Comparative Study of Damage Detection in Symmetric and Asymmetric Buildings

Y. Wang[1], D.P. Thambiratnam[1], T.H.T. Chan[1], and A. Nguyen[1]

[1] Queensland University of Technology, Brisbane, Australia

ABSTRACT: Aesthetics and functionality requirements have made most buildings asymmetric in recent times. Such buildings exhibit complex vibration under dynamic loads as there is coupling between the lateral and torsional components of vibration, and are referred to as torsionally coupled buildings. These building require three dimensional modelling and analysis. In spite of much recent research and some successful applications of damage detection and assessment methods to civil structures in recent years, the applications to asymmetric buildings remains a challenging task for civil engineers. Less investigation has been made on the methodologies for detecting and locating damage specific to torsionally coupled asymmetric buildings. This paper aims to investigate and compare the difference in vibration behavior between symmetric and asymmetric buildings and the use of vibration characteristics for predicting damage in them. The need for developing a special method to detect damage in asymmetric buildings becomes evident. Towards this end, the paper presents a technique based on a modified version of the traditional modal strain energy method. The modified approach is developed from Stubbs' modal strain energy damage index by decomposing the mode shape into lateral and vertical components. The procedure is illustrated through numerical studies conducted on a three dimensional five-story symmetric and asymmetric frame structure with the same layout. Vibration parameters obtained from finite element analysis of the intact and damaged building models are then applied into the proposed algorithms for detecting and locating the damage in these buildings.

1 INTRODUCTION

An asymmetric building can be defined as one in which there is either geometric, stiffness or mass eccentricity. Dynamic behavior of asymmetric building may cause interruption of force flow and stress concentration (Ansari and Bhole, 2016). Due to this, there is produce of torsion in the building which leads to increase in shear force, lateral deflection and ultimately causes failure. The development of a robust technique for early damage detection and localization for these structures is crucial in order to avoid the possible occurrence of a catastrophic structural failure. Traditionally, damage in civil structures were often assessed by visual inspection or Non-Destructive Testing (NDT) techniques such as X-ray and ultrasonic waves to measure cracks and permanent deformations (Dowling and Rummey, 2004). Some major drawbacks are that all of these techniques require that the damaged region is readily accessible, and collected data may not be enough for effective prediction of the remaining life of a structure. This has led to the development of methods that examine changes in the vibration characteristics of the structure (Chan et al., 2011). Vibration Based Damage Identification (VBDI) methods have effectively addressed the drawback of traditional methods. Many VBDI methods basically rely on measuring the vibration properties such as natural frequencies and mode shapes. The collected data is analyzed which can then be used solely or along with the numerical model of the structure to detect and locate damages. Initially, implementation and operation of VBDI techniques have been mainly in aircraft structures, railway systems and other machinery (Balageas et al., 2006). In the past decades, civil engineers have made great effort to identify damage in civil structures. Most of the existing studies on identifying vibration based damage were verified by numerical or non-in-situ experimental simulations. Generally, the performance of a damage indicator or a damage identification technique depends on the type of structures (Shih et al., 2011) . The structures that received greatest research interest include beams, plate elements, trusses, offshore platforms, and bridges. Despite the many successful applications in those structures in recent years, the identification of damage in complex structures such as buildings, especially asymmetric buildings remains a challenging task for civil engineers. There is less investigation on the methodologies for detecting and locating damage specific to torsionally coupled asymmetric buildings.

Modal Strain Energy (MSE) based method was first developed by Stubbs and Kim (1996), (1995). It has been successfully applied to data from a damaged bridge and has been found to be the most accurate algorithm in comparison with several other algorithms being currently investigated (Li et al., 2006). The principle of this method is that damage reduces structure stiffness and hence changes the strain energy. This method has been used in further studies by Law et al. (1998) to detect and locate damage in structures with incomplete and noisy measured modal data. The proposed method was validated by undertaking a laboratory experiments on a two storey steel frame structure. The experiment was divided into three stages: (1) expanding of the measured mode shapes, (2) locating damage using elemental strain energy difference, and (3) quantifying damage based on sensitivity of natural frequency. Results showed that the proposed method was capable of detecting and quantifying single or multiple damages in the experimental structure. Au et al. (2003) further extended the method developed by Law et al. (1998) in damage identification by adopting a micro-genetic algorithm in the damage quantification stage. Shi et al. (1998), (2000) proposed a damage localization technique using the MSE Change Ratio (MSECR) of each structural element. This method only requires mode shapes and elemental stiffness matrix. The application of the proposed method to a truss structure and a two-storey frame structure demonstrated the capability of this method in locating single and multiple damages.

