Engineering Structures 61 (2014) 61–72

Contents lists available at ScienceDirect

Engineering Structures

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

Serviceability limit state of vibrations in under-deck cable-stayed bridges accounting for vehicle-structure interaction

A. Camara [a], K. Nguyen [b], A.M. Ruiz-Teran [a,*], P.J. Stafford [a]

[a] Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, Exhibition Rd., London SW7 2AZ, United Kingdom
[b] Department of Mechanics and Structures, School of Civil Engineering, Technical University of Madrid (UPM), Prof. Aranguren s/n, Madrid, Spain

ARTICLE INFO

Article history:
Received 3 July 2013
Revised 15 November 2013
Accepted 21 December 2013
Available online 6 February 2014

Keywords:
Vehicle-bridge interaction model
Under-deck cable-stayed bridges
Moving vehicles
Comfort
Road roughness
Disc model
Vibration
Serviceability
Road traffic loading

ABSTRACT

Verification of the serviceability limit state of vibrations due to traffic live loads can be neglected in conventional types of concrete road bridges but becomes critical in the design of slender structures like under-deck cable-stayed bridges. The novelty of the work presented in this article is that an innovative vehicle-bridge interaction model is employed, in which realistic wheel dimensions of heavy trucks, road roughness profiles and the cross slope of the road are considered in nonlinear dynamic analyses of detailed three-dimensional finite element models. An extensive parametric study is conducted to explore the influence of the bridge parameters such as the longitudinal and transverse cable arrangement and the support conditions, in addition to the load modelling, road quality, the wheel size, the transverse road slope and the vehicle position and speed on the response of under-deck cable-stayed bridges. It has been observed that the vibrations perceived by pedestrians can be effectively reduced by concentrating the cable-system below the deck at the bridge centreline. The Fourier amplitude spectrum of the acceleration at critical positions along the deck proved that the response of under-deck cable-stayed bridges is not dominated only by contributions at the fundamental mode and, consequently, the conventional deflection-based methods are not valid to assess the users comfort. Instead, Vehicle-Bridge Interaction analyses are recommended for detailed design, considering the wheel dimensions if the pavement quality is bad and/or if the wheel radius is large. Finally, we verify through multiple approaches that the comfort of pedestrian users is more critical than that of vehicle users. However, the comfort of vehicle users is shown to be significantly affected when the road quality is poor.

1. Introduction

Verification of the Serviceability Limit State (SLS) of vibrations due to traffic live loads has historically been ignored in the design of conventional road bridges with reinforced and prestressed concrete decks. While this design approach is generally justified for traditional bridges, this does not imply that the approach can simply be translated to other less-conventional and slender concrete bridges, such as Under-Deck Cable-Stayed Bridges (UD-CSBs) [1]. UD-CSBs have been shown to be very efficient when used for medium spans under persistent [2–5] and accidental situations such as sudden breakage of cables [6] or earthquake actions [7]. The very high efficiency of the cable stay system (with the stay cables working in tension and the struts and the deck working in compression) allows for more slender designs (depth-span ratio of 1/80 for medium spans of around 80 m) in comparison with conventional schemes. Internationally renowned structural engineers like Leonhardt, Schlaich, Virlogeux, Cremer and Manterola have designed remarkable bridges with this typology. Previous research on these bridges has also been recognised through the 2009 FIB diploma for research [8], which further demonstrates that there is active interest in these bridge types within the structural engineering community. Due to the large slenderness of the deck, these bridges are subjected to significant traffic-induced vibrations that cannot be neglected in the design. In fact, the depth of the deck is limited by the SLS of vibrations due to traffic load.

In order to develop design criteria for the SLS of vibrations due to traffic live load, all of the components of the problem must be considered: the vibration source (movable vehicle or load), the vibration path (the structure), and the receiver (pedestrians or vehicle users). In short and medium span road bridges the most important source of vibration is the road traffic. In most cases pedestrians are the first users to feel discomfort. People inside vehicles are more tolerant to vibrations and are also partially isolated from these as a result of vibration mitigation measures

* Corresponding author. Tel.: +44 2075946005.
E-mail addresses: a.camara@imperial.ac.uk (A. Camara), khanh@mecanica.upm.es (K. Nguyen), a.ruiz-teran@imperial.ac.uk (A.M. Ruiz-Teran), p.stafford@imperial.ac.uk (P.J. Stafford).

http://dx.doi.org/10.1016/j.engstruct.2013.12.030
0141-0296/

incorporated into the vehicle [9]. Pedestrians are typically considered as the receiver of the vibration in codes, standards and research works, with the vehicle users' comfort being ignored as pedestrian comfort is usually only considered in footbridges. There are road bridges, mainly highway bridges, where the only users that should be considered for persistent situations are those inside the vehicles. The vibration felt by drivers and passengers is mainly transmitted through the floor of the cab as well as the seats and the highest ride vibrations occur in the vertical and fore-and-aft directions [10]. The maximum human sensitivity to vertical acceleration falls in the frequency range from 4 Hz to 12.5 Hz [11], higher than the first UD-CSBs and vehicle frequencies.

