AUSTRALIAN NETWORK OF STRUCTURAL HEALTH MONITORING

Newsletter

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Contents

President Message

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Structural Health Monitoring (SHM) is a term that we are very familiar with. However sometimes for people not working in SHM fields, they may mix up this with human health monitoring. I am sure some of you may have received some invitations from conference organisers, journal editors, etc, stating something like "We are aware of your own academic and industry profile and award-winning, wide-ranging research..." feeling good about being recognised, but it follows "so we would like to invite you to give a presentation at the "the latest World Congress of Regenerative Medicine & Stem Cell" or "review a paper submitted to the Journal of Medicine", etc. It always makes me laugh when I receive this kind of letters of invitation. However, on the other hand, to monitor the health of a structure is also similar to monitor the health of a human body. Since we have been affected by COVID-19 for that many months, we could see how False Negatives and False Positives, Symptoms and Vaccines of COVID-19 relate to similar areas corresponding to SHM.

False Negatives and False Positives

A false positive is where one receives a positive result for a test, when one should have received a negative result. In SHM context, it is called a "false alarm". Likewise, a false negative is where a negative test result is wrong. The problems of false positives and false negatives have been a significant issue in the damage detection of SHM. False negatives and maybe false positives could also be significant for the COVID-19 tests. Because of the COVID-19 transmission rate (RO) could be as high as 4.0 as compared to the common flu as 1.3 and SARS as 2.0 (https://www.worldometers.info/coronavirus/), it is important to use appropriate COVID-19 tests to identify invisible spreader. The tests are mainly to detect the causative virus, SARS-CoV-2, or an immune response to SARS-CoV-2 In Australia, the two main types of SARS-CoV-2 tests are: i) Nucleic acid detection tests; and ii) Serology tests. For COVID-19, it is more damaging for false negative results than false positive results. As one has been diagnosed with a negative test result when one has COVID-19, he or she may keep spreading the virus. Therefore, it is important to know the performance of the tests including the accuracy or the false negative percentages. According to an article, the false negative percentages could be more than 20% (https://www.abc.net.au/news/2020-07-15/covid-19-testing-not-as-accurate-missing-coronavirus-cases-grow/12455076). In the same article, a graph showing the percentage of false negative tests each day after infection is shown in Figure 1 below:

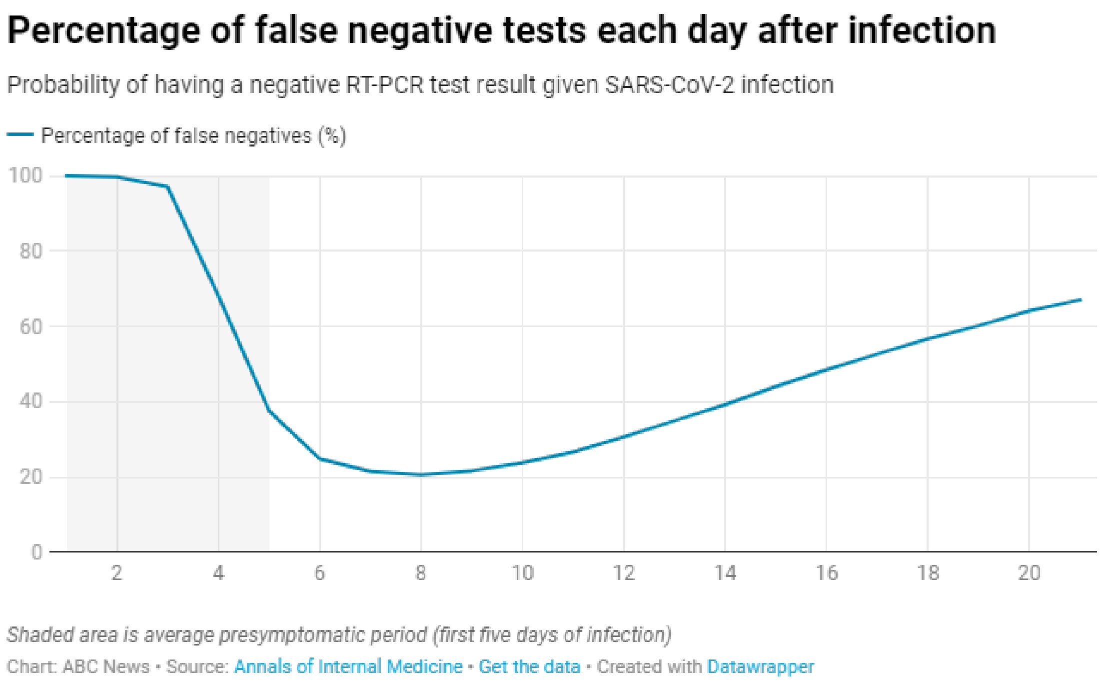

Figure 1. Illustration of false negative rates

The false negative rate could be a complicated factor which relates to a term called (sensitivity), the probability of getting a correct positive result when one has COVID-19 and the disease prevalence and it is not the same as the percentage of false negatives. However, we could still use the percentage of false negatives as some indication of the false negative rate. Any percentage of false negatives less than 50% could be considered that you are still not sure whether you have contracted the virus or not, as we could toss a coin to give better results. As we are advised that if one is feeling unwell, it is really important to get tested as soon as possible. However, it does not mean that you should not do a test as soon as possible. If one gets a positive result (of which false positive is far less common and it will be discussed later), then she or he will be under proper treatment and proper isolation, and will not become an invisible spreader. However, if one has a negative result, based on what it has been discussed about the percentage of false negative, she or he still needs to take every safety precautions to avoid spreading the virus and delay the proper treatment. Having said that, please note that I am working in the area of Structural Health Monitoring with some experience in assessing the detection accuracy, e.g. Nguyen et. al. 2019[1], but not in the area of medical health monitoring, so I am not in a position to give you advice on how to deal with false negatives in COVID-19 results.

I can tell you for sure is that false negatives for damage detection are also annoying. A successful damage detection method should avoid any false negatives in the detection so that it will not give the impression that, "'Peace, peace, when there is no peace." (Jeremiah 6:14)

Regarding False Positives, this is far less common and obviously carries fewer risks for COVID-19. However, for the damage detection in SHM, it will be as bad as false negatives, as it will cause unnecessary work trying to identify where the damage is. Also, instead of giving peace of mind, this kind of false positives, will make the management team feel that there may be some hidden damages that could not be identified. All these will adversely affect one's trust on SHM. I always mention that too many false positives (false alarms) from a SHM system will have the same effect as the fable of the boy who cried wolf.

Therefore, the practical methods for damage detection should try to avoid false negatives and false positives and advise the detection accuracy where possible, e.g. the percentage of false positives and percentages of false negatives. It should also be pointed out that for an SHM system, one should not solely rely only on damage detection methods, which will be discussed in the next section.

Symptoms

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[1] Nguyen, K.D., Chan, THT, Thambiratnam, DP and Nguyen, A. (2019), "Damage identification in a complex truss structure using modal characteristics correlation method and sensitivity-weighted search space", *Structural Health Monitoring*, 18 (1), 49-65.

We are now well aware of the symptoms of COVID-19, like fever, cough, sore throat, shortness of breath, runny nose, fatigue, loss of smell and/or taste. It is recommended if one has any of these symptoms, no matter how mild, s/he should get tested. For structural health monitoring, we should not rely only on damage detection methods. We should have a lot of health indicators assisting the management team to make decisions and plan for the corresponding repair, replace and rehabilitation, and such health indicators should be not only based on damage detection methods. As I always adress, SHM is not equivalent to damage detection. As early as 10 years ago, I had commented some misleading definitions of SHM at that time confining SHM to or making it equivalent to damage detection, in the first chapter of the first publication of ANSHM. In this book, Structural Health Monitoring in Australia[2], I defined SHM as

> *...SHM should be composed of two components: Structural Performance Monitoring (SPM) and Structural Safety Evaluation (SSE). Structural Performance Monitoring refers to the monitoring (observation) of structural performance in structure and its components under its (their) designated performance limits (or criteria) at serviceability limit states (SLS) by on-structure instrumentation system; whereas Structural Safety Evaluation refers to the evaluation of possible damage in structure or its components and/or the assessment of its health status by analytical tools, which are developed and calibrated in the course of structural health monitoring, basing on its (their) designated performance limits at ultimate limit states (ULS).*

I am so pleased that the latest AS5100.7 adopted my definition of SHM as

> *The use of various sensing devices and ancillary systems to monitor in situ behaviour of a structure to assess the performance of the structure and assess its condition. (Cl 3.15)*

Hence, performance monitoring is also important in a SHM system. Performance monitoring will help identify any anomalies of a structure which will be just like symptoms of a disease. The performance monitoring and various condition assessment methods using different damage detection methods, will provide various health indexes real time for the management team to make decisions and prepare plans, which is even better than taking a test for COVID-19 as an effective SHM system

2. Chan, T.H.T. and Thambiratnam, D.P. (editors) (2011) *Structural Health Monitoring in Australia,* Nova Publishers.

could be able to show all these health indexes at any time and it is not necessary to go to a testing centre.