The focus of the present study is to evaluate and compare the dynamic behavior and the use of modal strain energy method for damage locating in symmetric and asymmetric framed structures. It adopts two structures (i) 5 storey symmetric structure and (ii) 5 storey asymmetric structure which are modelled and analyzed utilizing ANSYS software (ANSYS Inc., 2011).

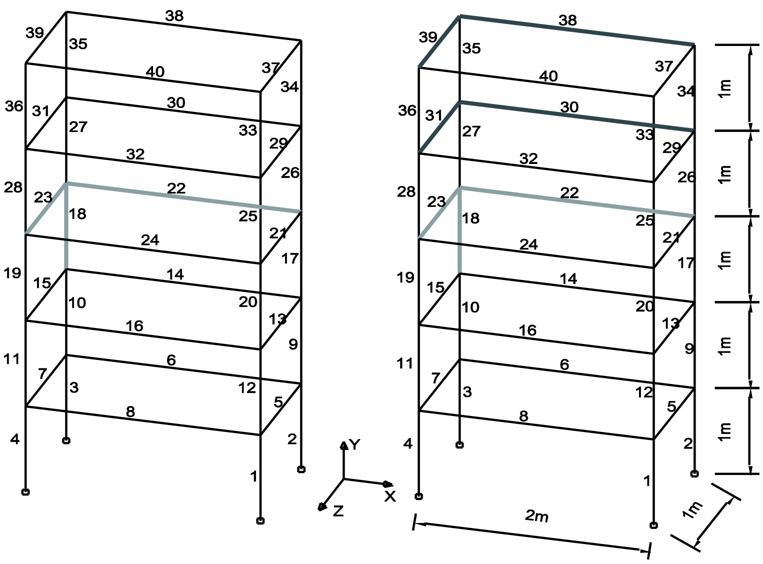
2 MODELS CONSIDERED FOR STUDY

2.1 *Symmetric model*

A 3 dimensional five-storey symmetric frame structure (Li et al., 2006) is considered and simulated using Finite Element software ANSYS as presented in Figure 1(a). The lengths of the members are presented in Figure 1. Young's modulus is equal to 2.1×10^{11} Pa for all members, and the cross section area for all members is $A=2.825\times10^{-3}$ m^2.

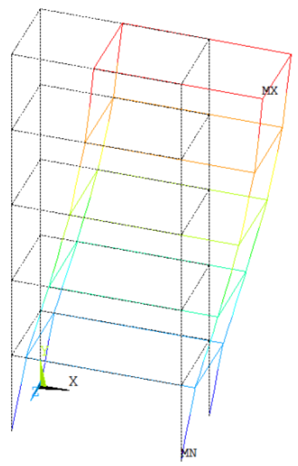
2.2 *Asymmetric model*

The asymmetric frame structure is designed by doubling the density of beam elements (30, 31, 38, and 39) as show in Figure 1(b). All the other properties are same as symmetric model.

