analysis (OMA)

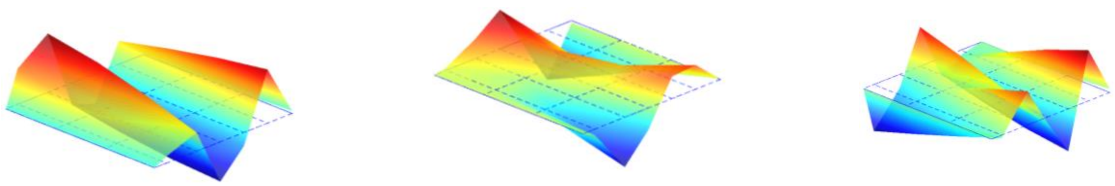
Operational Modal Analysis (OMA) methods are widely used in the extraction of structural modal features such as natural frequencies, damping ratios and mode shapes. These parameters represent the characteristics of the structure and are widely used as key indicators for damage detection, damage-severity determination, damage localization and tracking the damage evolutions of a structure over time. OMA is a generic approach and is mostly suitable for studying the dynamic behavior of large-scale civil structures such as bridges without disruption to traffic. The results from OMA not only are beneficial for SHM application but also provide important ground truth information for numerical analysis i.e. finite element analysis. A modified Covariance-driven Stochastic Subspace Identification was developed and applied for one month of collected vibration data (Sun et al, 2017). Table 1 shows the obtained modal parameters and the corresponding statistics. Figure 9 illustrates the first nine mode shapes of the deck. Figure 10 shows damage index obtained from modal strain energy method (Samali et al, 2010) for two cases that a light car is first sitting at ¼ of the bridge span and second when the car is sitting at mid-span. Although, some false alarm can be seen, in general the highest index corresponds to the damage location.

Table 1. The first nine vibration modes from one month of observation.

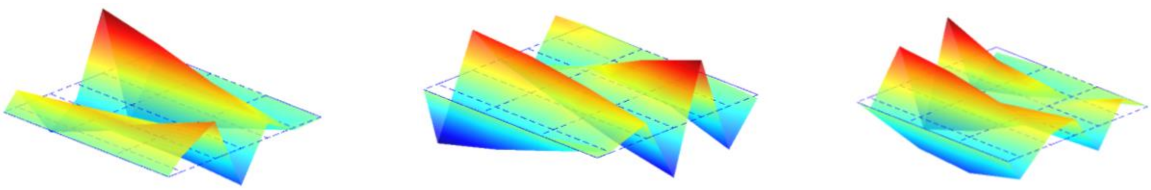
Mode number	ω_{mean}	ω_{RSD} (%)	ξ_{mean} (%)	ξ_{RSD} (%)	Identified modes
1	2.032	0.98	0.9	42.23	100%
2	3.548	1.66	2.5	60.00	85%
3	3.649	1.15	2.2	63.14	81%
4	5.584	1.45	1.9	57.89	67%
5	6.136	2.33	2.8	42.85	82%
6	8.044	1.71	1.7	52.94	73%
7	8.671	2.09	1.7	70.58	60%
8	11.561	1.89	1.8	27.77	64%
9	12.31	1.46	1.4	42.86	76%



Mode 1: 2.014 Hz Mode 2: 3.51 Hz Mode 3: 3.645 Hz



Mode 4: 5.538 Hz Mode 5: 6.068 Hz Mode 6: 7.852 Hz



Mode 7: 8.628 Hz Mode 8: 11.281 Hz Mode 9: 12.164 Hz

Figure 9. Illustration of the first none mode shapes of the deck.

(a) (b)