Vaccines

As of 25th August, the World Health Organization (WHO) reported there are 31 vaccine candidates in clinical evaluation, of which there is one from Australia (University of Queensland/CSL/Seqirus). Out of these 30 candidates, six (three from China, and the other three from USA, UK and Germany separately) are in the last phase (Phase 3 of Clinical Stage). There are another 142 candidate vaccines in preclinical evaluation. Therefore, it is expected that there should be at least 1 vaccine to be ready very soon, excluding the Russian Sputnik V, making Russia as the first country in the world to license a coronavirus vaccine. However, Sputnik is not on the list of vaccine candidate of WHO. In Australia, our Prime Minister, Scott Morrison declared 19th August ‘a day of hope' as on the date, Australia signed an agreement that will allow every Australian to get a free dose of a potential COVID-19 vaccine being developed by Oxford University if it is proved successful in human trials. A lot of people believe that our life should be back to normal once a vaccine is available. However, the fact is that COVID-19 vaccine will not immediately bring us back to normal. According to advices from some experts on Epidemiology (disease control and prevention), there should be over 70 percent of the population that has got to be immune before we even begin to see any impacts on herd immunity.

How about SHM, will a SHM system ensure a structure to be immune from any damage? The answer is definitely ‘No’. However, if more and more structures installed with an SHM system, more information on a structure (with respect to its types and materials, traditional or new) relating to its responses and loads could be obtained and accumulated using these SHM systems. These will definitely be helpful for future designs of these kinds of structures. When we are looking forward to having the COVID-19 vaccines to be available and more and more people will be immune from the disease, Scientists in Hong Kong on 24th Aug reported what they say is the first confirmed case of coronavirus reinfection, raising questions about immunity and vaccines. Nevertheless, the development of vaccines as well as we know more about the disease will help bring our life back to normal. Likewise, I also look forward to having more SHM systems to be developed and installed on more structures so that more information about the behaviours of our traditional and new structures and structural materials to improve our design, construction and maintenance methods. Besides, we should also develop more guidelines for SHM to avoid false negatives and false positives for much effective structural health monitoring.

Below are the updates of the month.

Research Collaboration

As mentioned in the last update, we will focus our direction towards more on using the ANSHM platform to showcase our development, publicise SHM, help the engineers and public to understand better SHM, and to promote SHM so that more SHM system will be installed on more structures in Australia and effective guidelines on how to use SHM will be developed. At the same time, we will also explore opportunities for research collaboration, but not necessary to have all of us to be involved in a single project. We could disperse it into various projects, working collaboratively together if possible but we could still share the benefits of such projects by sharing the data generated for the development and validation of our developed methods, promoting ANSHM and enhancing our track records.

As mentioned earlier, we will try our best to get involved in the two CRCs (Building 4.0 and SmartCrete), both of which have strong components in the area of SHM. Both two CRCs are still at their early stages, we will try as much as we can to ensure their SHM components will be aligned with ANSHM objectives. Besides, we are also liaising with some of our industry partners secured for our previous proposed ARC Industry Transformation Training Centres to support a few linkage projects. Our Research Collaboration Task Force will act as a coordinator to ensure these projects will not be competing with one another in a round. We are also investigating the opportunity of joining the proposed ARC Research Hub for Resilient and Intelligent Infrastructure Systems (RIIS) in Urban, Resources and Energy Sectors with University of NSW, University of Melbourne, Western Sydney University and QUT.

The 12th ANSHM Workshop

As mentioned in my last update, we decided to move our original 12th ANSHM Workshop in Sydney to late November or early December of 2021, assuming by that time, most of the COVID-19 restrictions be relaxed. Then the 12th ANSHM Workshop will be an online workshop with different WebForums/ sessions including ANSHM AGM and ABM, to be held in in November or December 2020.

At the moment Lei is working with Xinqun, John and Richard together with Andy, our ANSHM Workshop Coordinator, to schedule the date of the workshop that could fit most of us, identify the topics and call for titles, abstracts for presentations, EOI as forum facilitators/coordinators, and how to publicize, etc.

More details will be announced in due course. Please take note of the updates and announcements for the 12th ANSHM Workshop (online), our important annual event.

ANSHM Special Issue in IJSSD

As mentioned in last update, the accepted papers in this special issue have been published online with International Journal of Structural Stability and Dynamics.

This issue has been scheduled to publish in Oct 2020. Thanks go to all the editors, authors and reviewers to make this issue successful. The papers could be downloaded via https://www.worldscientific.com/toc/ijssd/0/ja. Please cite your papers using the DOI numbers on the list.

Publication generated from the 11th ANSHM Workshop

We decided to prepare a monograph for the publication generated from the 11th ANSHM Workshop. We plan to have 10 to 11 chapters covering various topics on different areas of SHM. We intend to have these chapters to be more like textbook materials for undergraduate, postgraduate students and practising engineers to learn about SHM as well as showcase the 10-year development on SHM, celebrating the 10th Anniversary of ANSHM. Hong Guan is taking the lead together with Jianchun and myself for this monograph. Once we have sufficient number of abstracts or sample chapters, she can then start preparing for the book proposal and submit to a reputable publisher. Nowadays we need to be careful about predatory publishers. We are still awaiting the abstracts of many chapters, although there are few days left (at the time of writing this update) before 31 August 2020, the deadline of submission. As commented by Jianchun, "this year is very challenging for everyone, especially for colleagues in Victoria and NSW. It is hard to have time to focus on research when so many issues arising". We will discuss again the preparation of this monograph in the forthcoming Executive Committee meeting.

Mini-Symposium (MS26) in SHMII-10

As reported earlier, we are organising the Mini-Symposium (MS26, a forum for ANSHM members; SHM researchers and practitioners in Oceania). So far 360 abstracts have been submitted to SHMII-10 and 4 of which are for our MS26. It seems that many are quite optimistic that all the borders will be open, and flights would be available for the delegates to attend this international conference. Please visit the official webpage of this conference https://web.fe.up.pt/~shmii10 for details.

The Forthcoming Executive Committee Meeting

We plan to have our EC meeting in September to discuss our involvement in various research collaboration opportunities, the 12th ANSHM Workshop (online), the monograph preparation and others important matters related to ANSHM. You are welcome to suggest items to me for discussion by 9 September 2020.

The ANSHM Newsletter

As mentioned earlier, the Newsletter editorial team is formulating an article/technical note collection plan to have two to three articles for each issue for a two-year cycle current any time including submission schedules. Mehri is coordinating that. We will invite not only academic members to contribute. For the members from the industry, any articles reporting their successful stories in using SHM, what they expect SHM could work for them, or any other matters, issues, or stories related to SHM, are welcome.

In the next sections, we will have two articles from our members. The first article is from University of New South Wales in collaboration with Kyoto University and presents application of drive-by bridge inspection for damage identification in a cable-stayed bridge. The second article is from Queensland University of Technology and presents a damage identification technique based on Modal Kinetic Energy, which can separate mass from damage and incorporate mass variation between two different states of a structure. The industry brief written by our Advisory Board member, John Vazey of EngAnalysis, is also very worth reading.

With kind regards,

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Research profile | **Research publications** | **Google Scholar citations**

A Numerical Investigation of Cable Damage Identification Using Moving Vehicle Response

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Abstract

During the long service period of a bridge, the dynamic characteristics of the structure may be adversely affected by structural damage. If damage keeps propagating, it can cause severe safety issues. Therefore, it is crucial to apply a regular Structural Health Monitoring (SHM) system to the bridge. The conventional SHM techniques are quite expensive to be applied on large number of bridge structures. Therefore, development and validation of alternative cost-effective approaches is of great demand by the road authorities. This paper aims to present successful application of indirect structural health monitoring for identification of cable damage in a cable-stayed bridge structure. The premise of the work is to identify the presence and the location of a structural damage to the cables, solely by vibration response of a moving vehicle passing over the bridge. To this aim, a large-scale cable-stayed bridge located in the state of New South Wales (NSW), Australia is considered as a cases study. The three-dimensional finite element model of the bridge is constructed in Abaqus platform and is updated through extensive field-test data from static and dynamic test measurements. Multiple damage scenarios caused by a sudden change in structural stiffness of cables are introduced in the numerical model. A 6-parametric vehicle model is considered, and the vibration response of the vehicle is collected when it is travelling over the bridge at healthy state and damaged states. A damage index is established based on the difference in the Intrinsic Mode Functions obtained from the healthy state and damaged state. Through extensive numerical investigations it is demonstrated that the vehicle response has potential to provide useful information about presence and location of cable damage. The effect of vehicle speed is also studied, and it is demonstrated that for a successful identification of cable damage the vehicle should travel at slow speed over the bridge.

