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Deck–tower interaction in the transverse seismic response of cable-stayed bridges and optimum configurations

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ABSTRACT

Modern design solutions in cable-stayed bridges give a significant importance to the seismic response in the transverse direction. This work is focused on the dynamic interaction between the deck and the towers, exploring the key role of different vibration modes. An extensive parametric analysis is proposed to address the influence of the main span length, the tower geometry, the cable-system arrangement, the width and height of the deck and the soil conditions. It is demonstrated that the vibration modes that govern the seismic response of cable-stayed bridges in the transverse direction involve the interaction between the tower and the deck, but the order of these modes and the parts of the deck that are affected change with the main span length. It is also observed that the interaction between the deck and the towers during the earthquake is maximised if their isolated vibration frequencies are close to each other, leading to a significantly large seismic demand. Analytical expressions are proposed to obtain the critical frequencies of the towers for which these interactions arise, and recommendations are given to define the tower geometry in order to avoid such problematic scenarios.

1. Introduction

Cable-stayed bridges represent optimum solutions for an ever expanding range of spans and usually constitute the backbones of infrastructure networks. Their design is governed by the response to dynamic actions such as wind or earthquakes due to their characteristic flexibility and low damping [1]. Furthermore, complex modal couplings arise from the interaction between the towers, the deck and the cable-system and depend upon their relative stiffness and mass, as well as the frequency content of the excitation [2,3]. It is essential to have a clear understanding on these effects in order to ensure the adequate response of the structure under different loading scenarios.

The vibration of the cables can transfer energy between the deck and the towers during the earthquake [4] but, depending on the support conditions, the direct interaction between both members is potentially more significant. The connection of the deck to the abutments, intermediate piers and (especially) to the towers affects the response of the whole structure [5]. A considerable number of works address the influence of the deck–tower connection from the point of view of the static [6,7] and the seismic response [8–12]. The current trend in the design of cable-stayed bridges in seismic areas is to release the deck from the towers as much as possible in order to reduce the seismic demand in the towers, which are key elements for the integrity of the structure [13]. However, the deck needs to be fixed to the towers in the transverse direction in order to control its deformability under wind actions (e.g. Rion-Antirion bridge, Greece). Recent studies on cable-stayed bridges with this type of connection have found that the deck–tower reaction significantly increases the transverse shear force and bending moment in the towers, making the transverse component of the earthquake more demanding than the longitudinal (along-deck) and vertical directions [14,15]. Indeed, the damage in the tower of the Chi-Lu bridge tower during the Chi-Chi earthquake (Taiwan 1999) can be directly attributed to the transverse response, and it is arguably the most severe seismic damage ever reported in a cable-stayed bridge [16]. Unfortunately, studies focused on the transverse seismic response of cable-stayed bridges are scarce.

The magnitude of the transverse deck–tower reaction is determined by the interaction between several bridge components with very different dynamic properties, i.e. the deck, the towers and the cable-system. Different vibration modes involving the deformation of one or more of these three components play an essential role in the seismic response. Cable-stayed bridges below 400 m main span length present important modal couplings between the deck and

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the towers that affect the fundamental vibration modes [3]. However, in long-span bridges the first vibration mode involves exclusively the transverse flexure of the deck, with little or no interaction with the towers [17]. The large flexibility, important modal couplings and the typical broad frequency content of ground motions make the seismic response of cable-stayed bridges prone to strong high-order mode contributions (up to 25 Hz frequency), as observed in [18]. Code-based seismic analyses typically include as many vibration modes as needed to activate a certain percentage of the mass of the bridge, usually 90%. As a result, the relative contribution of different modes is not clearly considered in the design, which is based on iterative techniques that rely upon the experience of the designer [7]. Different authors proposed design techniques to define the cable prestressing forces in order to meet several requirements [19,20]. Few works include dynamic actions in the design procedure. Ferreira and Simoes [21] proposed a formulation to design a two-dimensional cable-stayed bridge with active control devices under longitudinal ground motion, without considering the influence of the tower shape. Calvi et al. [22] presented a conceptual design method that accounts for the seismic actions as well as the deck and tower configurations in the longitudinal and transverse directions, recommending further studies on the seismic response of the towers with transverse struts. Hayashikawa et al. [23] studied the seismic behaviour of steel towers in which the effect of the cable-system was simplified with equivalent springs and the interaction with the deck was ignored. However, the importance of this effect has been recently observed by [3,13,14].