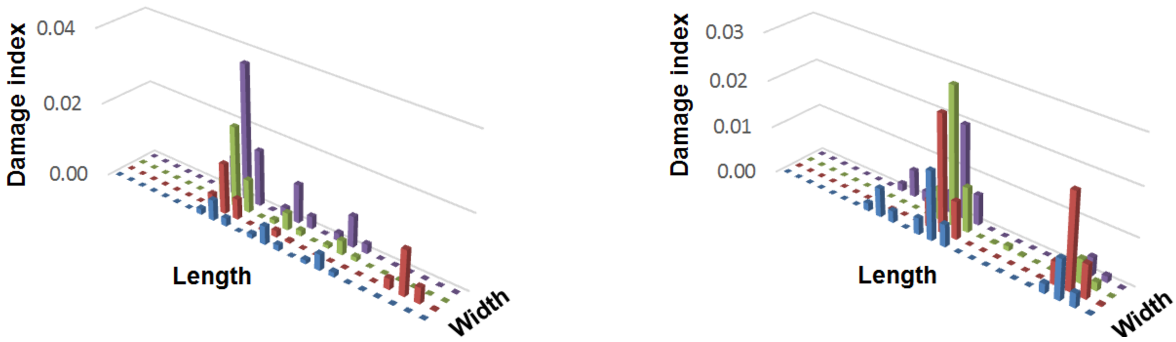
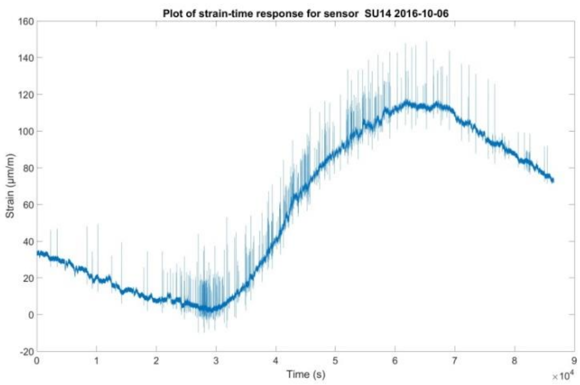


Figure 10. Damage localization using modal strain energy, (a) damage is emulated by a car sitting at ¼ of the bridge span, (b) damage is emulated by a car sitting at ½ of the bridge span.

Load Cycle Counting

Fatigue life assessment of a structure subjected to a non-constant amplitude loading can be performed in the time domain using rainflow cycle counting. The rainflow method is used for counting the fatigue cycles (stress-reversals) and to obtain equivalent constant amplitude cycles from the measured strain data. This method is adopted in order to reduce a spectrum of varying stress into a sequence of tensile peaks and compressive valleys to identify the major load excursions. As a result of the counting, several cycles and half-cycles with different amplitude are obtained. With the advantage of fatigue damage accumulation hypothesis e.g. Miners rule, the algorithm gives possibility to compute the expected fatigue life under random loading conditions subject to availability of material property e.g. S-N curve. In order to achieve this, measured strain responses are analyzed to identify the number of load cycles and the corresponding stress range the structure experiences. It can be further processed to estimate the remaining life of the structure (Rychlik, 1987). Figure 11 illustrates a typical daily bending strain response under the web of the girder. The presence of events, e.g. passing traffics along with cyclic temperature variation is quite obvious in this figure. These graphs can be further analyzed to identify any possible overloading on the bridge.

(a)



(b)

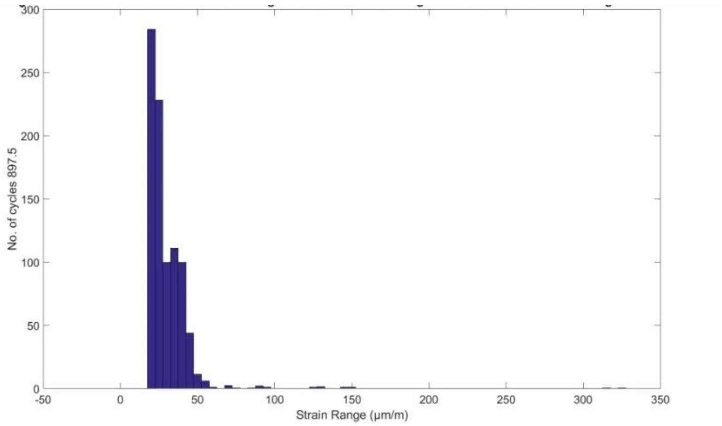


Figure 11. Illustration of, (a) a typical 24-hour bending strain time response, (b) a typical histogram from multiple day observation.

ACKNOWLEDGEMENTS

NICTA is funded by the Australian Government through the Department of Communications and the Australian Research Council through the ICT Centre of Excellence Program. CSIRO's Digital Productivity business unit and NICTA have joined forces to create digital powerhouse Data61. The instrumentation of this bridge has been planned and conducted by researchers at Data61. The authors also would like to thank the Western Sydney University and University of New South Wales for facilitating the field tests and data collection process.

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Modal characteristic correlation-based damage identification

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Modal-based Damage Identification using Correlation Approach

Damage identification is an important step within structural health monitoring (SHM) for the assessment of the structural integrity. It is very important to have a reliable damage identification procedure because if damage is not detected correctly, it can eventually lead to local failure of the structural elements and in consequence to the collapse of the whole structure. Previous studies have demonstrated that both natural frequency change and mode shape change represent change in structural properties. While natural frequency contains global information of the structure, mode shape shows spatial information in elemental level of the structure. It has been reported that mode shape is more sensitive to elemental damage but less accurately estimated whereas eigenvalue is measured with better precision but less sensitive to damage. Therefore, it is reasonably expected that combined use of them will give more reliable damage identification results.

