Vibration Based Structural Health Monitoring to Evaluate the Damage in Flexural Members

David P. Thambiratnam, Hoi Wai Shih, Tommy H.T. Chan, Zhi Xin Tan

***Abstract*—**Structures are built to last a long time. However, during their service life, they may suffer damage due to deterioration with age, changes in loading patterns and random actions such as impacts. This damage must be detected and assessed so that appropriate retrofitting can be carried out to prevent structural failure. Damage in a structure affects its stiffness and this in turn affects its vibration characteristics. This is the basis of vibration based structural health monitoring techniques which have emerged as a means of evaluating the health of a structure. This paper uses vibration based methods to develop and apply techniques to evaluate the damage in beam and plate structures that form important components in bridges and buildings. This paper selects two damage indices based on the vibration properties. These damage indices are called (i) modal flexibility and (ii) modal strain energy. Results show that these indices can successfully detect and locate damage in beam and plate structures. The success of this technique will enhance the safety and efficiency of structures and prevent unexpected and sudden collapse.

***Keywords*—**Beams, damage indices, plates, structural health monitoring, vibration characteristics.

I. Introduction

Mathematics and computers find increasing use in the development and application of techniques to analyze, design and monitor the performance of Civil Engineering systems in general and Structural Engineering systems in particular. Structural Engineering is an important part of Civil Engineering and deals with the design, analysis, construction, maintenance and retrofitting of structures such as buildings, bridges, pipelines, multi-purpose towers etc. Many of these systems are complex and require computer analysis based on sound mathematical models. In the new millennium, there are three major issues with structural engineering [1]. These are:

1. Vibration problems in slender structures such as thin floor structures, very long bridges and very tall towers which have emerged as a result of new materials technology and aesthetic requirements.
2. Random loadings such as blast, impact and seismic loadings on structures.
3. Aging structures whose health needs to be monitored so that onset of damage can be predicted and appropriate retrofitting can be carried out to prevent structural collapse.

Mathematics and computers have become indispensable to formulate the necessary theories and apply them in order to treat the above issues. This paper will describe and illustrate how mathematics and computers are applied in the area of structural health monitoring (SHM) to monitor the health of not only aging structures but also new structures. It will highlight some of our recent research in this area.

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II. Structural Health Monitoring

Civil infrastructure such as bridges, buildings, pipelines etc, is normally designed to have long life spans. Changes in load characteristics, deterioration with age, environmental influences and random actions may cause damage to structures. Continuous health monitoring of structures will enable the early identification of distress and allow appropriate retrofitting to prevent potential sudden structural failures. In recent times, Structural Health Monitoring (SHM) has emerged as an efficient means of evaluating the health of a structure and detects any damage to enable appropriate retrofitting. It can be defined as the process of evaluating the health and performance of a structure using an on-structure sensing system [2]. 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. The principle of VB methods is that the modal parameters (modal frequencies, damping and mode shapes) of a structure are functions of its stiffness and mass distributions. When there is structural damage, these parameters change which in turn cause variations in the modal parameters. Changes in vibration characteristics can also be correlated to the porosity in a concrete specimen [3]. The variations in modal parameters can hence be used as an effective indication of structural damage. There are four different levels in damage assessment [4]. They are damage detection (Level 1), damage localization (Level 2), damage quantification (Level 3), and prediction of the acceptable load level and the remaining service life of the damaged structure (Level 4).

Fast computers, advanced mathematical models and sophisticated finite element programs have enabled the growth

in SHM. This paper introduces two damage indices (DIs) for damage assessment in beam and plate structures which are important flexural members in buildings and bridges, in addition to using changes in natural frequency as an indicator of the presence of structural damage. This is because changes in frequency are very small even though there is a significant reduction in moment of inertia of a structure [5]. These DIs are based on the modal flexibility (MF) and the modal strain energy (MSE) which in turn depend on the vibration characteristics of natural frequencies and mode shapes of the structure. Variations of natural frequencies and mode shapes with the state of health of the structure will cause variations in DIs to enable damage assessment. The objective of this paper is to demonstrate the feasibility of the proposed method to identify and localize single and multiple damages in numerical models of the flexural members [6] and a slab-on-girder bridge [7]. Results show that SHM using these two DIs is effective in damage assessment of beam and plate structures, as well as slab-on-girder bridges. DI based on modal flexibility is also applied to the next level of damage assessment procedure which is Level 3, damage quantification. A linear relationship between damage intensity (in terms of damage length on beam in this case) and max DI based on MF for each damage case can be observed from the results. There is an ongoing research in quantifying damage severity using the DI based on MF in different regions of beam and the research will be extended to plate structures and then to slab-on-girder bridge structures.

