Preserving Our Structures through Structural Health Monitoring

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***Abstract*—Civil structures such as bridges, buildings, dams, etc., are normally designed to have long life spans. However, changes in load patterns, deterioration with age and environmental effects may initiate damage in these structures. Structural Health Monitoring (SHM) has emerged as an efficient means of evaluating the health of a structure and detect damage. Structural failure can be prevented if damage is detected at its onset and appropriate retrofitting carried. Vibration based (VB) SHM methods have attracted much attention in recent times. The principle of VB methods is that the modal parameters (natural frequencies and mode shapes) of a structure change when the structure is damaged. These variations can hence be used to detect structural damage. Sophisticated instrumentation and numerical methods have enabled the rapid growth in VB SHM research and its applications to structures in which the onset of damage can be easily missed as it is not easily visible or accessible. This paper presents the basics of VB SHM and the research carried out by the author and his team on its applications to a variety of structures. They include (i) beams which are important flexural members in buildings and bridges, (ii) suspension bridge (iii) arch bridge, (iv) dam and (v) hyperbolic cooling tower.**

Keywords-structural health monitoring, vibration data, beams, bridges, dam

1. INTRODUCTION

Structures keep our cities functional, but many of them may be aged and have tendencies for damage initiation due to changes in load patterns, deterioration with age, environmental effects and random actions. The 80 year old Story Bridge in Brisbane, shown in Fig. 1 is an example of an aged structure exhibitting high levels of vibration that could affect its safety. As it is in the vicinity of a big city, it carries havy traffic and an onset of distress in the bridge can be easily be missed. It needs continuous monitoring of its structural health as it is now subjected to heavier and faster moving loads, than what it was designed for and might have also suffered deterioration due to environmental effects. SHM techniques can be used to monitor the health of such structures and detect damage at its on-set [1]. If damage is detected during such an evaluation, appropriate retrofitting can be carried out to prevent collapse of the structure. Vibration based (VB) SHM methods, which give a global damage assessment, are promising and have attracted much attention in recent times.

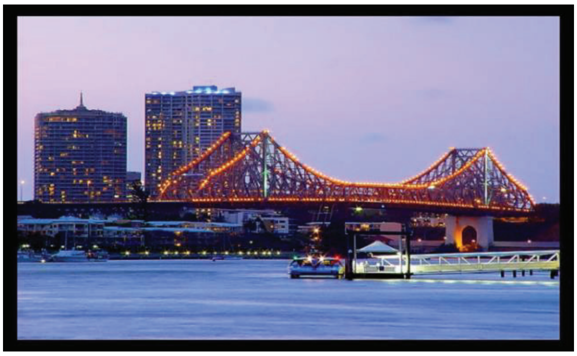

Fig 1. Story Bridge, Brisbane, Australia

II. VIBRATION BASED SHM (VB SHM)

There are 4 levels in damage assessment [2]. They are detecting damage (Level 1), locating damage (Level 2), quantifying damage (Level 3) and predicting the remaining service life of the damaged structure (Level 4). Most of the work done to date pertains to stages 1 and 2 while limited work, in conjunction with Artificial Neural Network (ANN) has ventured into stage 3. The theory presented below will pertain only to stages 1 and 2 (for want of space). Three basic VB damage indices (DIs) for damage assessment are those based on the modal flexibility (MF), modal strain energy (MSE) and mode shape curvature (MSC). They depend on the changes in the modal properties of the structure due to damage [2]. While the MF method depends on natural frequencies and mode shapes, both the MSE and MSC methods depend on the mode shapes and their derivatives in the healthy and damaged states of the structure. Only the basic theory of the MF based DI is presented in this paper for want of space. Basic theories of the MSE and MSC methods are presented in [2] and [3] respectively.