Optimization-based forward methods have been found to be effective for locating damage as well as estimating damage extent since they integrate advanced optimisation techniques to solve the damage problem. The principle of these methods is to search the change in structural properties which best reflect the change in the modal information. Several methods have been developed using an objective function formulated from correlation level between analytical change and measured change of a modal parameter. However, the accuracy of conventional methods relies very much on the number of analytical modal parameters used (i.e., frequencies and mode shapes) and the degree of matching between numerical models and real structures. Therefore, when dealing with structures containing high level of uncertainties, these correlation methods may become less practical and less accurate.

In this research, a new modal-based correlation method has been developed using ratio of modal strain energy to eigenvalue (MSEE). Different from the conventional methods, the change in MSEE due to stiffness reduction can be approximately formulated utilizing measured modal parameters rather than numerical parameters. For damage identification, soft computing optimization techniques (e.g., genetic algorithm) can be utilized to estimate the damage extent vector using a correlation-based objective function.

The MSEE correlation method incorporates two parameters which are elemental MSEE and total MSEE. Change in elemental MSEE is a good indicator for locating damage as it directly represents the change in stiffness of each element. However, the sensitivity formula for the first parameter is less accurate due to the assumption that changes in eigenvalues of the structure are linear to stiffness changes. Meanwhile, change in total MSEE is calculated without the simplification, and therefore, it can be used to refine the prediction result.

The damage identification problem can be transformed to an optimization problem using a correlation function. The multiple damage location assurance criteria (MDLAC) proposed by Messina et al [1] is modified to evaluate correlation level between the measured and analytical MSEE changes:

$$\mathrm{MDLAC}(\delta\mathbf{D}) = \frac{\left|\Delta\mathbf{MSEE}^{\mathrm{T}}.\delta\mathbf{MSEE}\right|^2}{\left(\Delta\mathbf{MSEE}^{\mathrm{T}}.\Delta\mathbf{MSEE}\right).\left(\delta\mathbf{MSEE}^{\mathrm{T}}.\delta\mathbf{MSEE}\right)} \tag{1}$$

where $\Delta\mathbf{MSEE}$ is the measured MSEE change vector including the elemental MSEE change and the total MSEE change; and $\delta\mathbf{MSEE}$ is the analytical MSEE change vector for a known damage vector $\delta\mathbf{D}$. MDLAC values range from 0 to 1, indicating correlation level from no correlation to exact correlation between the patterns of measured and analytical MSEE changes. The damaged elements can be identified by searching the damage vector that gives the greatest MDLAC value. In this study, genetic algorithm (GA) is utilized for this task. If m modes are used, the measured and numerical MSEE change vectors are given by the following expressions:

$$\mathbf{\Delta MSEE} = \left[\begin{Bmatrix} \mathbf{\Delta W}_1 \\ \Delta W_1 \end{Bmatrix}^T \begin{Bmatrix} \mathbf{\Delta W}_2 \\ \Delta W_2 \end{Bmatrix}^T \cdots \begin{Bmatrix} \mathbf{\Delta W}_i \\ \Delta W_i \end{Bmatrix}^T \cdots \begin{Bmatrix} \mathbf{\Delta W}_m \\ \Delta W_m \end{Bmatrix}^T \right]^T \tag{2}$$

$$\mathbf{\delta MSEE} = \left[\begin{Bmatrix} \mathbf{\delta W}_1 \\ \delta W_1 \end{Bmatrix}^T \begin{Bmatrix} \mathbf{\delta W}_2 \\ \delta W_2 \end{Bmatrix}^T \cdots \begin{Bmatrix} \mathbf{\delta W}_i \\ \delta W_i \end{Bmatrix}^T \cdots \begin{Bmatrix} \mathbf{\delta W}_m \\ \delta W_m \end{Bmatrix}^T \right]^T \tag{3}$$

where $\mathbf{\Delta W}_i$ is the measured elemental MSEE change vector for the i^{th} mode where its component can be calculated directly from measured modal data and elemental stiffness matrix ($\Delta W_{ij} = U_{ij}^* / \lambda_i^* - U_{ij} / \lambda_i$); ΔW_i is the measured total MSEE change vector for the i^{th} mode which can be calculated as $\Delta W_i = U_i^* / \lambda_i^* - U_i / \lambda_i$; $\mathbf{\delta W}_i$ is the analytical elemental MSEE change vector for the i^{th} mode where its components can be obtained as $\delta W_{ij} = -U_{ij} / \lambda_i \, \delta D_j$; δW_i is the analytical total MSEE change vector for the i^{th} mode which is calculated as $\delta W_i = \sum_{j=1}^{n} -U_{ij} / \lambda_i \, \delta D_j$; U_{ij} and U_i are respectively the MSE of the j^{th} element and the MSE of all elements for mode i; and the asterisk (*) denotes the damage state.