A. Damage Detection using Modal Flexibility and Modal Strain Energy

A number of methodologies have been used to assess the damage in structures using numerical simulations with varying levels of success [4]. Pioneering work on the use of MF method was carried out by Pandey and Biswas who used experimental data to obtain an insight into how the MF is affected by the presence of damage in simple beam structures [8]. Patjawit and Kanok-Nukulchai had to develop a modified form of MF to detect the global health deterioration of a highway bridge using its dynamic response under forced vibration [9]. Cornwell et al. used MSE to detect damage in plate-like structures with the mode shapes before and after damage, obtained under ambient excitation [10]. Li et al. evaluated the performance of MSE based algorithm for detecting damage in a timber structure [11]. Their method was capable of detecting single damage but required modification for detecting multiple damages. Alvandi and Cremona studied the performance of both MF and MSE based methods for damage detection in a simply supported beam using the measured data from a few modes obtained under random force excitation [12]. They also assessed the performance of these techniques under different noise levels and concluded that both methods had limitations and were capable of detecting and localizing damage only under certain conditions.

Past research has shown that neither MF nor MSE by itself was capable of successfully detecting damage under all possible scenarios. A comprehensive research program carried out by the authors has shown that the combined use of DIs based on natural frequencies, MF and MSE enables successful detection and localization of damage in structures under a range of scenarios [4, 12]. This paper presents some of that research where DIs based on MF and MSE are chosen as (i) their corresponding algorithms can be applied to both beam and plate structures and (ii) good estimates of the corresponding DIs can be obtained with the inclusion of the first few frequencies and their associated mode shapes.

III. Theory – Use of Mathematics

A. DI Based on Modal Flexibility Abbreviations and Acronyms

Modal flexibility MF at location *"j"* includes the influence of both the mode shapes and the natural frequencies, as shown in Equation (1) below where summation in *"i"* includes the number of modes to be considered [13, 14].

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

In the above equation, $[\phi_{ji}]$ is the value of the *"i"*th mode shape at location *"j"* and $[1/\omega_i^2]$ is the reciprocal of the square of natural frequency at mode *"i"*. The 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 change in the MF due to structural deterioration is given by

$$\Delta F_j=[F_j]^d-[F_j]^h \quad (2)$$

where superscripts '*d* ' and '*h* ' refer to the healthy and damaged state respectively. Theoretically, structural deterioration reduces stiffness and increases flexibility and hence the DI based on the increase in structural flexibility can be used to assess the structural deterioration. The subscripts in all the above terms will be *"jk"* to indicate a location in a 2D plate structure.

B. DI Based on Modal Strain Energy

The strain energy U of a Bernoulli-Euler beam is given as follows:

$$U=\int \frac{EI}{2}\left(\frac{d^2y}{dx^2}\right)^2 dx \quad (3)$$

where x is the distance measured along the length of the beam, y is the vertical deflection, EI is the flexural rigidity of the cross section and d^2y/dx^2 is the curvature of the deformed beam. Deterioration of a structure results in a reduction of its stiffness which causes the changes in modal strain energy. The damage assessment method is based on the relative differences in modal strain energy between an undamaged and damaged structure. The equation used to calculate the damage index β_{ji} for the j^{th} element and i^{th} mode of a beam is given below [15].

$$\beta_{ji}=\frac{\left(\int_j[\phi_i''^*(x)]^2dx+\int_0^L[\phi_i''^*(x)]^2dx\right)\int_0^L[\phi_i''(x)]^2dx}{\left(\int_j[\phi_i''(x)]^2dx+\int_0^L[\phi_i''(x)]^2dx\right)\int_0^L[\phi_i''^*(x)]^2dx} \quad (4)$$

To account for all available modes, a DI for each location along the beam is given by

$$\beta_j = \frac{\sum_{i=1}^{NM} Num_{ji}}{\sum_{i=1}^{NM} Denom_{ji}} \quad (5)$$

where Num_{ji} = numerator of β_{ji} and $Denom_{ji}$ = denominator of β_{ji} in Eq. (4).