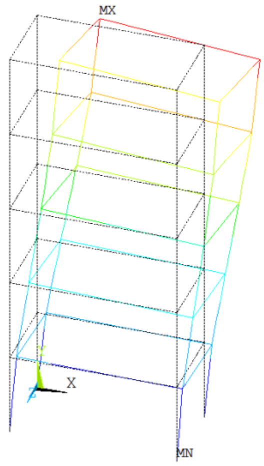


(a) Symmetric building model (b) Asymmetric building model

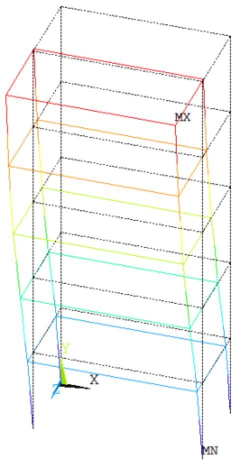
Figure 1 3D Structural diagrams of two building models



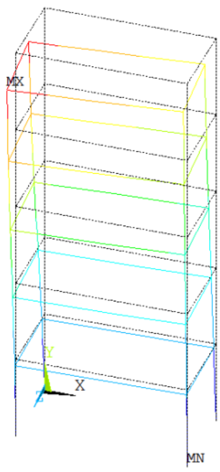
(a) Mode 1of symmetric model



(b) Mode 1of asymmetric model



(c) Mode 2 of symmetric model



(d) Mode 2 of asymmetric model

Figure 2 Typical mode shapes of two models

3 NUMERICAL ANALYSIS

It has been observed that for the first two mode shapes, the behavior of the developed structures is significantly different for symmetric and asymmetric condition. Comparison of first 2 mode shapes of symmetric and asymmetrical framed structures are shown in Figure 2.

For the symmetric building, the first mode vibrate along the long side direction and the second mode in the short side direction, it is realized that the first mode should vibrate in the 'weak' side of the structure. In the current numerical example, the weak side is in the long side direction; when all cross sections and material properties remain identical for all beams, the stiffness of those beams are inversely proportional to their lengths.

For the asymmetric building, it is clear that the first mode should vibrate dominantly in the long side direction however the joint displacements are considerably decreased compared to symmetric building and it is coupled with torsion in clockwise direction due to the mass eccentricity. The second mode vibrates dominantly in the short side direction; and as with the first mode, the amplitudes of the joint displacement also decrease and are coupled with torsion in the anti-clockwise sense.

The following damage scenarios are considered to further investigate the effects of torsional coupling in damage detection of the two different structures. Three single-damage cases have been proposed (1) Damage in a long span beam – element 22, (2) damage in a short span beam – element 23, and (3) damage in a vertical column – element 18.

4 DAMAGE DETECTION METHODS

In order to compare the difference between symmetric and asymmetric buildings in damage detection, the earlier modal strain energy based methods which proposed by Stubbs et al. (1995) is used in this study. The damage localization indicator β_{ij} can be defined to be the ratio of the strain energy of the intact structure to that of the damaged structure E_j/E_j^d . It can be obtains as

$$\beta_j = \frac{E_j}{E_j^d} = \frac{\sum_{i=1}^{Nm}\left\{\left(\Phi_i^{dT} K_{j0} \Phi_i^d + \Phi_i^{dT} K_0 \Phi_i^d\right)\Phi_i^T K \Phi_i\right\}}{\sum_{i=1}^{Nm}\left\{\left(\Phi_i^T K_{j0} \Phi_i + \Phi_i^T K_0 \Phi_i\right)\Phi_i^{dT} K \Phi_i^d\right\}} \tag{1}$$

For a more robust damage detection criterion, the normalized indicator is given by

