Journal of Sound and Vibration 344 (2015) 258–276

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Vibration based baseline updating method to localize crack formation and propagation in reinforced concrete members

Buddhi L. Wahalathantri, David P. Thambiratnam*, Tommy H.T. Chan, Sabrina Fawzia

School of Civil Engineering & Built Environment, Queensland University of Technology, GPO Box 2434, Brisbane, Queensland 4001, Australia

ARTICLE INFO

Article history:
Received 26 November 2014
Received in revised form
23 January 2015
Accepted 25 January 2015
Handling Editor: L.G. Tham
Available online 18 February 2015

Keywords:
Baseline updating method
Damage index
Reinforced concrete structures
Flexural cracks
Crack formation
Crack propagation
Damage localization

ABSTRACT

Structural Health Monitoring (SHM) schemes are useful for proper management of the performance of structures and for preventing their catastrophic failures. Vibration based SHM schemes has gained popularity during the past two decades resulting in significant research. It is hence evitable that future SHM schemes will include robust and automated vibration based damage assessment techniques (VBDAT) to detect, localize and quantify damage. In this context, the Damage Index (DI) method which is classified as non-model or output based VBDAT, has the ability to automate the damage assessment process without using a computer or numerical model along with actual measurements. Although damage assessment using DI methods have been able to achieve reasonable success for structures made of homogeneous materials such as steel, the same success level has not been reported with respect to Reinforced Concrete (RC) structures. The complexity of flexural cracks is claimed to be the main reason to hinder the applicability of existing DI methods in RC structures. Past research also indicates that use of a constant baseline throughout the damage assessment process undermines the potential of the Modal Strain Energy based Damage Index (MSEDI). To address this situation, this paper presents a novel method that has been developed as part of a comprehensive research project carried out at Queensland University of Technology, Brisbane, Australia. This novel process, referred to as the baseline updating method, continuously updates the baseline and systematically tracks both crack formation and propagation with the ability to automate the damage assessment process using output only data. The proposed method is illustrated through examples and the results demonstrate the capability of the method to achieve the desired outcomes.

1. Introduction

Establishing safer performance levels of structures has been a dominant subject matter for many decades to minimise the negative effects on social and economic development of a society while saving human lives. In this context, Structural Health Monitoring (SHM) has emerged as a means of monitoring the performance of a structure and detecting the onset of damage so that appropriate retrofitting may be carried out to prevent the collapse of the structure. Research in vibration

* Corresponding author. Tel.: +61 7 3138 1467.
E-mail address: d.thambiratnam@qut.edu.au (D.P. Thambiratnam).

http://dx.doi.org/10.1016/j.jsv.2015.01.043
0022-460X/

based damage assessment techniques (VBDATs) has been a major part of SHM research during the past two decades. Technological developments such as wireless sensors, high speed computers and modern data acquisition systems have expedited the research on vibration based damage assessment techniques (VBDAT). Non-destructive nature and minimum hindrance to the functionality of the structure are the main attributes that promote VBDATs over other damage assessment methods.

VBDATs use changes in vibration properties between two states to identify the existence, location and severity of damage with or without using a computer model [1–3]. In this context, Damage Index (DI) methods based on the modal properties of a structure, are straightforward, fast, inexpensive and have the ability to automate the damage assessment process [4]. Furthermore, they can successfully assess damage using real measurements alone and hence classified as non-model, response or output based VBDATs [2,4,5]. DI methods have been mostly successful in detecting and localizing single and multiple damage in structures made of homogeneous materials such as steel [6–9]. Lele and Maiti [8] developed a method to asses crack propagation using frequency measurements for steel structures. Mahto and Maiti [9] presented a method to detect the formation of new cracks in a steel beam with pre-existing cracks. As illustrated herein, though DI methods have been successfully used to assess damage in homogeneous structures, their potential to assess damage in RC structures has been limited [10].

The complex damage pattern of RC structures is the main cause that reduces the damage assessment ability of DI methods. Some other reasons are sensitivity to environmental variations, creep and shrinkage effects, modelling difficulties arising from non-homogeneity and lack of experimental investigations, all which are beyond the scope of the present paper. The predominant damage type, flexural cracks, in RC structures propagate non-uniformly in orthogonal directions. More specifically, flexural cracks have a propensity to spread in longitudinal and/or transverse directions than in the depth direction, due to the presence and effect of tensile reinforcement. Therefore, widely spread crack zones are more prominent in RC structures under flexural loading. Severity of such cracks reduces non-uniformly with distance from the centre or the crack initiation point. Change in load pattern and magnitude may cause the formation of new cracks and/or propagation of existing cracks. Although some model-based VBDATs have achieved reasonable success in assessing the complex nature of cracks in RC structures [11–14], the same success level has not been achieved with DI methods [10].

The present study addresses this knowledge gap and proposes a novel baseline updating technique that will improve the overall damage assessment ability. The developed method has the ability to automate the damage assessment process with enhanced accuracy in assessing damage in RC structures using the DI method.

1.1. Damage index method

The DI method evaluates changes in vibration properties of the structure between two states using a comparative indicator, which is named as the damage index. A large number of DIs have been proposed in the literature based on different types of vibration properties such as frequencies [7,15–17], damping factors [18,19], mode shapes [4,20–23], derivatives of mode shapes [5,24,25], flexibility values [26,27], flexibility curvatures [28] and modal strain energy values [29–32]. The first state where the vibration properties are measured defines the baseline, whereas all subsequent measurements correspond with evaluation states of the damage assessment process. Vibration properties of the undamaged structure are most commonly used to define the baseline. Alternatively, vibration properties at the best known healthy state or computer simulations are used, if the undamaged state is not attainable, such as in case of existing structures. Existing DI methods do adhere to a single baseline during the damage assessment process and hence the authors classify them as constant baseline methods in this paper.

Firstly, this paper evaluates damage localization ability of the constant baseline method using the Modal Strain Energy based Damage Index (MSEDI). Findings of this study highlight that MSEDI does not detect and locate sequentially propagating flexural cracks in RC structures, with respect to a constant baseline. A baseline updating method was therefore developed as a part of a comprehensive SHM research project carried out at the Queensland University of Technology (QUT), Brisbane, Australia [10]. Improved damage localization ability of this method was then verified using different crack patterns such as overlapped cracks, formation of new cracks and propagation of existing cracks. Section 2 of this paper presents details of the proposed baseline updating method. Details of the crack patterns and verification of improved damage localization ability of the proposed baseline updating method are presented in Section 3.

2. Proposed baseline updating method

2.1. Modal strain energy based damage index (MSEDI)

The baseline updating method presented in this paper uses the Modal Strain Energy based Damage Index (MSEDI) proposed by Wahalathantri et al. [32] due to its superior damage localization abilities. However, all steps presented in this paper can easily be replaced with a different damage index, if there is a need.

Eq. (1) represents the MSEDI based on individual modes. It should be noted that generalized subscripts 'b' and 'e' have been used to denote baseline and evaluation states, instead of commonly used subscripts 'h' and 'd' for healthy and damaged