The strain energy of a plate of size a x b is given as follows:

$$U = \frac{D}{2}\int_0^b\int_0^a \left(\frac{\partial^2 w}{\partial x^2}\right)^2 + \left(\frac{\partial^2 w}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 w}{\partial x^2}\right)\left(\frac{\partial^2 w}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2 dxdy \quad (6)$$

where $D = Eh^3/12(1-\nu^2)$ is the bending stiffness of the plate, ν is the Poisson's ratio, h is the plate thickness, w is the transverse displacement of the plate, $\partial^2 w/\partial x^2$ & $\partial^2 w/\partial y^2$ are the bending curvatures, $2\partial^2 w/\partial x \partial y$ is the twisting curvature of the plate. If the plate is subdivided in the x and y directions, the energy U_{ijk} associated with the particular mode shape $\phi_i(x, y)$ in the sub-region jk for the i^{th} mode is given by

$$U_{ijk} = \frac{D_{jk}}{2}\int_{b_k}^{b_{k+1}}\int_{a_j}^{a_{j+1}} \left(\frac{\partial^2 \phi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)\left(\frac{\partial^2 \phi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_i}{\partial x \partial y}\right)^2 dxdy \quad (7)$$

so

$$U_i = \sum_{k=1}^{N_y}\sum_{j=1}^{N_x} U_{ijk} \quad (8)$$

where N_x and N_y are number of divisions in the x and y directions respectively. The fractional energy at location jk is defined to be

$$F_{ijk} = \frac{U_{ijk}}{U_i} \quad \text{and} \quad \sum_{k=1}^{N_y}\sum_{j=1}^{N_x} F_{ijk} = 1 \quad (9, 10)$$

Similar expressions can be written using the modes of the damaged structure ϕ_i^*, where the superscript * indicates damaged state. A ratio of parameters that is indicative of the change of stiffness in the structure can be determined as shown in Eqs. (11, 12). A complete derivation of the DIs for beam and plate can be found in [6, 10, 15].

$$\frac{D_{jk}}{D_{jk}^*} = \frac{f_{ijk}^*}{f_{ijk}} \quad (11)$$

where

$$f_{ijk} = \frac{\int_{b_k}^{b_{k+1}}\int_{a_j}^{a_{j+1}} \left(\frac{\partial^2 \phi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)\left(\frac{\partial^2 \phi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_i}{\partial x \partial y}\right)^2 dxdy}{\int_0^b\int_0^a \left(\frac{\partial^2 \phi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)\left(\frac{\partial^2 \phi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_i}{\partial x \partial y}\right)^2 dxdy} \quad (12)$$

and an analogous term f_{ijk}^* can be defined using the damaged mode shapes. In order to account for all measured modes, the following formulation of DI for sub-region jk is used:

$$\beta_{jk} = \frac{\sum_{i=1}^{m} f_{ijk}^*}{\sum_{i=1}^{m} f_{ijk}} \quad (13)$$

IV. Applications

As a single DI is not always reliable, especially in the case of multiple damages, the 2 DIs based on modal flexibility ΔF and modal strain energy β are used in the damage assessment of beam and plate structures. Initial beam and plate-like structures are first developed as Finite Element (FE) models and their modal responses are obtained using the FE software package SAP2000. After validation of these initial FE models, additional FE models of the beam and plate structures, first without damage and then with different damage patterns are selected for investigation. The beam is of steel with a length of 2.8m and cross-sectional dimensions of 40mm width by 20mm depth. The Young's Modulus, Poisson's ratio and mass density for the beam structure are 200GPa, 0.3 and 7850kg/m^3 respectively. It is modelled using plane stress elements. The plate is also of steel with dimensions of 2.5m long x 1m wide and 2mm thick. The Young's Modulus, Poisson's ratio and mass density for the plate structure are 210GPA, 0.3 and 7800kg/m^3 respectively.

A. Damage Scenrios and Validation of Techniques

As shown in Fig. 1, two damage sizes, size A and size B can be observed. Size A represents a smaller damage size than size B. Dimensions of size A are 10mm long x 5mm deep x 40mm wide while dimensions of size B are 20mm long x 5mm deep x 40mm wide. Fig. 1a represents a single damage at mid-span of a single-span beam while Fig. 1b shows a two-span continuous beam structure with size A and size B damages at the middle of the first and second spans respectively. To simulate damage on the beam structures, the selected damaged elements are removed from the bottom of the beams in the FE models. The damage in the plate as illustrated in Fig. 2 is simulated by reducing the Young's Modulus of the selected element by 80%.

The primary modal parameters of natural frequencies and mode shapes of the first five modes of these structures, before and after damage, are extracted from the results of the FE analysis. These parameters are then used to determine the DIs and thereby assess the damage state of the test structure. The peak values of the parameter in each method indicate the location of simulated damage in the corresponding damage scenarios. The accuracy of the damage detection method is then evaluated through observations of the plots. The details of modal testing and FE modelling on beams and plates are described elsewhere [6].