Keywords

Cable-stayed bridge, vehicle bridge interaction, vibration, natural frequency.

Introduction

It is acknowledged that more than 11% of bridges are structurally deficient in the United States and in Europe, most bridges were constructed from 1945 to 1965 (Malekjafarian et al. 2015). Issues faced by involve not just increase in traffic loads but also the gradual deterioration due to the environmental impacts over time. Thus, it is necessary to apply the continuous monitoring on bridges, the key components of transport infrastructure, aiming at guaranteeing the structural integrity and reliability. Generally, successful application of Structural Health Monitoring (SHM) can effectively reduce the maintenance cost and extend the structure life. The conventional SHM, known as the "sensor-based monitoring", requires numerous sensors to be placed on the bridge, and its performance is highly dependent on the location and sensitivity of sensors (Sohn et al. 2003). Moreover, the sensor installation has been regarded as a costly and challenging exercise, especially for a bridge under ongoing traffic.

To achieve a better performance in feasibility and cost efficiency, an indirect-SHM method, by employing the passing vehicle, was proposed by Yang et al. (2004), which is regarded as a more effective approach for bridge damage detection. Compared with the conventional SHM methods, advantages of indirect-SHM or drive-by inspection method are generally in economy, simplicity, mobility and feasibility. Instead of employing numerous instrumentations attached to the bridge, the drive-by method uses a vehicle as the "moving sensor" to obtain dynamic properties of the bridge via the vehicle-bridge interaction (VBI). Both vehicle and bridge vibrate when a vehicle passes over a bridge, and the vehicle response would be affected by the bridge vibration through the VBI. The vehicle employed is regarded as both exciter and receiver with the instrumentation placed on the vehicle axle or alternatively on axles of a cart towed by the vehicle, which aims at eliminating the noise from the vehicle engine (Lin and Yang 2005). It has been experimentally verified that the fundamental frequency of bridge can be successfully extracted by acceleration signals collected from the cart sensor. In addition, the feasibility of extracting the frequency change due to bridge damage by tracking the vehicle responses has been validated (Kim and Kawatani 2009). In a separate study, vehicle response was adopted to identify bridge damping, and it was then employed as an indicator for bridge health monitoring (McGetrick et al., 2009). Later, to reduce the adverse effects of road profile, Keenahan et al. (2014) proposed a method of subtracting axle accelerations, which applies the fast Fourier transform (FFT) to the signal difference between axles. The results showed significant improvement.

The feasibility of extracting bridge mode shapes was also investigated by several researchers. Zhang et al. (2012) used a specialized vehicle to control the applied force on the bridge, then the point impedance was obtained based on the vehicle responses. It was shown that the amplitude of the point impedance spectra is proportional to the square of the mode shapes. Yang et al. (2014) introduced an approach to extract bridge mode shapes employing the passing vehicle, which gives results with the high resolution, and it is found that the instantaneous amplitude for the extracted bridge component response of specific mode is equal to the mode shape. By increasing the ongoing traffic load and subtracting axle accelerations, the blurring effects of road roughness effects was reduced which resulted in better accuracy estimation of mode shapes (Malekjafarian and Obrien 2014). Miyamoto and Yabe (2012) employed a city bus with accelerometers placed on rear axles to process the drive-by inspection. In their research, the bridge deflection shape was acquired using wave integrals and in order to eliminate the influence of noise, they averaged different readings obtained by numerous travelling of the bus. Results demonstrated that the peak occurred in the displacement profile difference between the healthy and the damaged bridge could indicate the existence of damage.

Although, successful applications of VBI for bridge health monitoring have been reported in the past research works, many of these studies are based on simplified models of vehicle and bridge being far from the realistic conditions. To address this research gap, this paper is aimed at presenting the results from extensive numerical investigations of applying VBI for health monitoring of a large-scale cable stayed bridge. To this aim, finite element (FE) simulations are employed to realistically determine structural responses of the bridge considering real-time interaction between the vehicle and the bridge. Further, a damage identification method based on Empirical Mode Decomposition (EMD) is proposed for damage detection and localization to characterize sudden change in structural stiffness due to cable loss. EMD is one of the most robust time-frequency analysis techniques, well-recognized for self-adaptive decomposition of non-stationary signals (Xu et al., 2004).

Cable-Stayed Bridge

A short-span cable-stayed bridge, in the state of New South Wales (NSW), Australia, is chosen as a case study in this paper. The bridge span and width are, respectively, 46.2 m and 6.30 m. Sixteen semi-fan arranged pre-tensioned stayed-cables are anchored on tower and cross girders (Alamdari et al., 2019). Figure 1 shows illustration of the cable-stayed bridge adopted in this study.

Figure 1 Illustration of the cable-stayed bridge.

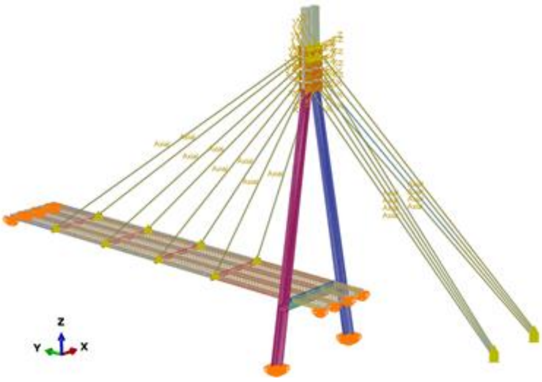

Figure 2 Illustration of FE model of the bridge.

Numerical FE model of the bridge was generated in Abaqus platform as shown in Figure 2. To ensure the established FE model is reliable in predicting the vibration response, the first two vibration modes of the bridge and the corresponding mode shapes obtained from the ambient vibration testing and numerical eigenvalue analysis in Abaqus were compared. The first two vibration modes obtained from Abaqus platform, are 2.06Hz and 3.43Hz which corresponds to a difference of 2.48% and 3.38%, respectively, for the first and the second mode, compared to the field test measurement (Sun et al., 2017), demonstrating satisfactory agreement between the prediction and the measurement. Additionally, the modal assurance criterion (MAC) for the first two vibration modes was calculated based on the measured and the calculated mode shapes. The obtained MAC values for the first two modes are, respectively, 0.99 and 0.98 which illustrates the predicted mode shapes perfectly match with the measured mode shapes. In the next section, the coupling equations between a moving vehicle and the bridge is developed which is the basis for the proposed damage identification method in this paper.

Governing Equations for Vehicle-Bridge Coupling

A vehicle model with 2 degrees of freedom as shown in Figure 3 was adopted in this study. These two degrees of freedom refer to bouncing motion of the vehicle and axle hop.

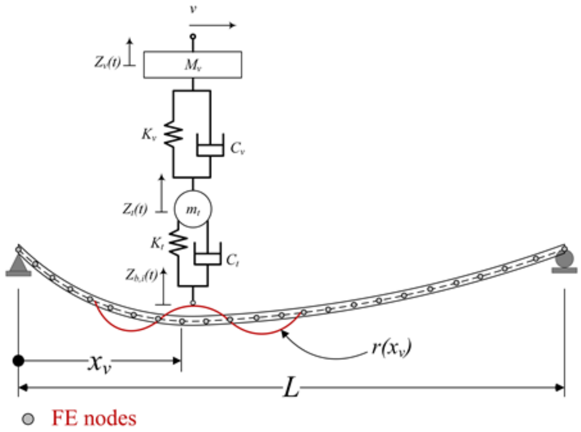

Figure 3 Illustration of the vehicle model.

