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Dynamic behaviour of steel–concrete composite under-deck cable-stayed bridges under the action of moving loads

Fernando Madrazo-Aguirre, Ana M. Ruiz-Teran *, M. Ahmer Wadee

Department of Civil and Environmental Engineering, Imperial College of Science, Technology & Medicine, London SW7 2AZ, UK

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ABSTRACT

The dynamic response of under-deck cable-stayed bridges with steel–concrete composite decks under moving loads is presented, and different parameters are considered. The vibrational modes with a strong contribution in the response, the key parameters that control the modal frequencies, and those that reduce the maximum accelerations registered on the deck in a cost-effective manner, are identified. It is found that relatively high accelerations occur and that these can be increased by large load eccentricities. It is also found that maximum accelerations are conditioned by the amplification and cancellation speeds of the loads. Increasing the depth of the deck is determined to be the most effective way to reduce the maximum accelerations. Decks formed by I-beams seem to be quite appropriate from the perspective of dynamic behaviour, while box sections tend to increase the overall cost of the bridge. The findings provide effective strategies to define the most efficient configurations that satisfy the limit state of vibrations, which is critical for this type of bridge.

1. Introduction

Prestressing is a very powerful technique that consists of introducing a set of stresses into a structure to improve the structural performance during its service life. This technique has allowed the construction of efficient structures, leading to more economical, slender and durable with longer span bridges. One of the applications of prestressing has been in the design of cable-stayed bridges. The first modern cable-stayed bridge was designed by Eduardo Torroja in 1926 (Tempul aqueduct), in which the inclined stays were tensioned by jacking the saddles upwards over the pylons. After this, Albert Caquot designed the Donzere canal bridge in France (1952), and Franz Dischinger collaborated in the construction of the Stromsund bridge in Sweden (1955). Since then, the design of this type of bridge has seen tremendous advances [1–5].

Since the late 1970s, a new type of cable-stayed bridge has been designed and built: under-deck cable-stayed bridges (UDCSB) [6]. In UDCSBs the stay cables follow non-conventional layouts in comparison with those of conventional cable-stayed bridges the stays being located underneath the deck. Several bridges can be found that have employed this cable-staying system [6], and some examples are included in Fig. 1(a) and (b). UDCSBs have been reported to present several advantages in comparison with conventional bridges without stays [9]: (1) highly efficient structural behaviour by reducing the flexural demand on the deck and enhancing axial response; (2) higher deck slendernesses can be achieved; (3) smaller amounts of material are required, consequently allowing for a more sustainable design; and (4) multiple construction possibilities [10]. Moreover, UDCSBs present, arguably, strong aesthetic characteristics [11].

Steel–concrete composite decks seem *prima facie* to be very appropriate for UDCSBs. Apart from being lightweight solutions with high durability and being aesthetically pleasing, composite decks allow for a high proportion of prefabrication with its obvious advantages: quality, precision, safety and construction speed [12,13].

However, when slender decks are designed in conventional bridges in general, and in cable-stayed bridges in particular, vibrations due to live loads start to be perceptible by the bridge users. The reduced mass and stiffness of more slender solutions can make serviceability limit states (SLS) critical and determine the design configuration. In fact, for medium-span UDCSBs with prestressed concrete decks, the SLS of vibrations under live traffic load governs the maximum slenderness of the deck [9]. Moreover, steel–concrete composite decks present lower self-weight to live load ratios [14], and as a consequence it may be presumed that

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* Corresponding author.

E-mail addresses: f.madrazo-aguirre11@imperial.ac.uk, fmadrazoaguirre@gmail.com (F. Madrazo-Aguirre), a.ruiz-teran@imperial.ac.uk (A.M. Ruiz-Teran), a.wadee@imperial.ac.uk (M. Ahmer Wadee).

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Fig. 1. Two recent examples of under-deck cable-stayed bridges with composite decks: (a) San Miguelito creek footbridge in Queretaro (Mexico) designed by Carlos Fernandez Casado SL and completed in 2008 (photo courtesy of Arturo Perez Aguilar and Christian Balcazar Benitez, Mexpresa) [7]; (b) Okuno bridge in Japan (photo courtesy of Toshiyuki Nakagawa) [8].

comfort criteria for bridge users could be one of the governing limit states.

