Structures 1 (2015) 67–75

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

Using the vibration envelope as a damage-sensitive feature in composite beam structures

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ARTICLE INFO

Article history:
Received 6 August 2014
Received in revised form 2 October 2014
Accepted 9 October 2014
Available online 16 October 2014

Keywords:
Composite bridges
Damage detection
Moving load problem
Structural health monitoring
Non-destructive evaluation

ABSTRACT

A novel approach of damage detection in composite steel–concrete composite beams is suggested.
Based on the idea of using the envelope's profile deflections and rotations induced by a moving load, this approach can lead to a practical cost-effective alternative to the traditional use of accelerometers and laser vibrometers.
A parametric study has been undertaken, quantifying the sensitivity of the dynamic response of a realistic composite bridge to the presence of damage at different levels of partial steel–concrete interaction and velocity of the moving load.
When compared to shifts in the natural frequencies, it has been verified that the proposed approach generally enjoys a higher sensitivity (so damage can be detected at an early stage), is more effective when closer to the ends of the bridge (where shear studs are more likely to be damaged), and displays an ordered set of results (which would reduce the possibility of a false damage).
Further work is required to assess the effects of uncertainties and the adoption of more refined models for the moving load.

1. Introduction

Composite steel–concrete beams are widely used in structural engineering, offering the advantages of construction efficiency, durability and improved economy [1–3]. Their performance is strongly influenced by the flexibility of the connection between concrete slab and steel, which generally allows a partial interaction between the two materials. In bridge engineering applications, faster trains and augmented traffic have significantly increased the number and amplitude of loading cycles experienced on a daily basis by composite bridges. This higher demand accelerates the occurrence of damage in the shear connectors, which in turn affects the overall integrity of the structure.

Conventional approaches of damage detection (including ultrasonic, thermal, eddy current and X-ray testing) were termed as cumbersome and expensive, and their application is often limited to the evaluation of local structural performance [4], while visual inspections represent an unreliable solution [5] (also because shear connectors are often inaccessible). Vibration-based damage detection methods have therefore emerged, as they allow identifying meaningful changes in the dynamic characteristics of the composite beam due to alterations in the mechanical properties of the structure [6], with little or no need for the user to know a priori where the damage might be located. Accelerometers have been extensively employed for this purpose, although their application to large structural systems like composite bridges may be difficult because of long cabling, number of sensors and installation time. Laser Doppler vibrometers (LDVs) can be used as a viable non-contact alternative to accelerometers, especially when targets are difficult to access, but large displacements can adversely affect measurements [7] and the simultaneous acquisition of vibration at multiple points would make very expensive the dynamic testing.

In the general framework of structural health monitoring, vibration-based methods can be classified into “model based methods”, which iteratively update the numerical model of the structure to match some dynamic characteristics experimentally measured, and “non-model based methods”, which directly compare changes in these characteristics, without any numerical model being required [8]. In both cases, various dynamic characteristics can be exploited as a damage-sensitive feature (DSF), including: natural frequencies and modal shapes [9]; modal beam curvatures [10]; frequency response function (FRF) [11]; modal flexibilities [12]; modal strain energy [13].

An early review of different methods of damage detection using natural frequencies can be found in Ref. [14]. However it has become apparent that environmental factors affect eigenfrequencies, which can then mask changes due to damage events [15]. It was also argued that damage does not equally affect all modal frequencies [4,16].

Pascual et al. [17] suggested the use of operating deflection shapes (ODSs) for assessing the presence of damage, while Limongelli [18] proposed an interpolation damage detection method (IDDM), in which the

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http://dx.doi.org/10.1016/j.istruc.2014.10.001

deviation of the deformed shape from a smooth behaviour is used as DSF. Zhang et al. [19] proposed the global filtering method (GFM) as detection algorithm for beam- and plate-like structures, using ODS curvatures extracted from the dynamic response to moving loads.

When compared to other structural and mechanical systems, limited attempts have been made to apply damage detection methods to shear connectors in composite bridges, with the implementation of vibration-based methods being further restricted by modelling uncertainties of the connectors and low sensitivities. Queiroz et al. [1] investigated full and partial shear connections using nonlinear springs in the FE (finite element) model of composite beams, demonstrating that partial interaction effects should be considered in the analysis. Xia et al. [8] introduced a local identification approach based on the vertical vibration of slab and girders, which does not require baseline data. Dilena and Morassi [20–22] proposed a Euler–Bernoulli beam model to describe the dynamic response of damaged composite beams based on frequency shifts, showing that damage at interior connectors tends to cause lower variations in the modal frequencies, while Liu and De Roeck [23] performed a parametric study, investigating the behaviour of shear connectors during train passages. It was shown that train speed influences the global behaviour of the bridge, and that the longitudinal shear force are not uniformly distributed along the span, with critical regions located near the supports.