The dynamic equations for vehicle can be described as,

$$M_v\ddot{Z}_v(t) + C_v(\dot{Z}_v(t) - \dot{Z}_t(t)) + K_v(Z_v(t) - Z_t(t)) = 0 \tag{1}$$

$$\begin{aligned} & m_t\ddot{Z}_t(t) + C_t[\dot{Z}_t(t) - \{\iota_{\mathbf{b}}(x_v)\}^T\{\dot{\mathbf{Z}}_b(t)\} - vr'(x_v)] - C_v(\dot{Z}_v(t) - \dot{Z}_t(t)) \\ & + K_t[Z_t(t) - \{\iota_{\mathbf{b}}(x_v)\}^T\{\mathbf{Z}_b(t)\} - r(x_v)] - K_v(Z_v(t) - Z_t(t)) = 0 \end{aligned} \tag{2}$$

The parameters shown in Eqs. (1) and (2) can be easily understood from Figure 3. The governing equation for the bridge can be explained by Eq. (3) as,

$$[\mathbf{m_b}]\{\ddot{\mathbf{Z}}_b(t)\} + [\mathbf{c_b}]\{\dot{\mathbf{Z}}_b(t)\} + [\mathbf{k_b}]\{\mathbf{Z}_b(t)\} + \{\iota_{\mathbf{b}}(x_v)\}R(t) = 0 \tag{3}$$

where, $R(t)$ can be described by Eq. (4) as,

$$R(t) = -C_t[\dot{Z}_t(t) - \{\iota_{\mathbf{b}}(x_v)\}^T\{\dot{\mathbf{Z}}_b(t)\} - vr'(x_v)]$$
$$-K_t[Z_t(t) - \{\iota_{\mathbf{b}}(x_v)\}^T\{\mathbf{Z}_b(t)\} - r(x_v)] + (M_v + m_t)g \tag{4}$$

These sets of coupled equations can be solved in Abaqus using the Hilber-Hughes-Taylor time integration scheme which is performed iteratively using Newton's method. In the next section, the vehicle response by solving equations 1 to 4, is used to distinguish bridge with different structural states with regards to structural integrity of the cables.

Cable Damage Identification Using Moving Vehicle Response

Empirical Mode Decomposition

In this research, Empirical Mode Decomposition (EMD) technique is adopted to analyse the calculated vehicle response, $Z_t(t)$. EMD starts with constructing two envelopes, i.e. an upper envelope and a lower envelope, respectively, by connecting the local maxima and minima through a cubic spline. A new time signal, Intrinsic Mode Functions (IMF) i.e., $h_1(t)$ can be constructed by subtracting the mean of the two envelopes from the original time response, i.e., $Z_t(t)$. This process is continued in a successive manner until the residue becomes very small, i.e., the second IMF, i.e., $h_2(t)$ is generated by taking the difference between $Z_t(t)$ and $h_1(t)$ and treating it as a new time history. As a result of this procedure, the intrinsic mode functions, representing the embedded time scales in the signal are generated. More details on this can be found in (Kildashti et.al. 2020).

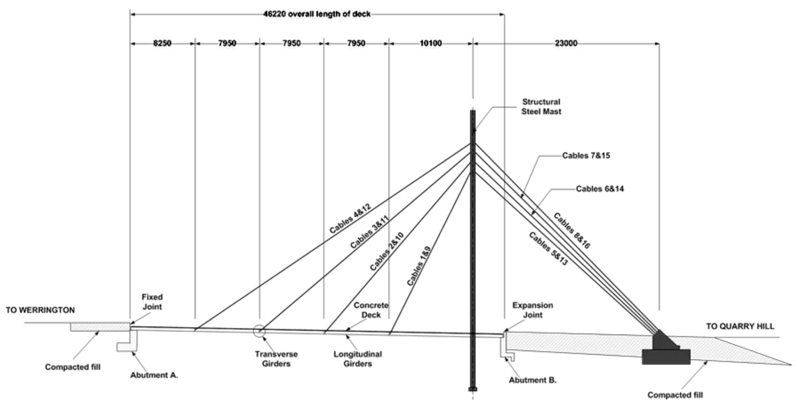

Figure 4 Schematic diagram of the cable-stayed bridge.

Bridge Damage Conditions

In this study, four different states of the bridge are investigated and labelled as H, BC1, BC2 and BC3. H corresponds to the healthy state of the bridge while BC1:BC3 correspond to damaged states of the bridge. Damage is introduced in the cables at one side of deck in an asymmetric manner by reducing the stiffness of the cable by 20%. The location of the cable damage in the bridge states of BC1, BC2 and BC3 are, respectively, Cable L1 (the shortest cable connecting the deck to the mast), Cable L2 (the second shortest cable connecting the deck to the mast) and Cable L3 (the third shortest cable connecting the deck to the pylon (see Figure 4). Details of these four bridge conditions are summarized in Table 1.

Table 1. Details of four different bridge conditions.

Bridge Condition	Description
H	Benchmark state
BC1	20% reduction in axial stiffness of Cable L1
BC2	20% reduction in axial stiffness of Cable L2
BC3	20% reduction in axial stiffness of Cable L3

For each bridge state, eigenvalue analysis was conducted in Abaqus platform to find out the impacts of damage on the first two vibration modes of the bridge and the results are presented in Table 2. From Table 2, it can be readily understood that the maximum change in the first and second vibration modes happen when damage is, respectively, at location L3 and L1. This is expected as the first and the second mode shapes have their maximum amplitudes, respectively, close to cable location L3 and L1 (Sun et al., 2017). Moreover, from Table 2 it can be drawn that the effect of damage on the first two vibration modes is in less than 1.5% which corresponds to a minor damage.

Table 2. Bridge's first two vibration modes in different states.

Bridge Condition	f_1 (Hz)	f_2 (Hz)	Δf_1 (%)	Δf_2 (%)
H	2.06	3.42	---	---
BC1	2.05	3.39	0.39	1.05
BC2	2.04	3.41	1.20	0.40
BC3	2.03	3.43	1.50	0.11

In the next section the response of the moving vehicle is obtained once it is passing over the four bridge states elaborated in Table 1.

Damage Identification Results

For a given vehicle parameters as *Mv = 2,000 kg*, *mt = 100 kg, Kv =100,000 N/m, Cv = 2800 Ns/m, Kt = 300,000N/m,* and *Ct = 0Ns/m*, the response of the vehicle is collected for each of the four bridge states at a sampling frequency of *20Hz*. With the given dynamic characteristics, the natural frequencies of the vehicle for the two vibration modes are obtained as $f_{1v} = 1.13Hz$ and $f_{2v} = 8.72Hz$. A road surface roughness with class A, as shown in Figure 5, is also considered to obtain the response of the vehicle once passing over the bridge. The vehicle is passing over the bridge at a speed of *5m/s*. Figure 6 illustrates the response of the vehicle ($Z_t(t)$) once passing over the healthy bridge (H) and damage bridges (BC1:BC3). From this figure, no visible information about presence and location of damage is identifiable; hence, further processing of data is required. To this aim, EMD is applied to extract the IMFs of the time response. Further, a damage index according to Eq. (5) is constructed to extract information about damage.

$$\delta = \left|\sum(h_{iD} - h_{iH})\right| \tag{5}$$

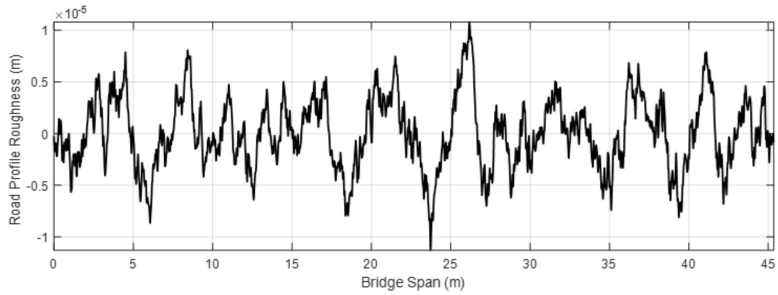

Figure 5 Illustration of road surface roughness with class A.

Figure 7 illustrates the obtained damage indices for damaged bridges BC1, BC2 and BC3. From this figure, it is implied that the proposed damage index not only can highlight the presence of damage in the structure as non-zero damage index is obtained, it is also capable of localizing damage as the highest value of damage index corresponds to location of damage. As observed, the maximum of damage index in BC1, BC2 and BC3, respectively occur at bridge span *15m*, *25m* and *32m* which correspond to cable locations L1, L2 and L3 (see Figure 4). Further, in order to investigate the impact of vehicle speed on damage identification, for three different speed of *10m/s, 15m/s* and *20m/s*, the same procedure for damage identification was conducted and the obtained damage indices were presented in Figures 8, 9 and 10, respectively. From these figures, identification of damage is successful, however as observed by increasing the vehicle speed, gradually some local peaks appear in the damage index which do not correspond to damage location, e.g. see Figure 10. The reason for these peaks is that at higher speed the effect of road surface profile is more dominant which adversely affect the damage index; thus, for a successful identification and localization of damage vehicle should travel over the bridge at slow speed.