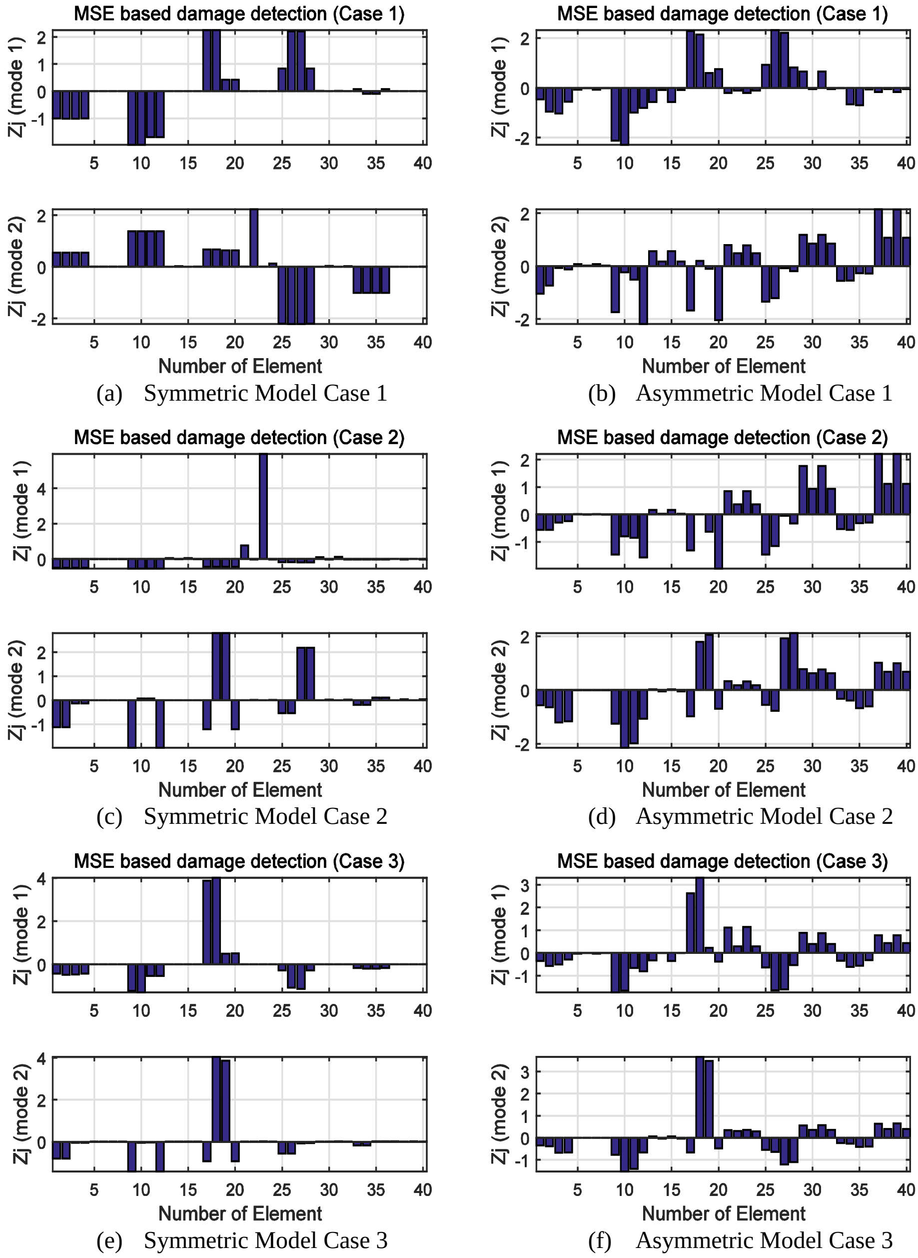
$$Z_j = \frac{\beta_j - \bar{\beta}}{\sigma_\beta} \tag{2}$$

where K_j is the element stiffness matrix, K_{j0} contains only geometric quantities and K is the system stiffness matrix which assembles all element stiffness matrices. Φ_i is the i^{th} intact mode shape and Φ_i^d is the i^{th} damaged mode shape.

4.1 Results and discussions

4.1.1 Damage Case 1

The first scenario is damage in long span beam element 22 with 5% loss of Young's modulus. Figure 3(a) shows the results for the symmetric model. In the first mode, the vibrating is dominated in x-direction. It is hence reasonable to have a larger value of the damage index in column elements 17, 18, 26, and 27, as their nodal coordinates are shared in this structure. So the damage is not only expected to be detected in the damaged member itself, but also in the members connected to it. And as the first mode predominantly vibrates in the long side direction, all long-span beams are (with negligible deformation) moving along with the columns; however, all short-span beams exhibit noticeable elongation and contraction especially those at upper floors to hold together the two planar frames formed by the long-span beams and columns. So in this case it is expected that the long-span beam damage could be influenced by the second mode which vibrates in z-direction (short-span direction), and this has been proved by the results using the second mode.