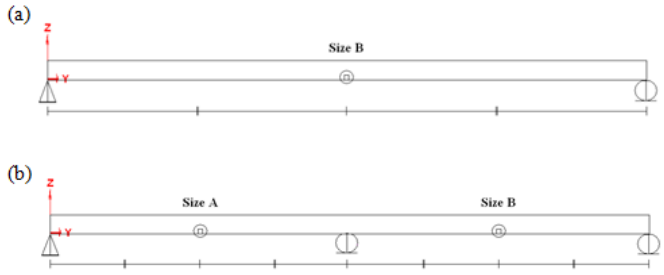


Fig. 1 Damage in Beam Structure: (a) Single Damage; (b) Double Damage

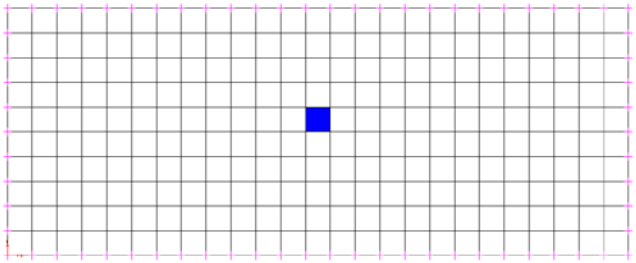
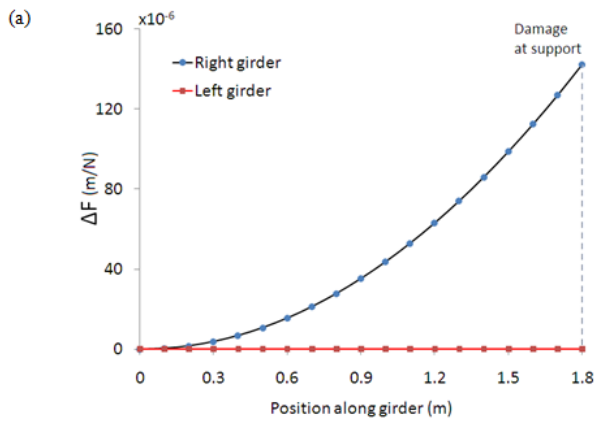


Fig. 2 Damage in Plate Structure

Experimental testing of a single-span slab-on-girder bridge model was conducted to validate the modelling techniques and to establish the feasibility of the procedure. The bridge model consists of beam-like and plate-like components. Experiments were conducted on the bridge model both in the healthy and damaged states under free vibration. Damage is induced on the experimental bridge model by physically removing the base plate of the right hand support to simulate settlement. The experimental results for natural frequencies and associated mode shapes compared reasonably well with the results from the FE analyses. The measured natural frequencies and associated mode shapes obtained from the testing were then used to calculate the DIs and the results confirm the damage scenario. Figs. 3a and 3b show the plots of MF and MSE along the two bridge girders. It is evident that the two plots clearly indicate the location of the support damage. The details of model testing and validation of the modelling techniques as well as establishing the ability of the chosen DIs to detect damage in slab-on-girder bridge model are described elsewhere [7]. These findings provide confidence in the numerical techniques used and hence the proposed damage detection procedure was applied to a full size slab-on-girder bridge with different damage scenarios.



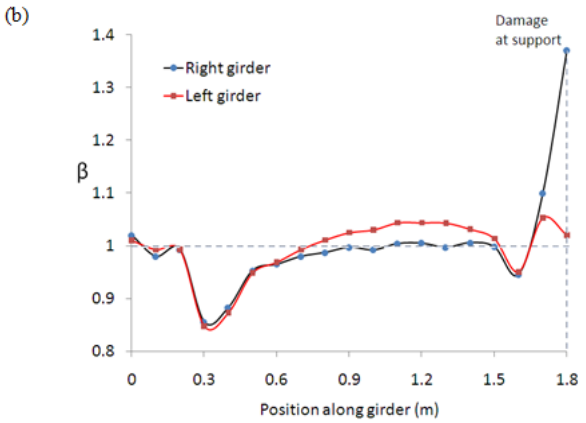


Fig. 3 Location of Support Settlement: (a) Plots of MF based DI (ΔF); (b) Plots of MSE based DI (β)

The full scale single-span slab-on-girder bridge simulated in the FE software, SAP2000 is comprised of a 4m wide and 20m long concrete deck supported on two 20m long steel plate girders with depth of 1.5m. The spacing between twin steel girders is 3m. The thickness of concrete deck is 200mm while the thickness of steel girder is 8mm. Steel diagonal bracings are installed between girders at a spacing of 1m to provide lateral restraint for slab and also stability for twin girders. Fig. 4 shows an isometric view of the FE model.