The Modal flexibility MF at a location *"j"* in a one-dimensional structure such as a beam includes the influence of both the mode shapes and the natural frequencies, as shown in (1) below where the summation in *"i"* includes the number of modes to be considered [2].

$$[F_j] = \Sigma\ [\phi_{ji}]^T[\phi_{ji}]/[1/\omega_i^2] \tag{1}$$

The value of "ith" mode shape at location "j" is indicated by $[\phi_{ji}]$ in the above equation in which $[1/\omega_i^2]$ is the reciprocal of the square of natural frequency of mode *"i"*. MF decreases as the frequency increases and hence it converges rapidly with increasing values of frequency. Therefore, from only a few of the lower frequency modes a good estimate of the MF can be made. The absolute or percentages change in MF or ΔMF due to structural deterioration at location "j" is given by (2a) and (2b) respectively.

$$\Delta F_j = [F_j]^d - [F_j]^h \tag{2a}$$

$$(\Delta F\%)_j = \{([F_j]^d - [F_j]^h)/[F_j]^h\} x100 \tag{2b}$$

In (1), (2a) and (2b) above superscripts 'd' and 'h*'* refer to the healthy and damaged states of the structure respectively. In 2D structures such as a floor slab or a bridge deck, subscripts "jk*"* will be used to indicate a location.

III. APPLICATIONS

The author, his colleagues and PhD students at QUT used VB SHM techniques to assess damage in a variety of structures. Both MF and MSE based DIs were used for damage assessment in (i) beam structures which are important flexural members in buildings and bridges, (ii) different types of bridges, (iii) dams, and (iv) asymmetric high-rise buildings, while MSC based DI was used for damage assessment in cooling towers for which it was the best candidate. Some applications and results are presented below.

A. Damage Detection in Beams

Finite Element (FE) models of a single span beam with mid-span damage and a two-span beam with mid-span damages in both spans as shown in Figs. 2a and 3a were developed, with damage B greater than damage A. Their modal responses were obtained using the FE software SAP2000. After validating these initial FE models through limited experimental testing, additional FE models of the beam structures, first without damage and then with the different damage patterns were developed for investigation.

The natural frequencies and mode shapes of the first 5 modes of these beams, before and after damage, were extracted from the FE modal analysis and used to calculate the DIs using Eq. (2b). The DIs were plotted along the 2 beams. Plots > 1 indicate that there is damage while the peaks of the DIs indicate locations of the damage in the beams. Details of modal testing, FE modelling of the beams and validation are described in [2].

Fig. 2 shows the mid-span damage in a simply supported beam and the plot of the DI along the beam. Fig. 3 shows the 2-span beam with midspan damages and the plot of the DI along the beam. It is evident that in both cases, peak values of the DIs accurately predict damage locations. Fig. 3b shows that the peak value of the DI is higher for the larger damage B. This information can be used in damage quantification. These results confirm that MF based DIs can successfully detect and locate damage in beams. Several other cases were treated to establish this feature and details are in [2].

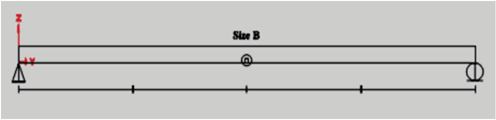

Fig. 2a. Mid span damage in beam

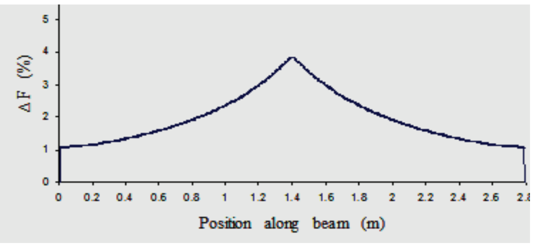

Fig. 2b. Damage detection in beam

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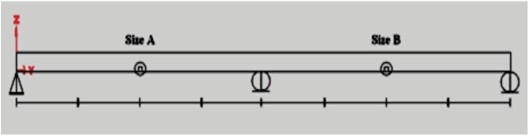

Fig. 3a. Two span beams with mid span damages

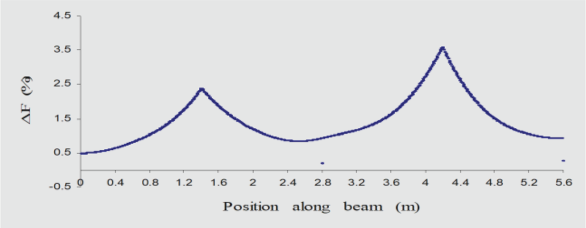

Fig. 3b. Damage detection in two span beams.

Research has progressed to quantify damage in conjunction with ANN techniques [4].

