Mechanical Systems and Signal Processing 60-61 (2015) 124–150

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Damage detection of shear connectors under moving loads with relative displacement measurements

Jun Li*, Hong Hao

Department of Civil Engineering, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia

ARTICLE INFO

Article history:
Received 30 March 2014
Received in revised form
1 July 2014
Accepted 16 September 2014
Available online 3 February 2015

Keywords:
Relative displacement measurement
Structural health monitoring
Composite bridges
Shear connectors
Damage detection
Moving loads

ABSTRACT

This paper investigates the use of relative displacement measurements from the newly developed relative displacement sensors to identify the damage of shear connectors in composite bridges. Continuous Wavelet Transform and Hilbert–Huang Transform are applied to analyze the measured dynamic responses and to identify the damage of shear connectors in the composite bridge model under moving loads. Comparative studies by using the relative displacement, acceleration and displacement measurements respectively for the damage detection are conducted. A comparative study of using relative displacements and acceleration responses of the bridge under ambient excitations to monitor the shear connector conditions is also conducted. Numerical and experimental studies demonstrate that both relative displacement and acceleration measurements can identify the location and the instant of damage occurrence in shear connectors when the bridge is under moving loads. The results demonstrate that relative displacement is a better response quantity for structural health monitoring of composite bridges.

1. Introduction

Damage detection is an important task in the areas of structural health monitoring and condition assessment of structures. The identification results will support the evaluation of structural integrity and load-carrying capacity. Composite structure represents a typical form for bridges on Australia highways. It consists of reinforced concrete (RC) slab and precast RC or steel girders. Shear connectors are used to link the slab and girders to increase the rigidity of composite bridges for uniform action under live traffic and other loadings. The shear connection between slab and girders subjects to the possible occurrence of corrosion and fatigue, as well as overstressing owing to the increased traffic weights and volume. Deterioration or failure of the shear connectors will significantly reduce the composite action so that the bridge slab and girder respond to traffic loadings independently, resulting in a decrease of the overall rigidity and ultimate load-carrying capacity of the bridge [1]. An example studied in [2] indicated that damage of shear connectors would result in shear slippage between the slab and girder and therefore may result in the stiffness reduction up to 17% in a short span bridge.

Assessment of the shear connection integrity is essential to evaluate the global behavior and safety of composite bridges. Since the inaccessibility of the shear connection for routine visual inspection, it is important to develop non-destructive techniques to identify the conditions of the shear connectors. Vibration-based damage detection methods have been used

* Corresponding author. Tel.: +61 8 9266 5140; fax: +61 8 9266 2681.
E-mail addresses: junli@curtin.edu.au, LI.Jun@connect.polyu.hk (J. Li).

http://dx.doi.org/10.1016/j.ymssp.2014.09.014

for the condition assessment of shear connectors in composite bridges. Xia et al. [3] proposed a local detection method by directly comparing the frequency response functions of simultaneously measured vibrations on the slab and girder. It has been found that the local method would give better identification results than global methods with modal information that may be less sensitive to the local damage of shear connectors. Recently, wavelet based Kullback–Leibler distance [4] and wavelet packet energy [5] have also been proposed for damage identification of shear connectors. Moyo et al. [6] presented the use of modal information, such as frequencies, for the integrity assessment of shear connectors in composite concrete bridges. Shih et al. [7] used modal flexibility change and modal strain energy change for damage localization of shear connectors. Liu and De Roeck [8] proposed a local condition assessment approach to identify the damage location of shear connectors by using the modal curvature and wavelet transform modulus maxima. Modal strains were measured and used for identification. Li et al. [9] presented a damage detection approach by using the concept of transmissibility as it reflects the local change of structures and increases the sensitivity in identifying the damage of shear connectors. The above studies made use of measured vibration responses, i.e. accelerations and strains, or vibration properties extracted from the dynamic measurements, i.e. frequencies and modal flexibility to evaluate the shear connection conditions. The global measurements may not be sensitive to the local shear connector damage. Local damage features are required to be defined and the sensitivity needs to be improved to detect the damage of shear connectors.