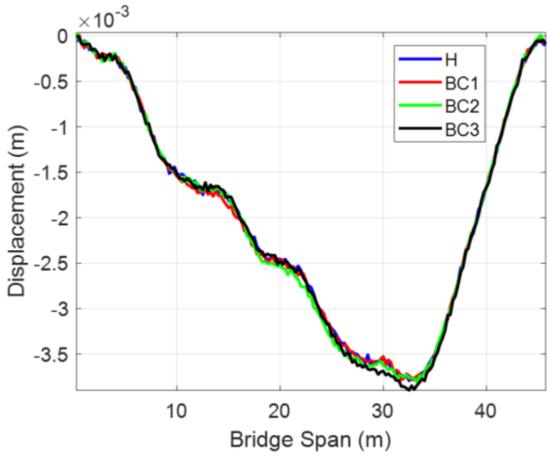

Figure 6 Illustration of the vehicle response passing over the bridge with conditions H, BC1, BC2 and BC3.

Conclusions

This paper presented a damage identification method relying on the response of a moving vehicle passing over a bridge. A damage indicator based on Empirical Mode Decomposition was presented in order to establish the Intrinsic Mode Functions (IMF) obtained from the vehicle response. The obtained IMFs from different structural states of the bridge were compared with the ones obtained from the benchmark state of the bridge. It was shown that the difference between IMFs has potential to provide useful information about presence and location of damage where induced in the cables by reducing the stiffness of the cables by 20%. This study was one of the early attempts which numerically investigated the feasibility of drive-by bridge inspection for a large-scale cable-stayed bridge.

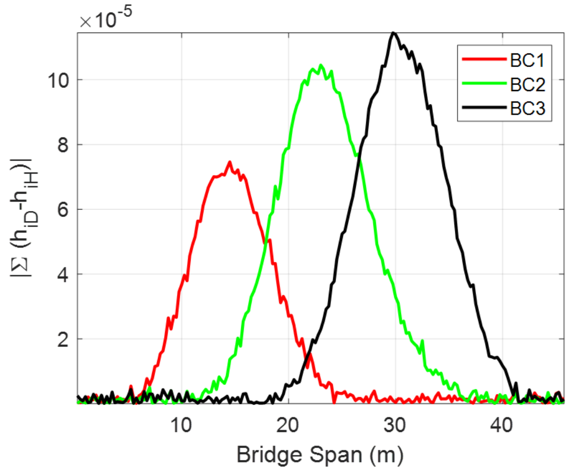

Figure 7 Illustration of damage index obtained for bridge conditions BC1, BC2 and BC3 once vehicle is travelling over the bridge at 5m/s.

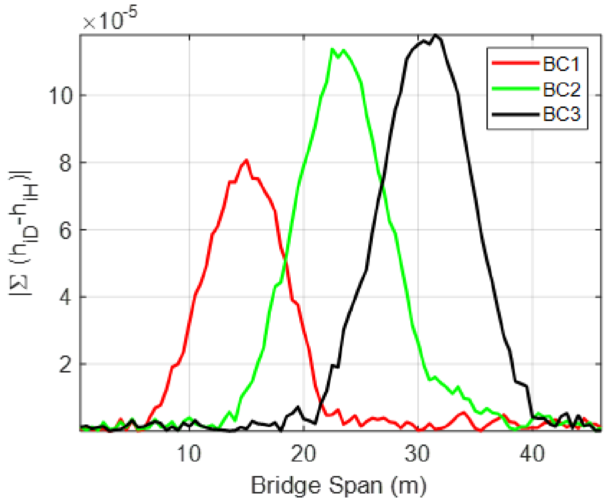

Figure 8 Illustration of damage index obtained for bridge conditions BC1, BC2 and BC3 once vehicle is travelling over the bridge at 10m/s.

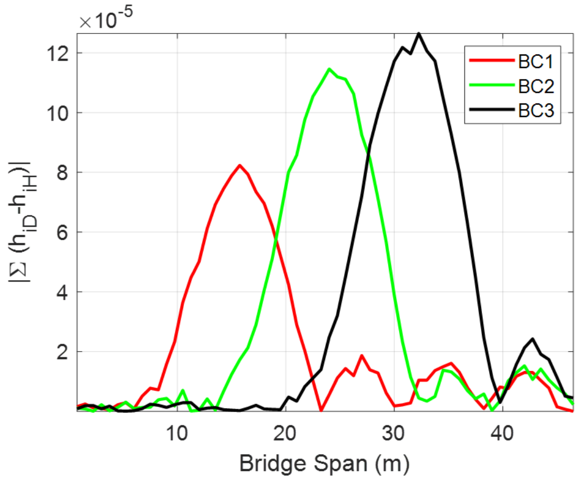

Figure 9 Illustration of damage index obtained for bridge conditions BC1, BC2 and BC3 once vehicle is travelling over the bridge at 15m/s.

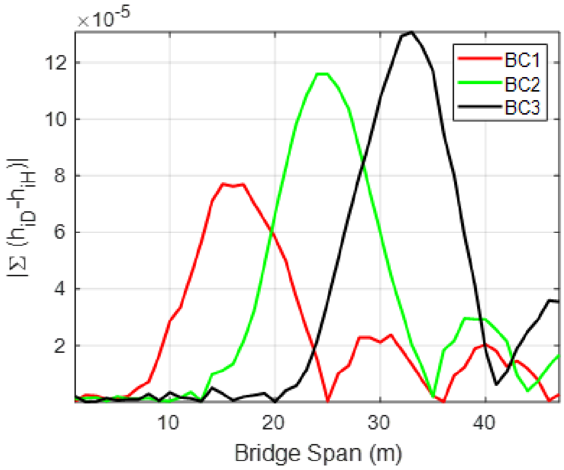

Figure 10 Illustration of damage index obtained for bridge conditions BC1, BC2 and BC3 once vehicle is travelling over the bridge at 20m/s.

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Sensitivity Based Damage Identification Using Modal Kinetic Energy Change

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Damage identification using Modal Kinetic Energy change

A well-developed, safe and reliable infrastructure is the backbone of any healthy nation. While investing on new infrastructure projects, it is equally important in maintaining the existing infrastructure systems to avoid structural failures due to aging and extreme loading. With the help of Structural Health Monitoring (SHM) technology performance and real-time condition of the structure can be evaluated continuously. It is often observed that damage detection methods based on combinations of different modal parameters provide better results than employing them separately. Modal Kinetic Energy (MKE), a product of mass matrix and square of mode shape vector, is one of such powerful combinations used for damage detection.

There has been an increasing trend of using powerful computational tools to detect damage in complex structures these days. The main advantage of using these computational tools is that it exploits the possibility of tolerance for inaccuracy and proximities during computation and decision making like a human mind. Genetic Algorithm (GA) is one such powerful computation tools used to solve wide variety of engineering problems by calculating the maxima or minima of a given objective function. This optimization tool has been successfully employed on damage detection problems.

The MKE-based methods have been widely used to identify the optimal locations of sensors and thereby increasing the accuracy of damage detection process. However, this combination of modal parameter has received little attention among researchers to use as a damage sensitive feature till recently. An approach based on the changes in MKE was first proposed by Fritzen and Bohle (2004). Many other researchers later followed the same combination of modal parameters and developed their damage detection approaches. However, none of these studies explored the inherent features of MKE in dealing mass variation in conjunction with perturbation in structures.

Researchers usually assume that the mass change between damaged and undamaged states of a structure is negligible. Another usual practice is to treat mass variation as either modelling error or damage to prove the robustness of the proposed methods. However, in real world, the mass of the damaged structure might be different when testing compared to that of the undamaged one. For instance, imposed load or vehicular load at two different states may be different in case of buildings or bridges respectively. The change in mass influences the modal properties and adversely alter the accuracy of damage detection results if not addressed adequately. The MKE based methods can separate mass from damage and incorporate mass variation between two different states of a structure more efficiently due to its inherent correlation with mass matrix. Another advantage of MKE methods is that while developing residual parameters, the changes of measured modal properties due to damage when used in combination with uncontaminated mass matrices are usually less susceptible to various errors compared to the combination with imprecise stiffness matrices, and hence, the methods usually provide better results.