B. Damage Detection in Suspension Bridge

Suspension bridges are large structures and onset of damage in their cables can often be missed as the cables are usualluy covered by tubing. The importance of SHM and damage detection in such structures is hence evident. Fig. 4 shows the Ölfusá Suspension Bridge in Iceland. This bridge was chosen for the SHM research as it had been tested and vibration data was available to validate the computer model. Details of this bridge can be found in [5].

A FE model of this bridge was developed in ABAQUS software, as shown in Fig. 5, and validated by comparing the numerical results of frequencies and mode shapes with measured results. Two damage scenarios were considered: (i) damage at mid span and (ii) damage at three quarter span on the upstream (blue) cable.

Fig. 4. Ölfusá Suspension bridge, Iceland

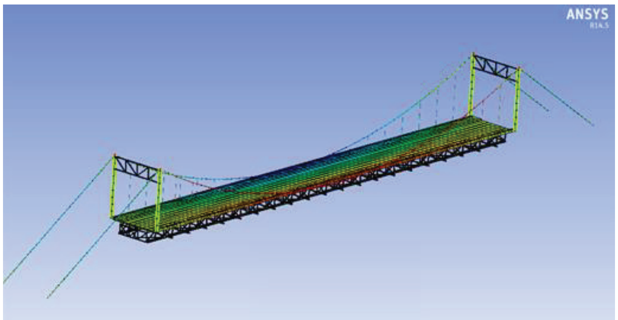

Fig. 5. FE model of Ölfusá Suspension bridge

The DI used in this research was also based on the MF and considered the first 5 natural frequencies and the vertical components of the first five mode shapes. Fig. 6 shows that the modified form of the DI can accurately detect and locate the damage in the 2 cases. Details of FE modelling, damage scenarios involving different damage intensities and multiple damages were also treated. Results showed the versatility of the selected DI to detect and locate damage in the cables of the suspension bridge. This information is available in [5]. Research also continued to further validate the method through experimental testing of laboratory models of a suspension bridge.

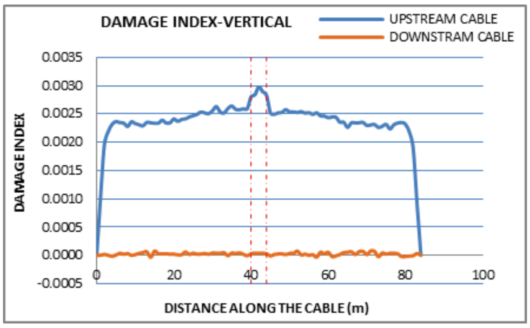

Fig. 6a. Mid-span damage in upstream cable

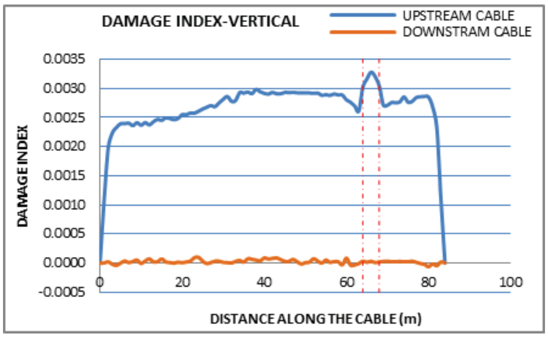

Fig. 6b. Damage in upstream cable at ¾ span

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C. Damage Detection in Arch Bridge

Arch bridges can span across 20 – 200m and beyond. They are large structures built across canyons, waterways or roads. Some parts of an arch bridge, especially on the arch rib and some of the struts (or hangers) may be neither visible nor easy to access. It is therefore necessary to detect and locate damage in them at the onset to enable appropriate retrofitting and prevent bridge failure.

DIs based on MF and MSE methods and mode shape components were used to develop a procedure in ABAQUS software to detect damage in the rib and struts of a deck type arch bridge. This procedure was validated using results from tests on a bridge model and then applied to the 200m long Cold Spring Canyon arch bridge shown in Fig 7.

Fig. 7. Cold Canyon arch bridge

Damage in the arch rib and the strut shown in Figs. 8a and 9a respectively were successfully detected. Results using the component specific DIs based on the MF method, termed, Zj, are presented in Figs 8b and 9b respectively.