(a) Symmetric Model Case 1 (b) Asymmetric Model Case 1

(c) Symmetric Model Case 2 (d) Asymmetric Model Case 2

(e) Symmetric Model Case 3 (f) Asymmetric Model Case 3

Figure 3 Compare results of the symmetric and asymmetric models

Figure 3(b) presents the results of asymmetric model. As it presented in the first mode, due to torsional coupling the damage presented in the column element which connects to the damage beam has a tendency to propagate to the column elements 19, 20, 25, and 28 through the beam connected to them. It is clearer to see this trend from the second mode. It can be seen that due to the torsional coupling, the damage in long-span beam 22 has been propagated to all beam element of the model and the severity has a tendency to increase from lower level to upper level.

4.1.2 Damage Case 2

The second scenario is damage in a short-span beam element 23 with 5% loss of Young's modulus. The results are presented in Figure 3(c) & (d). This damage has been successfully identified by the first mode of the symmetric model which vibrates in the x-direction. It confirms with the previous discussion that a mode vibrating predominantly in the z-direction must be utilized in calculation to locate a damaged long-span beam. Similarly the results of asymmetric model also confirms well with the discussion of the first scenario.

4.1.3 Damage Case 3

In this case as shown in Figure 3(e), the vibration of the first mode in the symmetric model is mainly in the x-direction. In view of the relative position between elements 17 and 18, it is reasonable that element 17 vibrates at a magnitude comparable to that of element 18. Therefore, when damaged element 18 has a large value, it is logical to have a large value on element 17 as well. In many ways, the second mode displays similar features as first mode. Because the direction of the vibration is now mainly in the z-direction, large values (of the damage index) are evident at elements 18 and 19, in contrast to elements 17 and 18 in the first mode.

The results of asymmetric model are present in Figure 3(f). Similarly to the damage case 1, damage of the column element has been propagated to all beam elements of the model due to the torsional coupling.

4.2 Method development

From the results presented in the above section, it is evident that, due to torsional coupling, the effect of damage in a beam element has a tendency to influence the other beam elements connected to it. This tendency is different to what occurs in symmetric buildings in which damage in a beam does not influence the other beams in the vicinity. Such a feature was also evident with columns in an asymmetric building. Probably due to their complex behavior, considerably less work is reported in the literature on detecting and locating damage specific to torsionally coupled asymmetric buildings. It is therefore timely to address the problem of detecting and locating damage in such common but rather complicated building structures.

Structural members of an asymmetric frame structure predominantly have two types of elements (1) horizontal members (beams) and (2) vertical members (columns). Normally vibration modes of a building structure are mainly horizontal instead of vertical; in this case MSE change in the vertical members would be dominated by the lateral MSE. On the other hand, MSE change of the horizontal members would be contributed significantly by the vertical MSE (Li et al., 2006). Therefore in this study two damage indicators, a lateral damage indicator and a vertical damage indicator, are formulated by decomposing Stubbs' damage index. The modified damage indicator could rewritten as

$$\beta_j^L = \frac{\sum_{i=1}^{Nm}\left\{\left(\Phi_i^{LdT} K_{j0} \Phi_i^{Ld} + \Phi_i^{LdT} K_0 \Phi_i^{Ld}\right) \Phi_i^{LT} K \Phi_i^{L}\right\}}{\sum_{i=1}^{Nm}\left\{\left(\Phi_i^{LT} K_{j0} \Phi_i^{L} + \Phi_i^{LT} K_0 \Phi_i^{L}\right) \Phi_i^{LdT} K \Phi_i^{Ld}\right\}} \tag{3}$$