Numerical Results and Discussion

A 2-D truss model [2] shown in Fig. 1 is chosen to evaluate the performance of the proposed damage identification method. The truss model consists of 25 bar elements of various cross sectional areas, and 21 active degrees of freedom (DOFs). Damage in the structure is simulated as a stiffness reduction of individual elements. Three damage scenarios are considered with different locations of damage, number of damaged elements and damage severities. In Case 1, elastic modulus of element 9 has been reduced by 20%; Case 2 refers damages at elements 4 and 11 by 20% and 30%, respectively; and Case 3 simulates damages at elements 7, 8 and 10 by 20%, 25% and 30%, respectively.

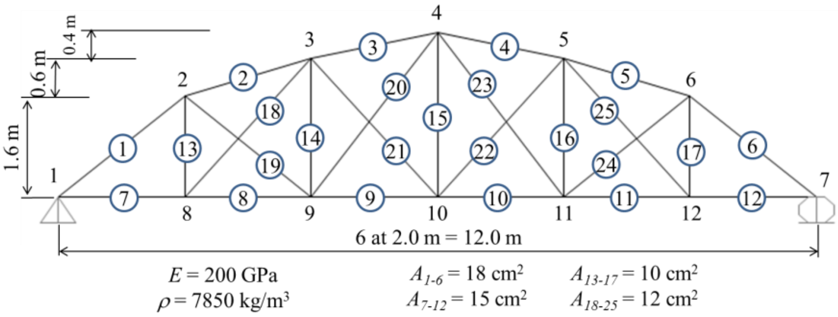

Figure 1. 25-element planar truss model (adapted from [2])

Performance of the MSEE correlation method under measurement noise is examined and compared with the results obtained by the traditional MSE correlation method. Since natural frequency is measured with much higher precision than mode shape, 5% noise is added to mode shapes while a marginal noise level of 1% is considered for natural frequencies. Statistical analysis is performed to evaluate the robustness of the proposed method under noise condition. Firstly, 100 identification results are generated for the undamaged state and each damage state. Secondly, a damage extent threshold is determined by examining 100 identification results of the undamaged state under noise. Considering the predicted damage extents at the undamaged state are a normal distribution, a damage threshold is defined at 1.3 times of the standard deviation that represents a confidence level of 90%. Finally, detection probability for each element is estimated by taking the ratio of number of times that its damage extent exceeds the threshold to the total number of identification results (i.e., 100).

Damage probability results by the MSEE and MSE methods using the first 4 modes are illustrated in Fig. 2. It is shown that the actual damaged elements have high damage probabilities and well distinguished from the undamaged elements by using the proposed MSEE method. Compared to the traditional MSE method, the proposed method gives higher probabilities for actual damaged elements and lower probabilities for most of undamaged elements (false positive detection).

Table 1 shows the errors of damage extents for the actual damaged elements compared to the predictions at noise-free condition. The proposed MSEE method is apparently more robust against noise than the traditional MSE method. All estimations by the MSEE method have smaller levels of errors compared to those from the MSE method. In particular, the MSEE method gives much smaller errors for element 9 in Case 1, elements 4 and 11 in Case 2, and element 8 in Case 3.

In summary, the proposed MSEE correlation method can be seen as more superior than the widely-used MSE method and hence can become a good tool for SHM. Further study is however required to improve the accuracy of damage quantification and to verify experimentally.