In this research, a Modal Kinetic Energy (MKE) based damage detection method has been formulated by developing a new damage sensitivity parameter using measured modal characteristics of baseline structure. The modal kinetic energy change (MKEC) concept is then employed to locate damage and to estimate relative perturbation at each element. The relative damage extent vector is estimated by searching the best correlation between the analytical and experimental MKEC vectors with the help of GA optimization tool. The extent of damage is calculated after computing damage scaling coefficient using measured eigenvalue change vector.

Damage in any structure can cause loss in stiffness and alter the mode shape conspicuously close to the damage. It also changes the energy distribution in the system. A sensitivity parameter can be thus developed by equating the change in MKE distribution between damaged and undamaged structure. Once the sensitivity parameter has developed, 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. (1998) is modified to evaluate the correlation between the measured and analytical MKE changes:

$$MDLAC^{MKE} = \frac{\left|\{R^{MKE}\}^T\{\Re^{MKE}\}\right|^2}{(\{R^{MKE}\}^T\{R^{MKE}\})\left(\{\Re^{MKE}\}^T\{\Re^{MKE}\}\right)} \qquad (1)$$

where $\{R^{MKE}\}$ is the modified MKE residual vector, which can be estimated experimentally for each j^{th} element in the i^{th} mode of vibration as follows:

$$R_{i,j}^{MKE} = \frac{\lambda_i^d}{\lambda_i}\{\phi_i^d\}^T[M]_j^d\{\phi_i^d\} - \{\phi_i\}^T[M]_j\{\phi_i\} - \{\phi_i\}^T[\Delta M]_j\{\phi_i\} - \frac{\Delta\lambda_i}{\lambda_i}\{\phi_i\}^T[M]_j\{\phi_i\}$$
$$- \sum_{j=1}^{L} 2\lambda_i\{\phi_i\}^T[M]_j\left\{\sum_{r=1}^{n}\frac{\{\phi_r\}^T[\Delta M]_j\{\phi_i\}}{\lambda_r-\lambda_i}\{\phi_r\}\right\} + \sum_{j=1}^{L}\{\phi_i\}^T[M]_j\left\{\left(\{\phi_i\}^T[\Delta M]_j\{\phi_i\}\right)\{\phi_i\}\right\}$$

and $\{\Re^{MKE}\}$ is the analytical counterpart, whose elements are calculated by

$$\sum_{p=1}^{L} S_{i,j,p}^{MKE}.\alpha_j = \sum_{p=1}^{L} -2\alpha_j\{\phi_i\}^T[M]_j\left\{\sum_{r=1}^{n}\frac{\{\phi_r\}^T[K]_j\{\phi_i\}}{\lambda_r-\lambda_i}\{\phi_r\}\right\} \quad \text{when } (r \neq i)$$

The MDLAC function, however, provides a solution for damage extent vector with an arbitrary scale factor represented as $\bar{\alpha}_j$. Thus, the actual extent of damage, α_j is to be estimated by multiplying the arbitrary scale factor, $\bar{\alpha}_j$ with damage scaling coefficient, *C*. The scaling coefficient can be computed by equating the fraction of modal kinetic energy with measured residual changes between the damaged and undamaged structure using the following equation:

$$\sum_{j=1}^{L} C_i.\bar{\alpha}_j.\frac{\{\phi_i\}^T[K]_j\{\phi_i\}}{\{\phi_i\}^T[K]\{\phi_i\}} = \frac{\lambda_i\{\phi_i\}^T[\Delta M]\{\phi_i\}+\Delta\lambda_i}{\lambda_i} \qquad (2)$$

where $\frac{\{\phi_i\}^T[K]_j\{\phi_i\}}{\{\phi_i\}^T[K]\{\phi_i\}}$ is the fraction of modal energy or modal sensitivity of the j^{th} member in the i^{th} mode of vibration and the RHS of Eq. (2) is the measured residual changes in the i^{th} mode of vibration.

Numerical Results and Discussion

To validate the performance of the proposed approach, a 2-D simply supported Euler-Bernoulli beam of uniform cross-section is considered as shown in Figure 2. The effective span of the beam is 6m. It consists of 21 equally spaced nodes and 20 elements with 42 degrees of freedom (DOF), neglecting axial deformation. The following mechanical properties of structural steel are considered for the beam: modulus of elasticity, E = 210 GPa; width of beam, b = 200 mm; depth of section, d = 35.5 mm; and mass density, ρ = 7800 kg/m^3.

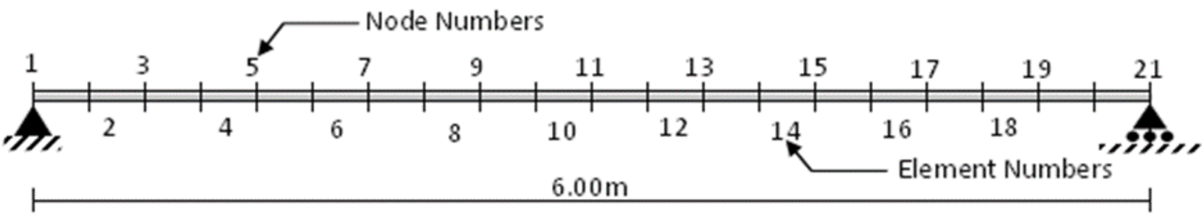


Figure 2: Simply supported beam model (adapted from Joseph et al., 2020)

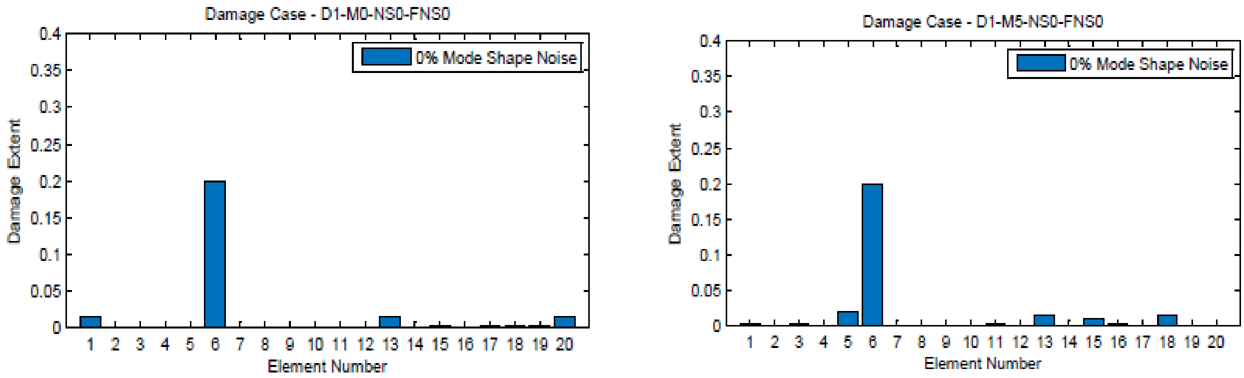
In the numerical simulation, mode shapes of all degrees of freedom (DOFs) can be considered for damage detection. However, it is almost impossible to obtain full modal data and expensive to measure rotational DOFs experimentally due to the limited number and types of sensors used for testing. In such cases, the modal data acquired from testing needs to be expanded to match with all DOFs of the system under consideration. Alternatively, mass matrices and undamaged system stiffness matrix to be transformed to the size equivalent to the active DOFs. This expansion or reduction process can be employed using System Equivalent Reduction Expansion Process (SEREP) proposed by O'Callahan (1989). In order to mimic the real field condition, only vertical mode shapes are considered for the current numerical simulation study and SEREP reduction process is employed to replicate the available modal data.

Table 1 shows the damage scenarios considered to authenticate proposed damage detection and quantification approach. The damage cases are simulated by reducing the Young's modulus of the damaged elements by a predetermined percentage. Mass change between damaged and baseline model is replicated by altering the density of specific elements of the damaged structure.