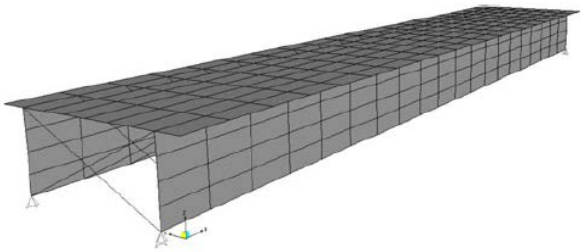


Fig. 4 Isometric View of Finite Element Model

The concrete deck is modelled using the Young's Modulus, Poisson's ratio and mass density of 24GPa, 0.2 and 2400kg/m^3 respectively. The Young's Modulus, Poisson's ratio and mass density used to model the steel girders are 200GPA, 0.3 and 7800kg/m^3 respectively. Both deck and girders are modelled using shell elements. Steel diagonal bracings between girders are modelled as truss elements with the dimensions of 3354mm x 20mm x 6mm. The twin girders are simply supported at their ends and it is assumed that there is a complete connection between the girders and slab. Damage on the girder is simulated by removing a selected element of size 500mm x 375mm from the bottom of the girder. Fig. 5 shows two damage elements on the girders, one at the three quarter-span of the right 'R' girder and the other at the mid-span of the left 'L' girder.

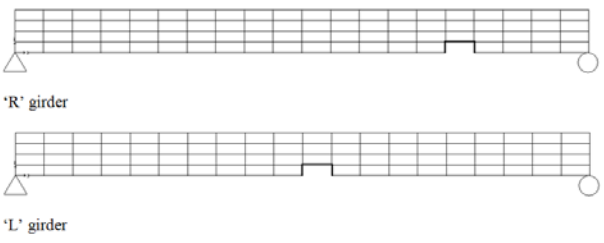


Fig. 5 Damage in Slab-on Girder Bridge

B. Damage Detection in Beam Structure

The first five natural frequencies and associated mode shapes obtained from the results of the FE analysis are used to calculate the 2 DIs by using Eqs. (2) & (5) respectively. The plots of DIs based on MF (ΔF) and MSE (β) along the beam are shown in Figs. 6 and 7 for the single and dual damage cases respectively. It is evident that in all cases, the peak values indicate the location of damage in the beam structure. Furthermore, it can be noticed that peaks of both the MF (ΔF) and MSE (β) plots are lower when the damage size is smaller.

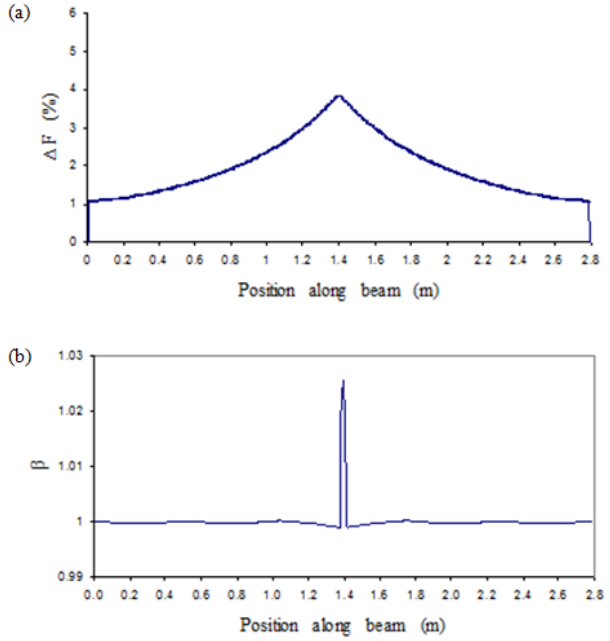


Fig. 6 Damage Detection in Beam – Single Damage: (a) Plots of MF based DI (ΔF); (b) Plots of MSE based DI (β)

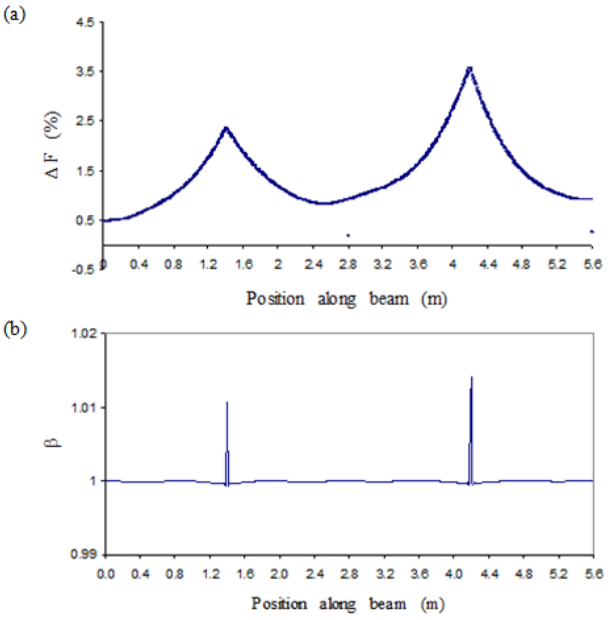


Fig. 7 Damage Detection in Beam – Double Damage: (a) Plots of MF based DI (ΔF); (b) Plots of MSE based DI (β)

C. Damage Detection in Plate Structure

The plots of the DIs based on MF (ΔF) and MSE (β) across the plate are shown in Fig. 8. Again in both cases, peak values indicate the location of damage in the plate structure and confirm that the chosen damage detection algorithms for the two DIs are able to locate the damage in the plate structure correctly.