In practice, two types of analysis procedure are typically adopted in order to verify the SLS of vibrations due to traffic live load [1]: deflection- and acceleration-based methods. In the deflection-based methods the accelerations of the bridge under the frequent traffic live load are intended to be indirectly controlled by limiting the deflection due to a static load. Several codes and guidelines [12] indicate that under the live load the bridge deflection must be smaller than a limit of around $L/1000$ (with L being the main span of the bridge) that has been prescribed on the basis of previous experience. This deflection limit dates back to the early 1930s and it is not sufficiently well justified for use in modern bridge design [13]. Another deflection-based method employed in codes [14] is a pseudo-static approach based on Smith's studies [9] in which the maximum vertical acceleration in the bridge is assumed to be directly proportional to the dynamic deflection at midspan, by assuming that the response is governed by a single mode of vibration. Deflection-based methods are the traditional and most common approaches used by practicing engineers but their shortcomings are widely recognised and come from the assumption that the structure is dominated by the fundamental vibration mode. As will be confirmed in this paper, this is not appropriate for UD-CSBs.

The acceleration-based strategy is more rational since the recorded acceleration is directly compared to a selected comfort criterion that takes into account the human perception of the vibration, which is particularly sensitive to vertical accelerations [15]. Several direct and indirect factors influence a pedestrian's perception of vibration when crossing a bridge: the position of the human body (walking, standing or seated), exposure time, expectations regarding the likely vibration of the bridge based upon its visual appearance [16], height above ground, sound generated, user's health [17] etc. Many studies have already established admissible vibration limits to meet different degrees of pedestrian comfort. This issue continues to receive attention from the academic community. A thorough state-of-the-art review for pedestrians was presented by [18].

The two main pedestrian comfort criteria used for bridge design (both for footbridges and road bridges with footpaths) are Irwin [17] and the British Standard [19]. Irwin [17] collected data about human response to vibration with respect to frequency and suggested maximum allowable limits for root-mean-square (r.m.s.) accelerations for bridges in the vertical direction. His work identified a frequency range of between 1 and 2 Hz, close to the typical natural frequency of UD-CSBs [4,7]. Irwin's recommendation distinguishes everyday use from storm conditions for which the admissible accelerations are multiplied by the factor of 6. On the other hand, the British Standard BS 5400: Part 2 [19] was the first design code to deal with vibration serviceability in footbridges and limits the peak vertical acceleration (rather than r.m.s.) to $a_{\text{lim}} = 0.5\sqrt{f}$ (where f is the fundamental frequency of the structure in Hz, and a_{lim} is in units of m/s^2). The main contributions in relation to the comfort of vehicle users have been provided by Griffin [20].

In relation to the description of the vibration source, which is essential in the acceleration-based approach, two main methods are employed to describe the traffic loading. The simplest solution is to ignore the dynamic characteristics of the vehicle (mass, damping and stiffness) and to define time-varying point loads applied to the deck nodes along the path that will be followed by the vehicle. In this case, triangular functions are employed to describe the load amplitude applied at each node against time, see Fig. 1a. However, this Point Load (PL) model is not able to capture the Vehicle-Bridge Interaction (VBI) and the influence of the pavement conditions, which have an important impact upon the overall system dynamics [21,22] and particularly influences the vibrations perceived by users. Moreover, if the bridge does not have footpaths the Point Load model ignores the vibration sensed by the only users of the structure, i.e. people within the vehicles. Current research on VBI typically employs a Multi-Degree-Of-Freedom (MDOF) model of the vehicle to describe the flexibility and damping of the tyre and suspension systems, allowing for the yaw, roll and pitching motions of the truck body to be captured. The H20-44 truck model defined by the American Association of State Highway and Transportation Officials (AASHTO) specifications [12] is appropriate for the SLS of vibrations since it may combine both heavy vehicle weight (18.6 t) and high velocities (up to 120 km/h). This model has been employed by several authors [21,23] and has 7 degrees of freedom which are described graphically in Fig. 1b. An important advantage of the vehicle model interacting with the bridge (VBI) is the ability to represent the pavement roughness. According to [21,22], among many other authors, the road surface roughness may be defined by means of an ergodic zero-mean stationary Gaussian random profile of imposed displacements ($r(x)$ in Fig. 1b) at the nodes of the vehicle in contact with the bridge.

In the present article the dynamic response of UD-CSBs is studied, focusing on the comfort of pedestrians walking along the sidewalks but also considering the vibrations perceived by people inside the vehicle. The paper starts by presenting the canonical UD-CSBs studied, the vehicle model and the contributions of the governing vibration modes. The results of an extensive number of nonlinear dynamic analyses are discussed next, clearly distinguishing the features related to the vehicle action (e.g. the wheel radius) from the influence of the structural configuration. The comparison between the results obtained with current simplified design approaches completes this work. These models are used to identify the most suitable bridge configurations to enhance the bridge behaviour under live load. In addition, a set of design criteria is ultimately proposed.

2. Definition of the studied bridges and vehicle

This paper is focused on medium span (80 m) under-deck cable-stayed bridges with in-situ prestressed concrete decks. A set of bridges designed by Ruiz-Teran and Aparicio [4] will be used for this study. Fig. 2a presents the elevation of the studied bridges with two or multiple (15) diverting struts. Fig. 2b presents the two considered transverse cable arrangements, designed with a concentrated or expanded layout. These configurations are selected so as to cover the current trends in design.

The deck has been designed to support two road lanes (3.5 m wide each). Using the British Standard criteria [19], two heavy vehicles of 400 kN crossing the bridge at 60 km/h and described as point loads were employed in the design of the bridges [4].

The maximum vehicle eccentricity in this original design case is limited to e = 2.475 m as shown in Fig. 2b. In this work the lane distribution is modified from the original design in order to accommodate vehicles with larger eccentricities that directly effect the flanges. Fig. 3a presents the new configuration with three road lanes and narrower sidewalks. Three load cases have been studied: (i) Load Case I with a centred passing vehicle (e = 0 m); (ii) Load