Table 1: Damage Scenarios for single span simple supported beam

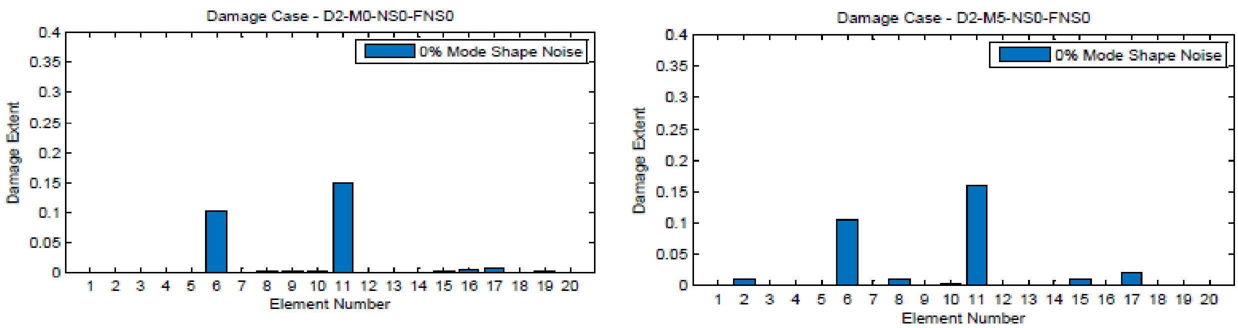
Damage Case	Damage		Mass Variation	
	Element No.	Extent of Damage	Element No.	Amount
Single Damage (D1-M0)	6	20%	-	-
Single Damage (D1-M5)	6	20%	6	+5%
Multiple Damage (D2-M0)	6	10%	-	-
	11	15%	-	-
Multiple Damage (D2-M5)	6	10%	6	+5%
	11	15%	-	-

The 2-D simply supported beam is simulated in a noise-free condition for the damage scenarios listed in Table 1. Both undamaged and damaged cases were simulated analytically. The physical properties are derived from undamaged structure. The modal properties such as frequencies and mode shapes are extracted from both damaged and undamaged models. The results of the simulated damaged scenarios without considering noise are shown in Figure 3 and Figure 4 (Reproduced the results from Joseph et al. (2020)).



(a) (b)

Figure 3: Single Damage indices without Noise; $\delta\alpha_6 = 20\%$; (a) Without mass change (D1_M0) and (b) With 5% mass change applied to Element 6 (D1_M5)



(a) (b)

Figure 4: Multiple Damage indices without Noise; $\delta\alpha_6 = 10\%, \delta\alpha_{11} = 15\%$; (a) Without mass change (D2_M0) and (b) With 5% mass change applied to Element 6 (D2_M5)

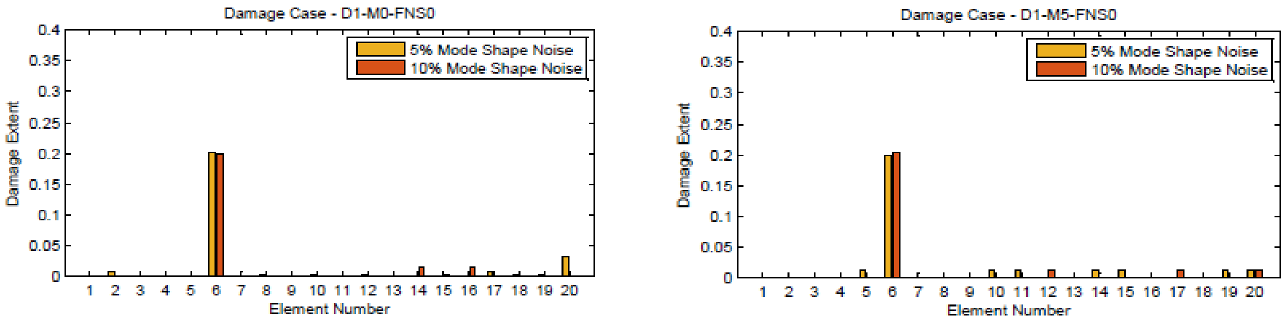
In both single and multiple damage simulation cases, the estimated damage extents are closely matching with the actual damage extents. The maximum deviation from the actual damage extent is found to be less than 1% & 3% in single and multiple damage cases respectively. No significant change in the damage estimation results is observed when simulated without and with mass variation up to 5% when simulated without noise.

In the real world, it is inevitable to avoid noise from the measured modal data completely. Therefore, various combinations of mode shapes and natural frequencies with different noise levels are applied to simulate field conditions. The various noise scenarios considered in the current study for single damage and multiple damage are tabulated in Table 2.

Table 2: Noise Scenarios

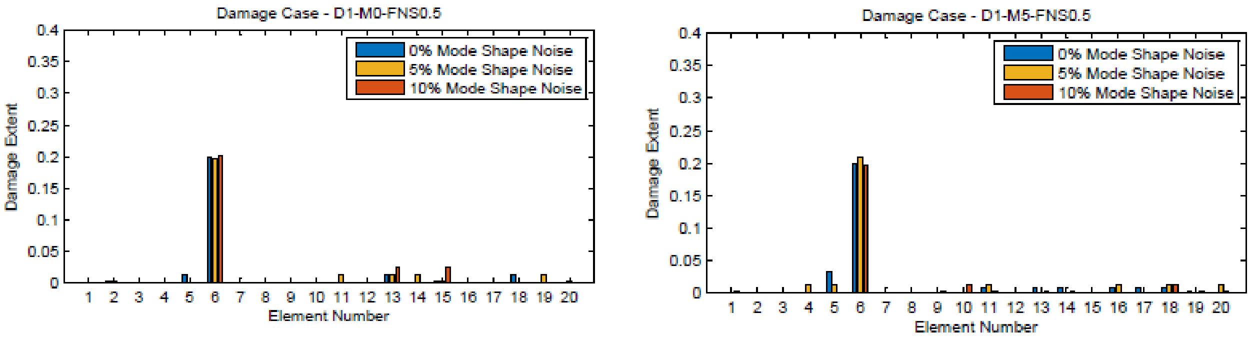
Combination	Noise in percentage applied to Mode shape & Natural frequency															
	Without mass variation								With 5% mass variation in Element 6							
Nat. Freq. Noise (NFS)	0	0	0.5	0.5	0.5	1	1	1	0	0	0.5	0.5	0.5	1	1	1
Mode shape Noise (NS)	5	10	0	5	10	0	5	10	5	10	0	5	10	0	5	10

All the test cases and noise scenarios are simulated analytically in MATLAB environment to detect and quantify damage in the test model and the results are depicted in Figure 5 – Figure 10 (Reproduced the results from Joseph et al., 2020).



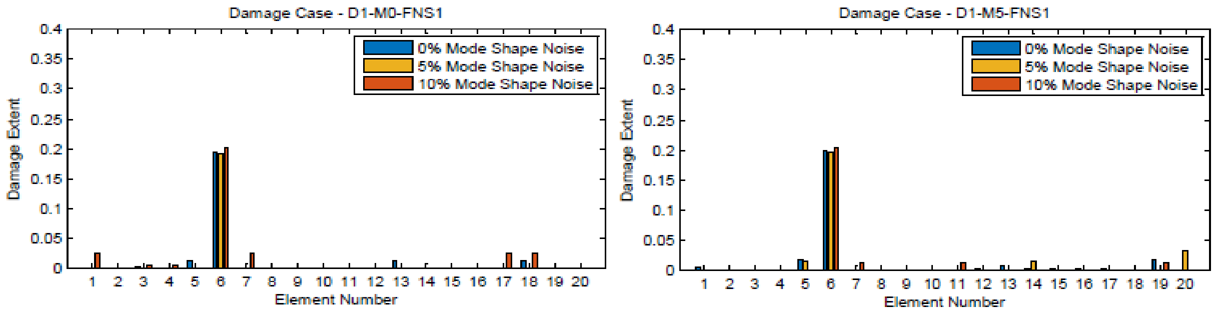
(a) (b)

Figure 5: D1-NS-FNS0: Single Damage indices for various Mode Shape Noise and without Natural Frequency Noise; $\delta\alpha_6 = 20\%$; (a) Without mass change and (b) With 5% mass change applied to Element 6



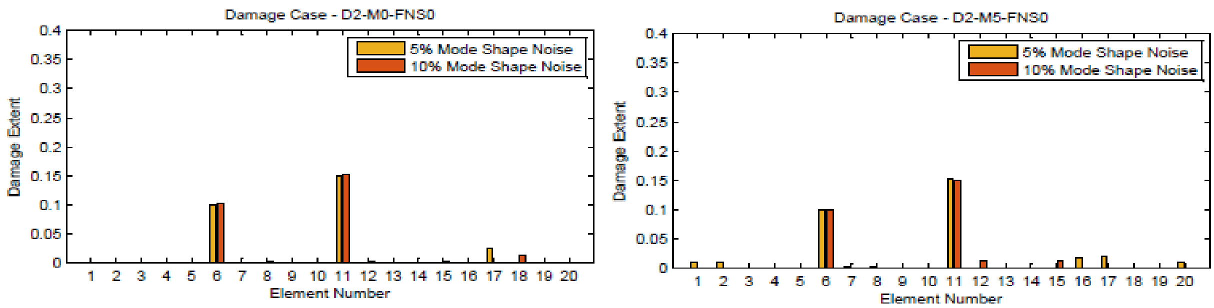
(a) (b)

Figure 6: D1-NS-FNS0.5: Single Damage indices for various Mode Shape Noise and with 0.5% Natural Frequency Noise; $\delta\alpha_6 = 20\%$; (a) Without mass change and (b) With 5% mass change applied to Element 6



(a) (b)

Figure 7: D1-NS-FNS1: Single Damage indices for various Mode Shape Noise and with 1% Natural Frequency Noise; $\delta\alpha_6 = 20\%$; (a) Without mass change and (b) With 5% mass change applied to Element 6



(a) (b)

Figure 8: D2-NS-FNS0: Multiple Damage indices for various Mode Shape Noise and without Natural Frequency Noise; $\delta\alpha_6 = 10\%, \delta\alpha_{11} = 15\%$; (a) Without mass change and (b) With 5% mass change applied to Element 6

From the single damage simulation results, it is observed that the noise has no significant effect on the accuracy of the extent of damage when different combinations of noise percentages applied to mode shapes and natural frequencies. In case of multiple damage scenarios, the maximum percentage of error is below 4% when the maximum mode shape noise of 10% is applied in combination with 1% noise to natural frequency.