To the best of the author's knowledge, there are no previous papers focused on the transverse seismic response of cable-stayed bridges accounting for the contribution of different vibration modes and the influence of the tower shape, among other structural features. This is the scope of the present work, which presents an extensive numerical analysis in a wide range of main span lengths, tower shapes, cable-arrangements, deck widths and distances between the deck and the foundation level. Altogether, a total of 1050 three-dimensional Finite Element (FE) models are studied. After presenting the proposed structures, the vibration modes of the individual towers and the complete bridges are studied. Two different analysis methods and modelling techniques are then compared. The Modal Response Spectrum Analysis (MRSA) represents the optimum balance between calculation speed and accuracy (for the purpose of the study), and it is adopted. As the main span length increases, it is observed that the transverse response is mainly dominated by higher-order modes that involve different parts of the deck. The tower geometry, deck width and height significantly influence the contribution of the governing modes, which allows for optimum designs aiming to reduce the seismic response. This work also demonstrates that the seismic response and the interaction between the deck and the tower in the transverse direction is maximised when their frequencies (calculated separately) are close to each other, proposing simple analytical expressions to predict these problematic scenarios.

2. Description of the proposed bridges

The bridges considered in this work have a conventional symmetric configuration with a composite (steel–concrete) girder and two concrete towers. Fig. 1 presents the different tower shapes proposed, the elevation and plan views, and the keywords employed to refer to the results in the following sections. The cross-sections of the tower, girder and cable-system are defined in terms of the main span length (L_P), which also configures the side spans (L_S) and the tower height above the deck (H). A complete description of the bridge sections and dimensions is available in [3]. Two different semi-harp cable arrangements have been defined: two Lateral Cable Planes (LCP) or a single Central Cable Plane (CCP). The deck has a composite (steel–concrete) cross-section that is constant along the length of the bridge and depends on the cable-arrangement: (1) LCP models present an open deck cross-section with two edge I-shape steel girders and a 25 cm thick concrete slab spanning transversely, (2) the deck in CCP bridges has a U-shape steel girder that forms with the top slab a closed-box section and provides with additional torsional resistance. The support conditions of the deck at the abutments and the towers are depicted in Fig. 1. The intermediate piers only constrain the vertical movement of the deck. The deck is rigidly connected to the towers in the transverse direction (Y), whilst it is released in the longitudinal (X) and vertical (Z) directions.

The parametric study is based upon the main span length (L_P), which completely defines all the elements of the bridge, with the exception of the width of the deck (B) and the distance between the foundation of the tower and the deck level (H_i, Fig. 1). The main span is modified from 200 to 800 m, each 10 m, considering four different deck widths: $B = 20, 25, 30, 35$ m and a conventional value for the deck level ($H_i = H/2$). In addition, two more values of H_i are considered for the whole span range: $H_i = H/1.5$ and $H_i = H/2.5$, setting the deck width to $B = 25$ m. Altogether, 1050 bridge models are implemented in a general-purpose finite element analysis package [24]. The elastic properties in the studied bridges are defined from the relevant Eurocodes [25,26]. No material nonlinearities have been considered.

A number of initial studies were conducted to ensure the accuracy and suitability of the modelling assumptions:

- The effect of the foundations at the towers in the H-LCP bridges was initially represented by means of springs, selecting their flexibility based on the dimensions of the foundation and the soil properties (both rock and soft soil conditions were considered). It was observed that the vibration modes below 3 Hz, which govern the transverse deck–tower reaction as discussed later, do not involve the movement of the bridge supports. Consequently, the supports of the towers, piers and abutments are completely fixed in this work in order to simplify the parametrisation of the model.
- The influence of the cable–structure interaction was explored in cable-stayed bridges with different main spans and central cable layouts (Y-CCP). It was observed that by including multiple elements per cable (MECS) the transverse deck–tower reaction is decreased by 0%, 30% and 25% in bridges with 200, 400 and 600 m main span, respectively, in comparison with the homologue models with one element per cable (OECS), in agreement with [27]. The authors propose OECS for this study in order to facilitate the parametrisation and allow for the analysis of a large number of models. OECS is considered a valid approach in this study because the scope is not to achieve the best accuracy in the deck–tower reaction, but to explore the interaction between the deck and the towers in a large number of models. This interaction is not deemed to be affected by the local vibration of the cables due to their reduced weight.

3. Modal analysis

The modal analysis of the tower models (in which the deck and the cable-system are removed) is presented in Fig. 2. The fundamental vibration modes are strongly influenced by the connections between the lateral legs.

The towers with inclined lateral legs connected exclusively above the deck (i.e. the inverted 'Y'- and 'A'-shaped geometries in Fig. 1) present vibration frequencies (ω) that are up to 70% larger than in the rest of the towers. This is because the transverse