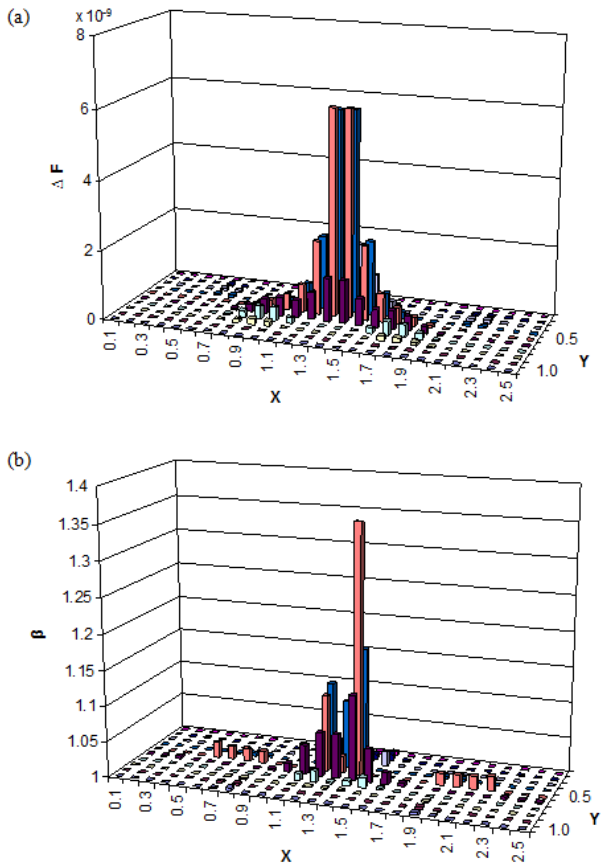


Fig. 8 Damage Detection in Plate Structure: (a) Plots of MF based DI (ΔF); (b) Plots of MSE based DI (β)

The results confirm that the DIs based on MF and MSE can successfully detect and locate damage in beam and plate structures. Several other cases were also treated to establish this feature. It was evident that neither DI by itself was capable of successfully detecting damage in all cases, especially under multiple damage scenarios. A combination of the two damage indices hence offers the best option to successfully detect damage. Results for the other damage cases can be found in [6]. These principles were then applied to treat damage detection in a full scale slab-on-girder bridge structure. Once again, the results confirmed the combined capability of the two chosen damage indices (DIs) to successfully detect and locate damage [7].

D. Damage Detection in Slab-on-Girder Bridge

The plots of the DIs based on MF (ΔF) and MSE (β) along both the left 'L' and right 'R' girders are shown in Fig. 9. The peaks of MF, shown in Fig. 9a correspond to damage locations. Peaks in the plotted MSE (β) curve that exceed the defined damage limit of 1.005 indicate the damage location. It is clearly evident that Fig. 9b shows distinct peaks at damage

locations. These features confirm that the proposed damage detection algorithms using MF and MSE are able to accurately locate the damages in slab-on-girder bridges.

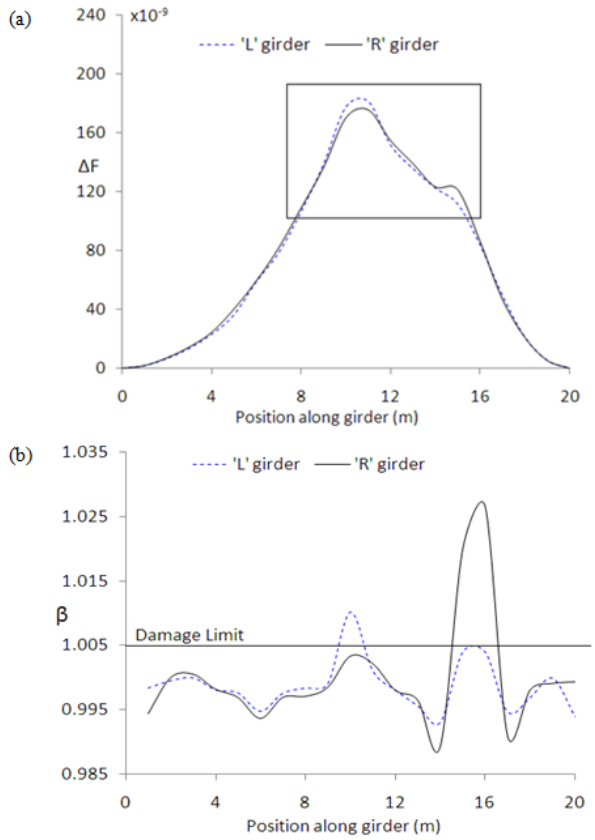


Fig. 9 Damage Detection in Slab-on-Girder Bridge Structure – Double Damage: (a) Plots of MF based DI (ΔF); (b) Plots of MSE based DI (β)