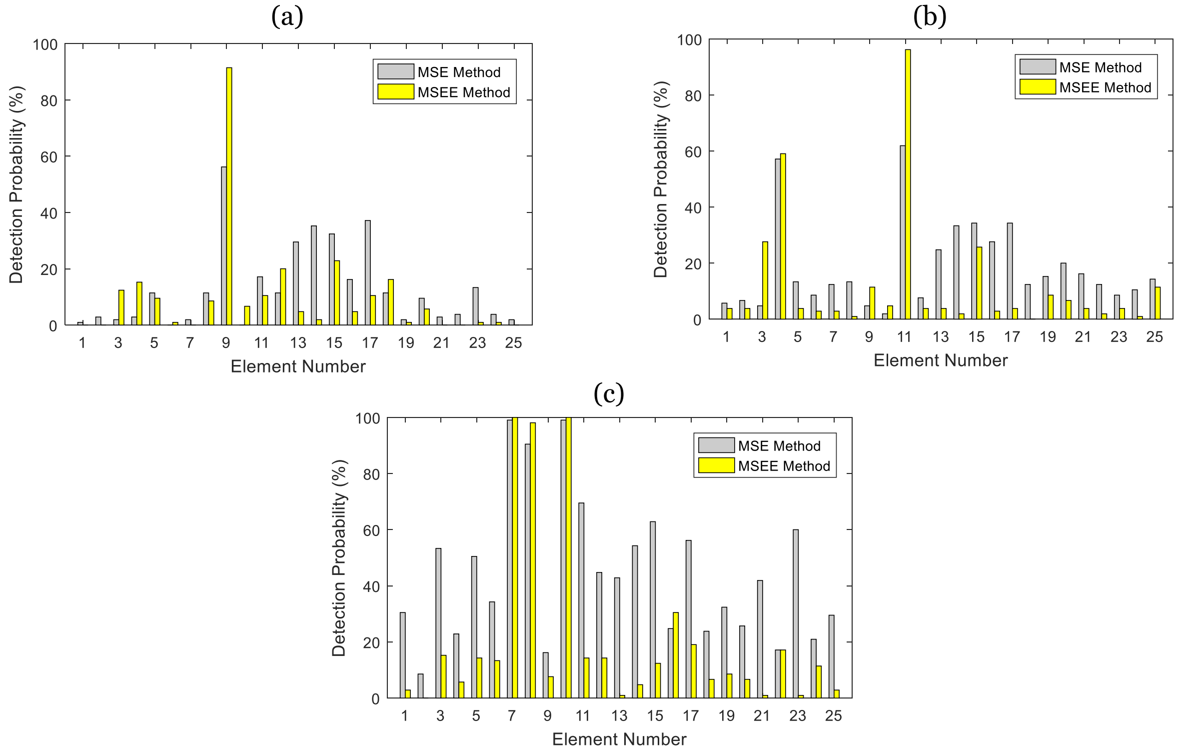

Figure 2. Damage probability results by MSE and MSEE correlation methods using 4 modes. (a) Case 1 (element 9); (b) Case 2 (elements 4 and 11); (c) Case 3 (elements 7, 8 and 10)

Table 1. Damage extent quantification error caused by measurement noise

Damage Scenario	Damaged Elements	Damage extent (%) by MSE Method			Damage extent (%) by MSEE Method		
		Noise free	5% Noise	Error (%)	Noise free	5% Noise	Error (%)
Case 1	9	23.4	5.4	18.0	24.3	16.0	8.3
Case 2	4	24.3	6.0	18.3	19.2	10.3	8.9
	11	37.2	6.4	30.8	42.5	28.8	13.7
Case 3	7	19.4	13.2	6.2	18.4	15.4	3.0
	8	24.1	15.4	8.7	22.4	21.8	0.6
	10	36.7	21.8	14.9	52.4	40.6	11.8

References

[1] Messina A, Williams E and Contursi T 1998 Structural damage detection by a sensitivity and statistical-based method *J. Sound Vib.* 216 791-808.

[2] Rahai A, Bakhtiari-Nejad F and Esfandiari A 2007 Damage assessment of structure using incomplete measured mode shapes *Struct. Control Hlth.* 14 808-829.

Conference News

- Mini-symposium ***"Recent Research Advances on Structural Control and Health Monitoring in Australia"*** in the ***7th World Conference on Structural Control and Monitoring (7WCSCM)***, in Qingdao, China, 22-25 July 2018. Organized by Prof Hong Hao, Dr Kaiming Bi, and Dr Jun Li (http://smc.hit.edu.cn/wcscm2018/)
- ***"SS11 - Structural Health Monitoring for Infrastructure Asset Management"*** in the **9th International Conference on Bridge Maintenance, Safety and Management**, Melbourne, 9-13 July 2018. (http://iabmas2018.org). Organised by Dr Jun Li and others
- ANSHM special session **"Latest advances on Structural Health Monitoring in Australia"** in the **25th Australasian Conference on the Mechanics of Structures and Materials (ACMSM25)**, 4-7 Dec 2018, Brisbane, Australia. Organized by Prof Tommy Chan and Dr Andy Nguyen.

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