Recently, an innovative relative displacement sensor [10] has been developed to track the shear slippage and failure of the shear connection in composite bridges by measuring the relative displacement between slab and girders. The accuracy of the developed relative displacement sensor has been validated. It has been demonstrated that the developed sensor gives accurate measurement of relative displacement between bridge girder and slab. It does not require a fixed reference point and can be directly installed on the target structure hence is easy to setup. Moreover, the developed sensor is more cost-effective than traditional displacement measurement approaches, i.e., based on lasers [11] and vision-based methods with high-resolution cameras [12].

Signal processing techniques process the measured responses to identify the possible existing damage and anomalies in structures and evaluate the structural safety condition. With the newly developed relative displacement sensor, it is of importance and emerging need to explore suitable signal processing techniques to take advantages of relative displacement measurements for condition assessment of structures. Among all the recently developed signal process techniques, time–frequency analysis methods, such as continuous wavelet transform (CWT) and Hilbert–Huang Transform (HHT), are popular and well adopted in structural health monitoring. The merits of time–frequency analysis methods lie in its ability to reflect both time and frequency domain information. A perturbation or spike in the wavelet coefficients could be observed in the wavelet transform diagram and indicate the moment when the structural condition change occurred [13,14]. Quek et al. [15] examined the sensitivity of wavelet technique to detect the cracks in beam structures. The effects of different crack characteristics, boundary conditions and wavelet functions employed were investigated. The introduced cracks in beam structures can be identified with the perturbations in wavelet coefficients with both simply-supported and fixed-ended boundary conditions. Ovanesova and Suarez [16] presented the applications of wavelet transform to detect cracks in frame structures, such as beams and plane frames. It was shown that the approach can detect the localization of the crack by using a response signal from static or dynamic loads. Later, CWT has been extended to identify the damage in plate structures [17]. Two-dimensional wavelet transform was adopted and the location of the damage was indicated by a peak in the spatial variation of the transformed responses. As an alternative time–frequency analysis tool, Huang et al. [18] developed an innovative signal processing technique known as HHT, which is able to analyze nonlinear system and nonstationary signals. It mainly relies on the empirical mode decomposition (EMD), which permits to decompose the acquired signal into a set of basis functions called implicit mode functions (IMFs). Xu and Chen [19] presented experimental investigation on the applicability of EMD for identifying structural damage in the form of a sudden change of structural stiffness. The damage time instants can be accurately detected in terms of damage spikes extracted directly from the measured responses with EMD. The damage location can be evaluated based on the spatial distribution of the spikes along the building. Peng et al. [20] compared the performances of using CWT and HHT for fault diagnosis of rolling bearings. An improved HHT was proposed. The wavelet packet transform was used as a preprocessor to decompose the original signal into a set of narrow band signals and then EMD was utilized to obtain the IMFs. It is found that the improved HHT has better resolution and efficiency than CWT. Bao et al. [21] proposed an improved HHT algorithm by using auto-correlation functions as input to EMD for time-varying system identification. Application of this improved method to the modal identification of a scaled composite beam with various damage scenarios demonstrated that this method is very sensitive to minor vibration parameter changes.

Condition assessment of bridge structures is usually conducted from the measured responses under moving traffic which serves as the excitation to bridges [22–25]. It has been explored and demonstrated that CWT and HHT have the potentials to detect the damages in structures with measured displacement and acceleration responses under moving loads [26–28].

This paper investigates if the relative displacement measurements from the newly developed relative displacement sensors can be used to identify the damage of shear connection in composite bridges. Time–frequency analysis methods, i.e., CWT and HHT, are applied to process the measured dynamic responses for identification of the damage of shear connectors on composite bridges under operational conditions. The design principle of the relative displacement sensor will be briefly introduced. Two examples are studied in this paper. The first example conducts the damage detection of the example bridge from the measured responses under a moving load. The measured relative displacement, acceleration and vertical deflection are used respectively for the damage detection to demonstrate the performance of different response quantities for