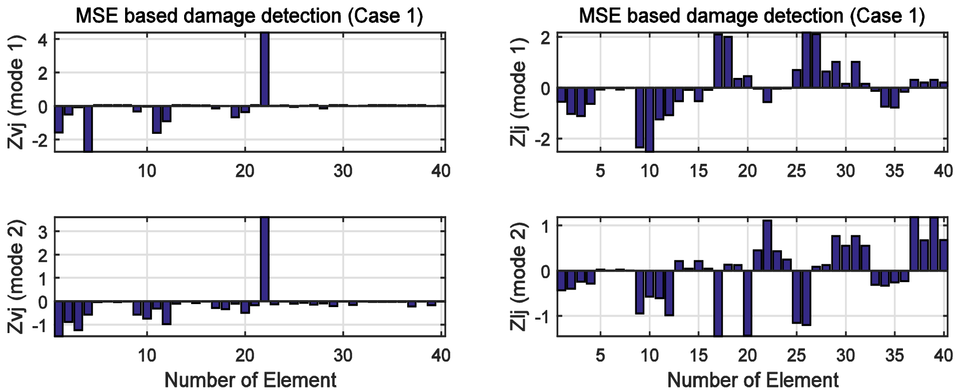
$$\beta_j^V = \frac{\sum_{i=1}^{Nm}\left\{\left(\Phi_i^{VdT} K_{j0} \Phi_i^{Vd} + \Phi_i^{VdT} K_0 \Phi_i^{Vd}\right) \Phi_i^{VT} K \Phi_i^{V}\right\}}{\sum_{i=1}^{Nm}\left\{\left(\Phi_i^{VT} K_{j0} \Phi_i^{V} + \Phi_i^{VT} K_0 \Phi_i^{V}\right) \Phi_i^{VdT} K \Phi_i^{Vd}\right\}} \tag{4}$$

Then the modified normalized indicator is defined as

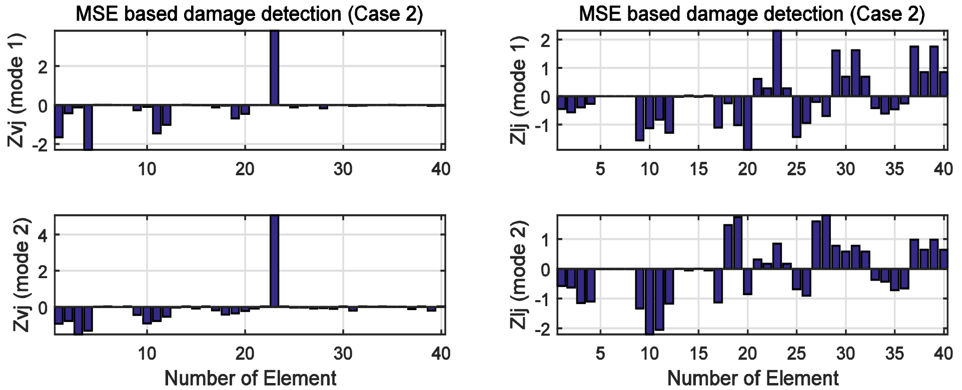
$$Z_j^L = \frac{\beta_j^L - \overline{\beta^L}}{\sigma_{\beta^L}} \qquad (5)$$

$$Z_j^V = \frac{\beta_j^V - \overline{\beta^V}}{\sigma_{\beta^V}} \qquad (6)$$

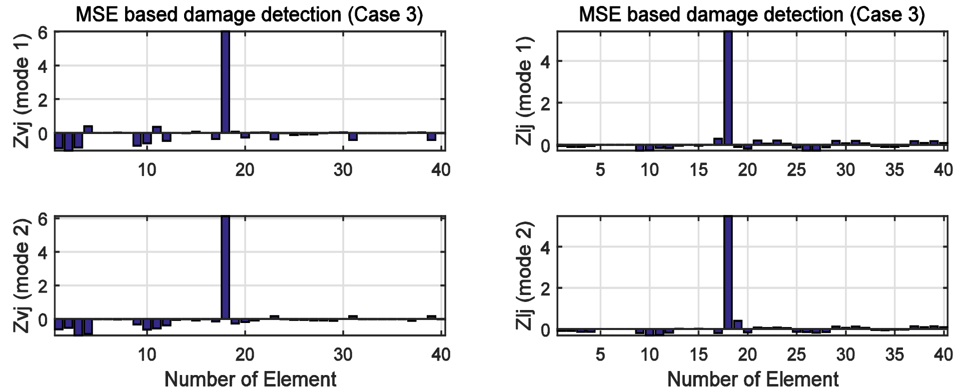
where Φ_i^L is the i^{th} intact mode shape using only the lateral components and Φ_i^V is the i^{th} intact mode shape ultilizing only the vertical components.