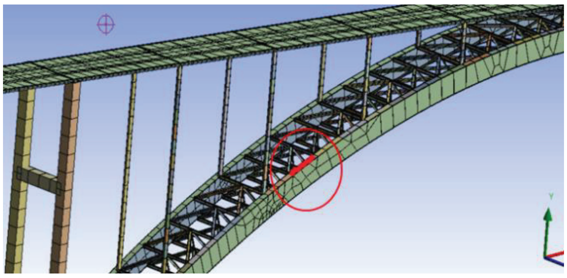

Fig. 8a. Damage in the arch rib

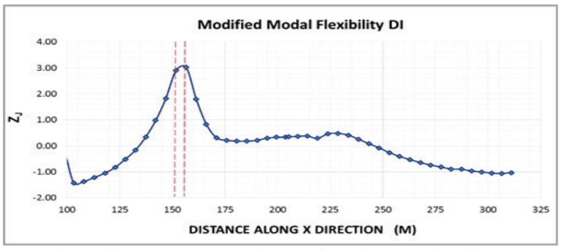

Fig. 8b. Damage detection in arch rib

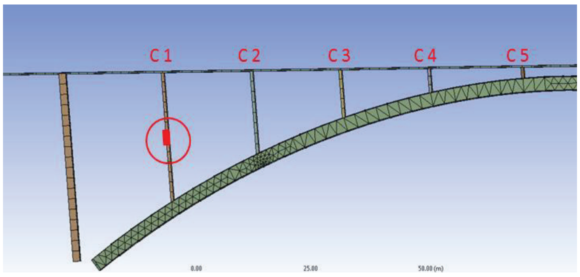

Fig. 9a. Damage in strut in arch bridge

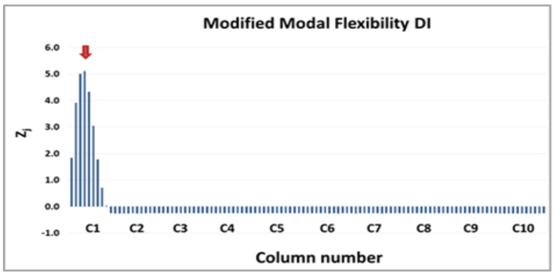

Fig. 9b. Damage detection in arch strut

Other damage scenarios, together with details of experimental testing, FE modelling and validation can be found in [6]. Damage detection in through type arch bridges will be similar with the hangers replacing the struts.

D. Damage Detection in a Dam

As shown in Fig. 10 dam structures are large structures. Damage in a dam structure can be catastrophic and must be avoided. It is quite possible that initial distress in a dam can be missed, and this can lead to dam failure. SHM research in dam structures is hence important to avert the drastic consequences of dam failure. Damage detection in a dam will involve 2 stages. First the damaged cross-section in this long structure must be identified and then the damage in that cross-section must be located. Towards this end, damage detection in a typical dam was carried out by using ABAQUS software and the MF based DI but, using either the vertical or the horizontal components of the mode shapes. Fig. 11a shows the FE model of the dam with base damage in section 2. Fig. 11b shows that both the component specific DIs can detect the damaged cross-section as well as the damage location accurately. More information on the method, FE modelling and damage detection at other locations can be found in [7].

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Fig. 10. Konya dam, India - 53 years, old

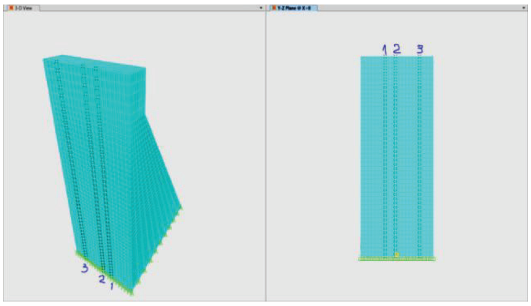

Fig. 11a. FE models of dam with base damage

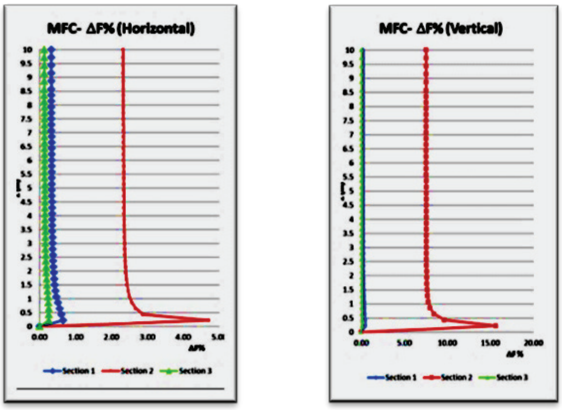

Fig. 11b. Damage detection with component specific DIs

E. Damage Detection in a Cooling Tower

Cooling towers are large shell structures, usually hyperbolic in shape, for cooling the hot wastewater from power generation plants. Image of the Stanwell cooling towers in Queensland, Australia, are shown in Fig. 12.

