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Method development of damage detection in asymmetric buildings

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ABSTRACT

Aesthetics and functionality requirements have caused most buildings to be asymmetric in recent times. Such buildings exhibit complex vibration characteristics under dynamic loads as there is coupling between the lateral and torsional components of vibration, and are referred to as torsionally coupled buildings. These buildings require three dimensional modelling and analysis. In spite of much recent research and some successful applications of vibration based damage detection methods to civil structures in recent years, the applications to asymmetric buildings has been a challenging task for structural engineers. There has been relatively little research on detecting and locating damage specific to torsionally coupled asymmetric buildings. This paper aims to compare the difference in vibration behaviour between symmetric and asymmetric buildings and then use the vibration characteristics for predicting damage in them. The need for developing a special method to detect damage in asymmetric buildings thus becomes evident. Towards this end, this paper modifies the traditional modal strain energy based damage index by decomposing the mode shapes into their lateral and vertical components and to form component specific damage indices. The improved approach is then developed by combining the modified strain energy based damage indices with the modal flexibility method which was modified to suit three dimensional structures to form a new damage indicator. The procedure is illustrated through numerical studies conducted on three dimensional five-story symmetric and asymmetric frame structures with the same layout, after validating the modelling techniques through experimental testing of a laboratory scale asymmetric building model. 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 single and multiple damages in these buildings. The results obtained from a number of different damage scenarios confirm the feasibility of the proposed vibration based damage detection method for three dimensional asymmetric buildings.

1. Introduction

An asymmetric building can be defined as one in which there is either geometric, stiffness or mass eccentricity. In such buildings, the lateral and torsional components of the response are coupled leading to complex behaviour. The dynamic

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behaviour of an asymmetric building can result in interruption of force flow, stress concentration and torsion [1]. This torsion can lead to an increase in shear force, lateral deflection and ultimately cause failure. The development and application of a robust technique to detect and locate damage at its onset is thus important in order to avoid the possible 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 [2], all of which require the damaged region to be accessible. The drawbacks of these methods are that the damaged region might not be readily accessible and the collected data might not be adequate for effective prediction of the remaining life of a structure. This has led to the development of vibration based methods which are global in nature and which consider the changes in the vibration characteristics of the structure [3]. 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 of both the healthy (or base line) and damaged structures. The collected data is analysed which can then be used solely or along with the vibration data from a 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 machinery [4]. During the past decades, structural engineers have made great efforts to identify damage in civil structures. Most of the existing studies based on vibration based methods for identifying damage used numerical simulations or non-in-situ experimental techniques. Generally, the performance of a damage indicator or a damage identification technique depends on the type of structures [5]. Structures that received greatest research interest include beams [6,7], plate elements [8,9], trusses [10–12], steel frames [13,14], offshore platforms [15–17] and bridges [5,18,19]. Despite the many successful applications in those structures in recent years, the identification of damage in complex structures such as 3D buildings, especially asymmetric buildings, remains a challenging task for structural engineers. There is relatively less investigation on detecting and locating damage in torsionally coupled asymmetric buildings.

Using natural frequency change as the basic feature for damage detection was one of the most common approaches. Frequencies can be easily measured with a small number of sensors and they are robust again measurement noise [20]. However, frequencies have been shown to be sensitive to temperature while their changes are unable to provide spatial information and hence damage detection methods relying solely on change in natural frequency may not be sufficient for locating damage [21,22]. The advantage of using mode shapes compared with natural frequencies is that mode shapes contain spatial information and are less sensitive to environmental effects. Although mode shape based methods contain spatial information, it is hard to capture accurate and reliable mode shapes in large structures with a limited number of sensors, especially if higher modes are deemed more favourable than the lower modes for damage detection [23]. Methods based on modal flexibility have also received considerable attention from many researchers. The motivation of using this method is that the complete vibration parameters for damage detection are not required [24]. The literature confirm that the Modal Flexibility (MF) based method has a wide variety of applications in damage detection studies. However there is no application in detecting and locating damage in large scale asymmetric building structures. Modal Strain Energy (MSE) based method was first developed by Stubbs and Kim [25,26]. 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 that are being currently investigated [17]. 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, Shi and Zhang [12] to detect and locate damage in structures with incomplete and noisy measured modal data. Their method was validated by using the results from laboratory experiments on a two storey steel frame structure. The experimental program 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, Cheng, Tham and Bai [27] further extended the method developed by Law, Shi and Zhang [12] by adopting a micro-genetic algorithm in the damage quantification stage. Shi, Law and Zhang [28,29], proposed a technique for locating damage using the MSE Change Ratio (MSECR) of each structural element. This method only requires mode shapes and the elemental stiffness matrix. The application of the proposed method to a truss structure and a two-storey frame structure demonstrated its capability to locate single and multiple damages. Shih, Thambiratnam and Chan [19] proposed a multi-criteria approach incorporating MF and MSE based methods for detecting damages in slab-on-girder bridges. It was found that for single damage both flexibility and strain energy changes provided accurate results for locating damage. However for multiple damage cases, only the MSE based method was capable of accurately locating the damage.

From the review of the many approaches above, it is evident that the MF change and MSE change methods have the capability to detect and locate damage. Moreover, the overall review of the literature indicated that it is unrealistic to expect damage to be reliably detected in all cases by using a single damage index especially in multiple damage scenarios. Combined methods have provided a better chance of structural damage detection. The focus of the present study is to develop a multi-criteria approach (MCA) based on a modified version of the traditional MSE method, along with the MF method. The method will be validated by simulated data of two structures (i) 5 storey symmetric structure and (ii) 5 storey asymmetric structure which are modelled and analysed utilizing ANSYS software [30].