(a) Vertical damage indicator (case 1) (b) Lateral damage indicator (case 1)



(c) Vertical damage indicator (case 2) (d) Lateral damage indicator (case 2)



(e) Vertical damage indicator (case3) (f) Lateral damage indicator (case 3)

Figure 4 Damage detection results using the modified method

The proposed method has been evaluated through numerical study. The results show that the vertical damage indicator is good at locating damage in horizontal beam elements as shown in Figure 4(a) and 4(c); while the lateral indicator is good at locating damage in vertical column element as shown in Figure 4(f), which confirm that proposed modified method is capable of localizing the damage in this asymmetric building structure.

5 CONCLUSION

Comparative investigation of damage detection in three-dimensional symmetric and asymmetric building was conducted. First the dynamic behavior of two proposed models was briefly reviewed. Next, the comparison of damage detection results between the symmetric and asymmetric model was made. Based on these findings, a modified approach was developed from Stubbs' modal strain energy damage index by decomposing it into two separate damage indices that use either the lateral or vertical components of the mode shapes. These modified damage indices are well suited for damage detection in asymmetric buildings, as demonstrated through the examples treated above. It can then be concluded that (1) different from the symmetric building model, there is torsional coupling in both the first two modes of the asymmetric model, (2) due to torsional coupling in the structure, the damage in one member of the structure has a tendency to influence the other elements connected to it and (3) the modified method is effective in detecting damage in both the horizontal and vertical members of the asymmetric building model.

6 REFERENCES

Ansari, S. J., and S. Bhole 2016. Comparative Study of Symmetric & Asymmetric L-Shaped & T-Shaped Multi-Storey Frame Building Subjected to Gravity & Seismic Loads with Varying Stiffness. *International Journal of Science Technology & Engineering,* 2**,** 734-742.

Ansys Inc. 2011. ANSYS Mechanical APDL Academic Research. Canonsburg PA.

Au, F., Y. Cheng, L. Tham, and Z. Bai 2003. Structural damage detection based on a micro-genetic algorithm using incomplete and noisy modal test data. *Journal of Sound and Vibration,* 259**,** 1081-1094.

Balageas, D., C.-P. Fritzen, and A. Güemes 2006. *Structural health monitoring*, Wiley Online Library.

Chan, T. H., K. Wong, Z. Li, and Y.-Q. Ni 2011. Structural health monitoring for long span bridges: Hong Kong experience and continuing onto Australia. *Structural Health Monitoring in Australia***,** 1-32.

Dowling, L., and G. Rummey 2004. Guidelines for Bridge Management: Structure Information.

Law, S., Z. Shi, and L. Zhang 1998. Structural damage detection from incomplete and noisy modal test data. *Journal of Engineering Mechanics,* 124**,** 1280-1288.

Li, H., H. Yang, and S.-L. J. Hu 2006. Modal strain energy decomposition method for damage localization in 3D frame structures. *Journal of engineering mechanics,* 132**,** 941-951.

Shi, Z., S. Law, and L. Zhang 1998. Structural damage localization from modal strain energy change. *Journal of Sound and Vibration,* 218**,** 825-844.

Shi, Z., S. Law, and L. M. Zhang 2000. Structural damage detection from modal strain energy change. *Journal of engineering mechanics,* 126**,** 1216-1223.

Shih, H. W., D. Thambiratnam, and T. H. Chan 2011. Damage detection in truss bridges using vibration based multi-criteria approach. *Structural Engineering and Mechanics,* 39**,** 187.

Stubbs, N., and J.-T. Kim 1996. Damage localization in structures without baseline modal parameters. *Aiaa Journal,* 34**,** 1644-1649.

Stubbs, N., J.-T. Kim, and C. Farrar. Field verification of a nondestructive damage localization and severity estimation algorithm. Proceedings-SPIE the international society for optical engineering, 1995. SPIE INTERNATIONAL SOCIETY FOR OPTICAL, 210-210.