The results confirm that the damage assessment algorithms using the two DIs based on MF and MSE can be extended to the slab-on-girder bridge structure and are able to successfully detect and locate multiple damages in this structure. Results for the other damage scenarios can be found in [7].

E. Damage Quantification in Beam Structure

Research is in progress to quantify the damage first in beam and plate structures and then in slab-on-girder bridges. This section reports the early part of the research carried out towards this end. It has been carried out through FE simulations on the same simply supported beam structure with damage at mid-span as in Fig. 1a. Effects of different damage lengths induced at mid-span of the beam on the DI based on MF (ΔF) are investigated. To simulate different damage intensities, the selected damaged elements are removed from the bottom of the beams in the FE models based on the damage lengths considered. The lengths of damages investigated at mid-span are 10mm, 50mm and 100mm. All damaged elements have depth of 5mm and width of 40mm.

By using only the first mode, the corresponding natural frequency and mode shape obtained from the FE analysis are applied into Eq. (2). The plots of DI based on MF (ΔF) along the beam for varying damage lengths are illustrated in Fig. 10a. These plots show that the peaks conform to centres of the damage locations and the peaks are more apparent when the damage intensity (in terms of length) increases.

Furthermore, a linear relationship between damage intensity and max ΔF for each damage case can be observed in Fig. 10b. This shows that MF has the capability of quantifying damage severity.

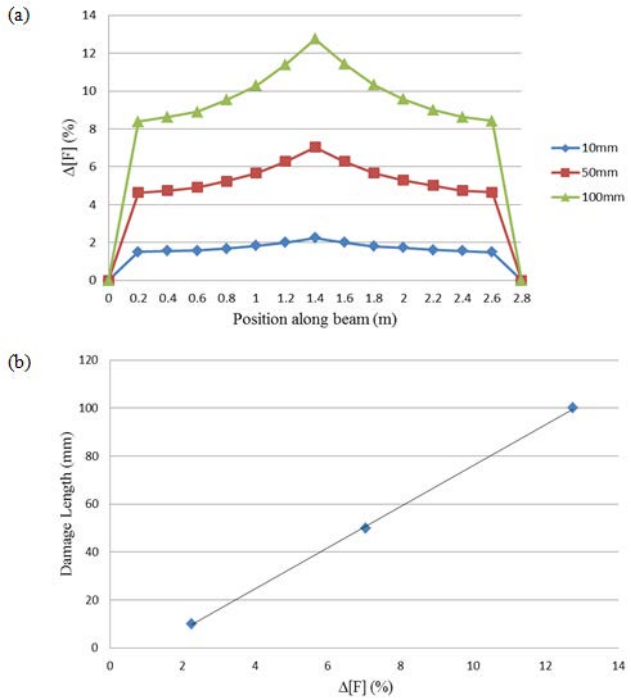
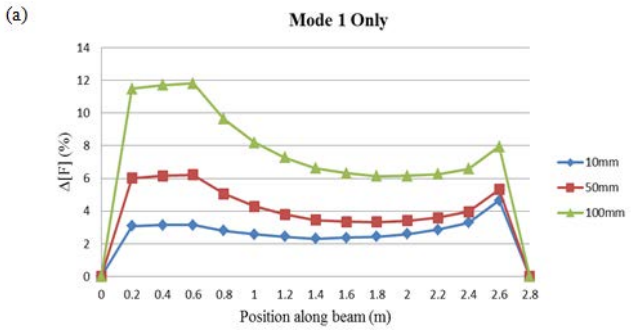


Fig. 10 Damage in Beam Structure at Mid-Span: (a) Plots of MF based DI (ΔF); (b) Plots of Max ΔF for Different Damage Lengths

Similar procedure (using only the first mode) is then carried out at the quarter-span of the simply supported beam structure. This is to determine the effects of varying damage lengths on the plots of MF (ΔF) when the damage is induced at a different location in the beam. Actual damage location is at 0.6m. As illustrated in Fig. 11a, false alarms of damage exist at 2.6m for all damage scenarios. The actual damage location is not obvious when the damage intensity is small and probably because only a single mode was used in the damage detection process. However, a linear relationship between damage length and ΔF at damage location (0.6m in this case) can be noticed in Fig. 11b.