The results of the simulation study thus revealed that the proposed approach is efficient in detecting and quantifying single and multiple perturbation in structures. This method can successfully predict and quantify damage even in a noisy environment with acceptable accuracy.

The influence of noise in the mode shapes and natural frequencies, of up to 1% and 10% respectively, did not significantly alter the accuracy of damage detection results. More details of this study can be found in our recently published paper (Joseph et al., 2020).

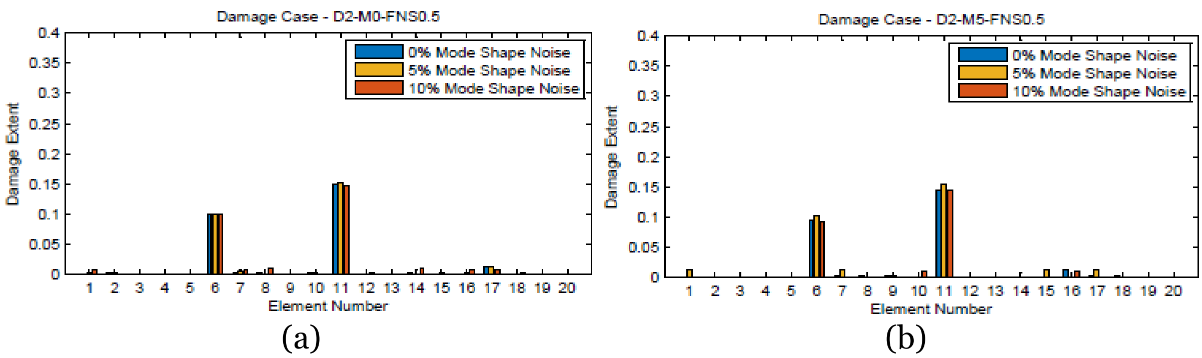


Figure 9: D2-NS-FNS0.5: Multiple Damage indices for various Mode Shape Noise and with 0.5% Natural Frequency Noise; $\delta\alpha_6 = 10\%, \delta\alpha_{11} = 15\%$; (a) Without mass change and (b) With 5% mass change applied to Element 6

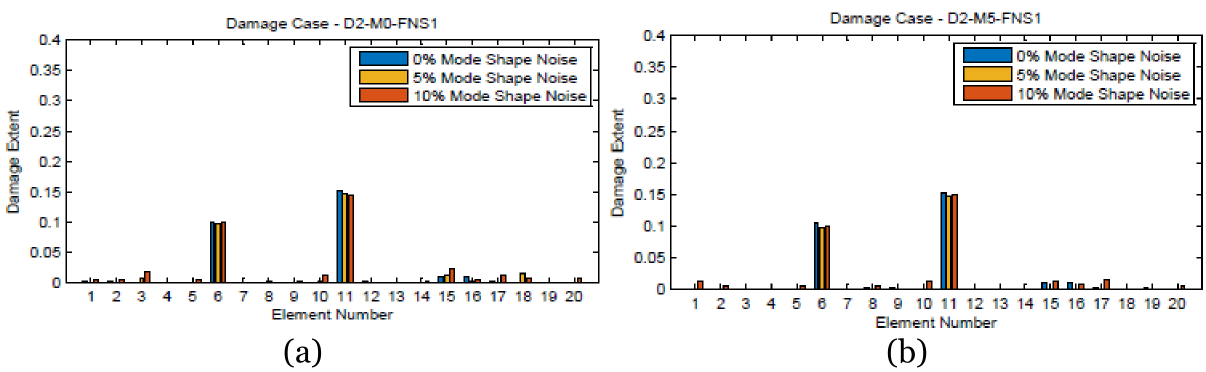


Figure 10: D2-NS-FNS1: Multiple Damage indices for various Mode Shape Noise and with 1% Natural Frequency Noise; $\delta\alpha_6 = 10\%, \delta\alpha_{11} = 15\%$; (a) Without mass change (b) With 5% mass change applied to Element 6

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Industry Brief

The SHM market is expanding with increased awareness of smarter structures and an expectation that greater quantities of data will provide greater insight. This market focus on cool-new-stuff with a limited understand of SHM methodologies introduces some interesting challenges for good operators and it is hoped that all of the ANSHM membership keep our clients focused on realistic expectations from a finite number of sensors and a near infinite array of failure modes.

The current SHM challenges from a practitioner's perspective are:

- Examining the cost & benefit of potential and existing systems.
- Reducing the cost, variability and complexity of sensor deployment.
- Reducing the specialisation, time and training required to deploy sensors.
- Improving telemetry systems with accurate time synchronisation.
- Improving diagnostic tools and defined diagnostic strategies.
- Improving failure criteria for civil structural displacement.
- Better understanding the limitations of any monitoring system or analysis approach
- There are some serious risks that are being ineffectively mitigated with measurement technologies and sometime soon one of these is likely to end in court.
- Erroneous and poorly specified Standards like AS 5100:2017
- Addressing the previously poorly specified or poorly deployed data acquisition systems.
- There is increased market scepticism in organisations that have negative experiences with SHM. And there are multiple examples of SHM systems with six noisy unreliable ill-documented strain gauges deployed on a complex multi-span bridge coupled to a low-cost data acquisition system with no analysis software.

To address these challenges the team at EngAnalysis would like to see research priorities focus on:

- The development of better adhesive technologies to simplify deployments
- Rapid low-cost production of bespoke strain-gauge based sensors
- Continued exploration into wireless DAQ systems and their specification
- Improved guidance on the failure criteria for structures
- Improved definition on what constitutes SHM
- Calling out the bullshit for SHM system deployments that fail to deliver

- Reduced cost in all aspects of photonics and light-based instrumentation
- Improved use of video-based technologies for persistent generalised measurement or strain, displacement and crack growth
- Improved guidance on the use of fracture mechanics in the investigation of cracking in large (low population) structures.

The team EngAnalysis is actively working in all of these areas and we are happy to collaborate with other research groups who would like to join the challenge.

There is opportunity for the right PhD candidates and post docs to spend time in the offices of the principal SHM practitioners and EngAnalysis welcomes the right people or projects into our group. Please contact me at john.vazey@enganalysis.com.au if you need access to our technology, deployment teams, or would like to join our group to provide industry relevance to your SHM projects.

Conference News

- The 10th Australasian Congress on Applied Mechanics (ACAM10), to be held at The University of Adelaide, Adelaide, Australia, from 25-27 November 2020. Chair: Assoc. Prof. Alex Ng. Webpage: https://acamconference.com.au/
  Abstract submission due: 27 April 2020

  Full paper due: 20 July 2020

- Mini Symposium "Latest advances on SHM and smart structures in Australia/Oceania" in the Tenth International Conference on Structural Health Monitoring of Intelligent Infrastructure, Porto, Portugal, from 30 June to 2 July 2021. Organised by Dr Andy Nguyen, Assoc. Prof. Alex Ng, and Prof. Tommy Chan.

  Webpage: https://web.fe.up.pt/~shmii10/conference/mini-symposia/

  Abstract submission due: 30 June 2020

  Full paper due: 10 Jan 2021

- Mini Symposium "Innovative data-driven techniques for Structural Health Monitoring" in the Tenth International Conference on Structural Health Monitoring of Intelligent Infrastructure, Porto, Portugal, from 30 June to 2 July 2021. Organised by Assoc. Prof. Jun Li and Prof. Ting-Hua Yi.

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