While all the above studies use the dynamic response in terms of accelerations and/or displacements at a few locations (analysed in the time domain and/or in the frequency domain), a radically different approach of damage detection and quantification is envisaged in the present research, which consists of analysing the envelope's profile of vehicle-induced deflections in the composite bridge. Instead of considering the whole time history of the dynamic response (and/or its frequency-domain counterpart), the proposed approach only uses the maximum and minimum values of displacements and rotations. Coupled with recent advances in the field of digital image analysis and processing (e.g. deblurring techniques for long-exposure imageries, recently developed by McCarthy et al. [24,25] for structural dynamics applications), this can lead to an alternative non-contact high-sensitivity method of structural health monitoring for composite bridges, capable of assessing at an early stage the presence and severity of damage.

A set of encouraging preliminary results are presented in this paper, proving the concept in the simple case of a single moving force, although further investigation will be required to assess the effects of uncertainties in the dynamic problem (e.g. random stiffness and random damping of the track [26,27]) and to extend this approach to more advanced models for the moving load (e.g. moving masses and moving oscillators [28,29]).

2. Envelope-based damage measure

Let us consider the vehicle-induced vibration of a composite steel–concrete bridge, whose sketch is shown within Fig. 1. If a set of moving forces is adopted to represent the dynamic load and the structure is assumed to respond within the linear range, the equations of motion for the FE model can be written as:

$$\mathbf{M}\cdot\ddot{\mathbf{u}}(t)+\mathbf{C}\cdot\dot{\mathbf{u}}(t)+\mathbf{K}\cdot\mathbf{u}(t)=\mathbf{g}+\mathbf{f}(t), \tag{1}$$

where $\mathbf{u}(t)$ is the array collecting the DoFs (degrees of freedom) of the model; $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the matrices of mass, equivalent viscous damping and elastic stiffness; while $\mathbf{g}$ and $\mathbf{f}(t)$ are the load vectors associated with the dead and moving forces, respectively. Interestingly, $\mathbf{f}(t)$ depends on the time t not because the magnitude of the applied forces varies, but because they move along the bridge.

It is worth mentioning here that, for the sake of simplicity, Eq. (1) does not include the inertia effects due to the moving mass and any vehicle-bridge dynamic interaction phenomena, as they would require time-dependent mass, stiffness and damping coefficients [30,31]. Such refinements of the model would be outside the scope of this work, which is aimed at assessing whether the envelope of the deformations caused by a moving load is sensitive enough to be used in a damage identification scheme instead of changes in the modal frequencies.

Once the governing equations are numerically integrated, the dynamic response of the bridge in terms of displacements and rotations can be expressed as linear combination of the DoFs:

$$\theta(t)=\mathbf{a}_\theta^\top\cdot\mathbf{u}(t), \tag{2}$$

where $\theta(t)$ is the generic response parameter (e.g. deflection at midspan, slope at the supports or the curvature at a given position along the bridge); $\mathbf{a}_\theta$ is the array collecting the associated influence coefficients; and the superscripted symbol $\top$ stands for the transpose operator.

It is now possible to introduce the envelope of the dynamic response $\theta(t)$ as the interval $[\Theta_1, \Theta_2]$ defined by its extreme values within the selected observation time interval $[0, T]$:

$$\Theta_1=\min_{0\le t\le T}\{\theta(t)\};\Theta_2=\max_{0\le t\le T}\{\theta(t)\}, \tag{3}$$

such that $\Theta_1\le\theta(t)\le\Theta_2$ for $0\le t\le T$, and the amplitude of the envelope is (see Fig. 2(a)):

$$E_\theta=\Theta_2-\Theta_1. \tag{4}$$

Alternatively, the amplitude of the envelope can be evaluated as:

$$E_\theta=\left(A_\theta^{(+)}+A_\theta^{(-)}\right)\theta_f \tag{5}$$

where $A_\theta^{(+)}$ and $A_\theta^{(-)}$ are the dynamic amplification coefficients for the response parameter $\theta(t)$, given by:

$$A_\theta^{(+)}=\max\left\{\frac{\theta(t)-\theta_g}{\theta_f}\right\};\quad A_\theta^{(-)}=\max\left\{-\frac{\theta(t)-\theta_g}{\theta_f}\right\}; \tag{6}$$

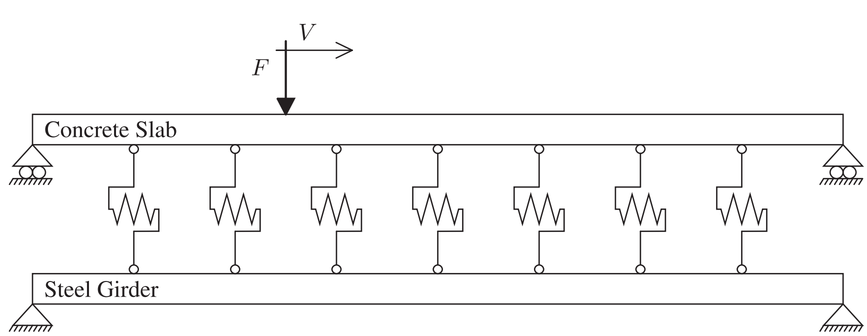

Fig. 1. Sketch of the structural problem.