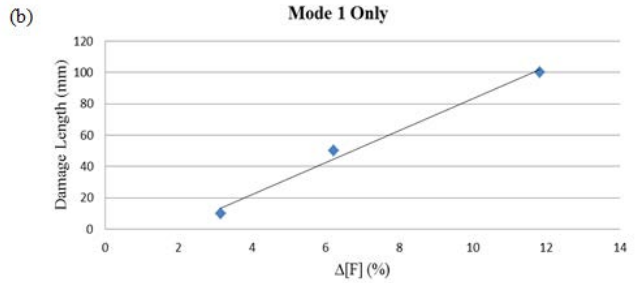


Fig. 11 Damage in Beam Structure at Quarter-Span using only Mode 1: (a) Plots of MF based DI (ΔF); (b) Plots of ΔF at 0.6m for Different Damage Lengths

The same amount of damage is simulated again using the same FE models, but the first 5 modes are used for damage analysis. Accordingly, the natural frequencies and the corresponding mode shapes of the first 5 modes are used to calculate and plot ΔF along the beam. Although false alarms still occur at 2.6m, more significant peaks of MF (ΔF) plots can be observed at the actual damage location, especially when greater damage intensities are induced, as illustrated in Fig. 12a. Fig. 12b shows a better result of a linear relationship between damage length and ΔF at actual damage location when more modes are used in the calculation as all the points are closer to the trend line. Although more modes give a better result, it is more practical to use fewer modes as experimental results provide only the first few modes [16]. This shows that MF is capable of quantifying damage severity once the damage has been detected and located.

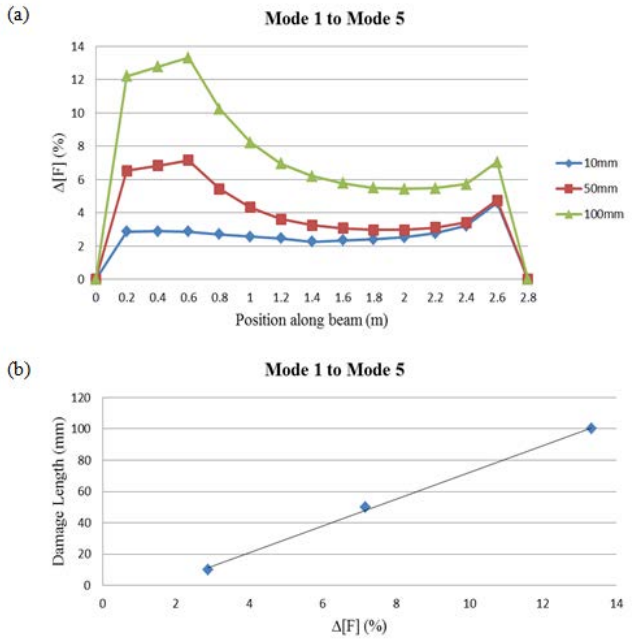


Fig. 12 Damage in Beam Structure at Quarter-Span using Mode 1 to 5: (a) Plots of MF based DI (ΔF); (b) Plots of ΔF at 0.6m for Different Damage Lengths

V. Conclusion

This paper is a demonstration on how mathematics and computers find use in modern structural engineering applications. Vibration based techniques have evolved to enable structural engineers to monitor the performance of structures and to detect damage. Appropriate retrofitting can then be carried out to prevent structural failure. This paper uses dynamic computer simulation techniques to develop and apply two damage indices based on modal flexibility and modal strain energy to detect and assess damage in beam and plate structures which are important flexural members in buildings and bridges. The procedure for damage detection and localization in a structure or a structural component is as follows: (i) develop and validate a Finite Element (FE) model of the structure, (ii) store its vibration data (frequencies and mode shapes) in its healthy state obtained from the physical structure, complemented and supplemented by that from the FE model, (iii) when damage occurs, there will be a change in the vibration data which will alert the presence of damage (iv) vibration data from the damaged physical model and the validated FE model are used to calculate the chosen DIs, (v) the DIs are plotted along the structure to locate the damage. Visual inspection of the damage will then enable to decide on the necessary retrofitting.

This paper also reports the application of the proposed DIs to detect and locate damage in a slab-on-girder bridge and the early research in determining the severity of damage. The results to date on detecting, locating and quantifying damage using the chosen vibration based DIs, have been promising and work is in progress to develop a comprehensive damage assessment procedure for slab-on-girder bridges which form the majority of bridge structures. The procedure can then be extended to buildings. It is believed that the proposed damage detection procedure will enhance the safety and performance of structures and prevent their sudden and unexpected collapse.

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