Codes and standards usually provide indirect methods to control these vibrations. The most common of these methods consists of limiting the deflections of the structure under certain static loading conditions. However, this method may lead to unconservative results in non-conventional bridges [15], in which higher vibrational modes might have a significant contribution in the response [16]. As a consequence, dynamic analyses seem to be necessary to assess the vibrations of UDCSBs under live traffic load. While moving loads are appropriate for preliminary design and analysis of the performance of a bridge typology, which is the aim of the current work, moving vehicles are required for detailed design of particular bridges since accelerations are amplified when considering the vehicle–structure interaction as well as the pavement roughness [16].

In previous studies on UDCSBs with prestressed concrete decks, the response under persistent [9] and accidental [17,18] situations has been studied, by considering different geometrical and mechanical configurations through parametric analyses. The objective of this study is to analyse the response of UDCSBs with composite decks under moving loads to identify the most appropriate structural configurations of this bridge typology to satisfy the SLS of vibrations.

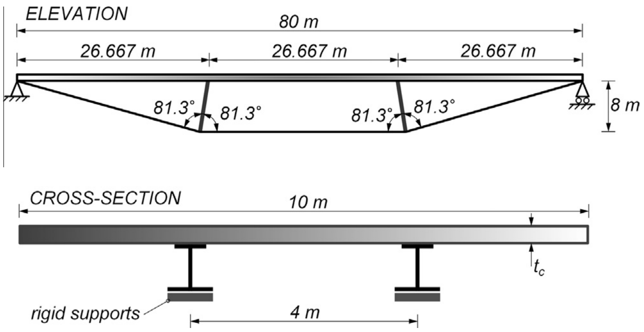

Fig. 3. Elevation and cross-section of the UDCSB considered in the analysis.

2. Numerical model

The current investigation is performed by employing the commercial Finite Element (FE) software Abaqus [19]. A single-span simply supported bridge is studied in the current work (Figs. 2 and 3). The span length that is considered is 80 m, so that results can be compared with previous studies [9], which demonstrated the appropriateness of this bridge type for this span range. Owing to the efficient structural behaviour, a UDCSB with two struts is analysed, in which the three subspans have identical lengths. Hence, the selected geometry is representative of the studied bridge typology. Initially, a deck formed by two longitudinal I-beams and a reinforced concrete slab is employed, although later new configurations will also be investigated. The total width of the bridge is 10 m, and the distance between the axes of the I-beams is 4 m. The elements of the bridge are dimensioned by performing static and fatigue analyses to fulfil the corresponding limit states, and a deck depth to span length ratio of 1/76 is achieved. Specific dimensions of this initial bridge and material properties are summarised in Fig. 4 and Table 1.

Six stays are employed, these are divided into two families in which each family is anchored at each I-beam at the support sections. The resultant force introduced by the stays at the supports is applied at the centroid of the composite section, and consequently the stays do not introduce any bending moment at the support sections. The eccentricity of stays at midspan is 10% of

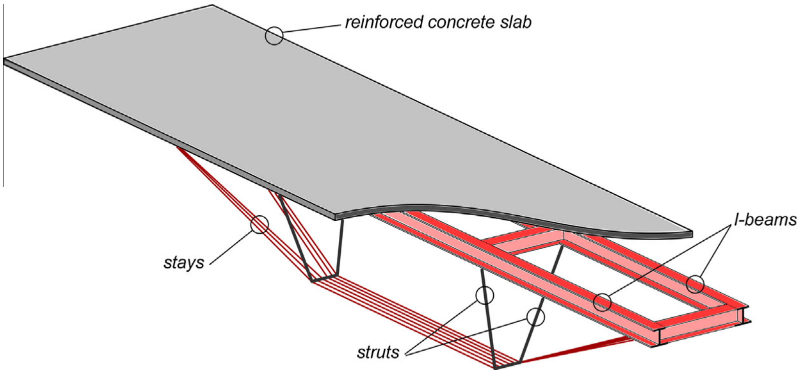

Fig. 2. Schematic view of a single-span 2-strut UDCSB and its elements.