Fig. 12: Stanwell cooling towers, QLD. Australia

The interior and the upper part of these structures are either not visible or not accessible and hence a small undetected damage at those locations can grow and trigger a collapse of the cooling tower. These structures have rather complex vibration shapes with multiple symmetric modes. The absolute mode shape curvature method was found to be best suited for damage detection in hyperbolic cooling towers.

A coupled method involving the analysis of a few vertical cross-sections to locate the height of damage and the horizontal cross-section at that height was developed in ABAQUS software and validated using experimental results. A FE model of one of the Stanwell cooling towers is shown in Fig. 13.

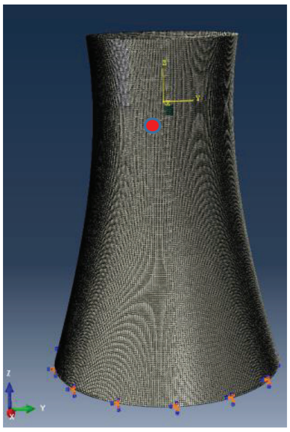

Fig 13. FE model of cooling-tower

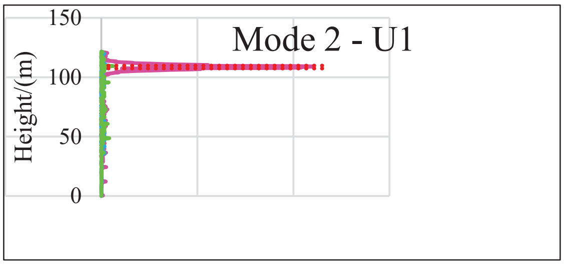

Fig 14. Damage in Stanwell cooling tower

In the proposed method the absolute change in the mode shape curvature (ACMSC) along a few vertical cross-sections of the cooling tower are plotted and the plot with the maximum peak indicates the damage location.

This method was used to detect damage in hyperbolic cooling towers in the height range 80m-200m. Results for the Stanwell cooling tower are presented herein. Fig. 13 shows the FE model of this cooling tower and the damage location. Fig. 15 shows the "best plot" of the DI with the peak indicating the correct damage location. Results for several other damage scenarios, details of the method and FE modelling are presented in [3].

IV. RESEARCH ADVANCEMENT

QUT initiated the Australian Network of Structural Health Monitoring (ANSHM) in 2009 in which many Australian and other universities, government agencies (which own and/operate infrastructure) and several industries such as those offering SHM services or dealing with instrumentation are members.

A living laboratory was established at QUT in 2010 when the new P Block (Fig. 15) was instrumented during its construction. The instrumentation measures deflections, settlements, and vibration (via accelerometers). These accelerometers continuously send data and will inform when there is any distress in the building, which can be attended to promptly. In September 2015, the sensor system was validated due to an earthquake of magnitude 5.5 that occurred at 125km north of QUT. Fig. 16 shows that the sensors picked up the excitation and the building was safe as evident from the vibration signature before and after the event. This living laboratory has been used in research and will be useful in the future to detect distress at onset when the P block deteriorates with age.

Fig 15: Fully instrumented P Block at QUT

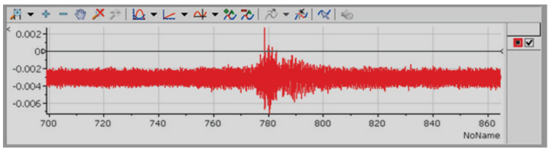

Fig 16: Vibration record before and after event

V. CONCLUSION

Civil structures are essential for the smooth functioning of cities. SHM has enabled to monitor structural health and address distress at the onset. This paper illustrated the application of VB SHM to detect and locate damage in a range of structures. Its outcomes will help towards their safety.

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