Comfort in Slender Bridges Subjected to Traffic Loading and Hammering Effects

Alfredo CAMARA
PhD, Civil Engineer
Imperial College London
London, UK
a.camara@imperial.ac.uk

Khanh NGUYEN
PhD, Civil Engineer
IETcc-CSIC
Madrid, Spain
khanh@ietcc.csic.es

Ana M RUIZ-TERAN
PhD, Civil Engineer
Imperial College London
London, UK
a.ruiz-teran@imperial.ac.uk

Peter J STAFFORD
PhD, Civil Engineer
Imperial College London
London, UK
p.stafford@imperial.ac.uk

Summary

The verification of the Serviceability Limit State (SLS) of vibrations due to traffic live loads is typically ignored in the design of road bridges with conventional concrete decks. However, the vibrations perceived by pedestrians usually govern the design in slender and light-weight modern structures that take advantage of the improvement in the structural efficiency, material performance and constructive procedures. On the other hand, the comfort of the vehicle users is traditionally ignored in the design of the bridge because pedestrians are usually more sensitive to vibrations. However, in many highway bridges without pathways the only users of the structure are those in the vehicles (drivers and passengers). Considering all the possible bridge users and their specific sensitiveness, this paper addresses the vibration serviceability in a slender under-deck cable-stayed bridge subjected to heavy traffic loading. In this structure the prestressed concrete deck spans a distance of 80 m with a depth-to-span ratio of 1/80. The vehicle-bridge interaction accounts for aspects traditionally ignored like the wheel dimensions and the cross-slope of the bridge. A large number of time-history analyses is conducted to address the influence of road and vehicle properties on the SLS of vibrations. This work is completed with the study of the vehicle impact when it enters and leaves the bridge. The results clearly demonstrate the influence of the wheel dimensions and the road conditions, as well as the importance of high-order modes on the response.

Keywords: Slender bridges; comfort criteria; pedestrians; vehicle users; wheel size; vehicle velocity; hammering effect.

1. Introduction

The verification of the Serviceability Limit State (SLS) of vibration has been traditionally ignored in the design of conventional bridges. However, traffic-induced vibration can be significant in slender structures. Vibrations are so relevant in the design of slender decks that usually limit its depth [1].

The simplest way of controlling the SLS of vibrations is by indirectly limiting the bridge static deflection under the live load [2]. Recently, it was shown that displacement-based methods can lead to unacceptably unsafe estimations of the vibrations perceived by the bridge users [3]. Two main reasons lay behind this relevant conclusion in slender bridges; (1) the response is not clearly dominated by the fundamental vibration mode; and (2) the pavement roughness is essential and it should be included through vehicle-bridge interaction models [4,5]. High-order modes have an important contribution in the overall response and time-history analyses of the accelerations recorded in three-dimensional (3D) Finite Element (FE) models are generally required in comfort studies.

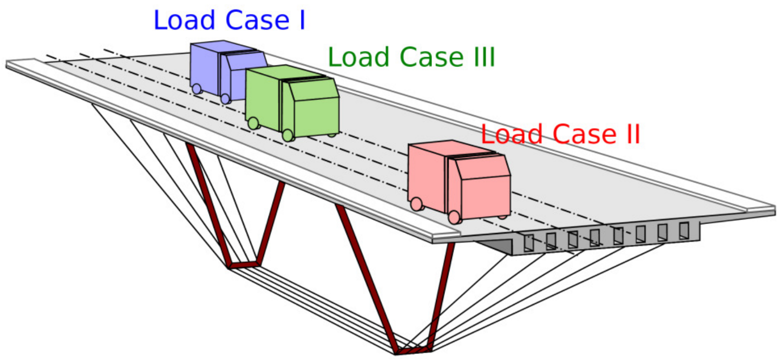


Fig. 1. Under-Deck Cable-Stayed Bridge (UD-CSB) and different load cases considered in this work.

Current Vehicle-Bridge Interaction (VBI) models define a Multi-Degree-Of-Freedom (MDOF) system to describe the vehicle. In this model it is included the flexibility and damping of the tyre and the suspension. The model accurately captures the yaw, roll and pitching motions of the truck body. The weight and velocity of the vehicle considered in comfort analysis is obviously decisive for comfort analysis. Typically small trucks are considered the worse possible vehicle in terms of vibrations as they may combine both heavy vehicle weights and relatively high velocities. One of the most employed vehicles is the H20-44 truck model [3,4,6] defined by the American Association of State Highway and Transportation Officials (AASHTO) specifications [2], which combines a mass of 18.6t and velocities up to 120km/h. The roughness of the pavement is usually defined as an imposed displacement in the wheels described by means of an ergodic zero-mean stationary Gaussian random profile.

The deck slenderness in Under-Deck Cable-Stayed Bridges (UD-CSBs) can reach depth-to-span ratios even beyond 1/80 (Fig. 1). UD-CSBs have been proved to span medium distances in a very efficient way [7-10] and to perform satisfactorily under extreme design conditions [11,12].

This paper considers a slender UD-CSB as the case study and presents an innovative VBI model in which the wheel size and the cross-slope of the road are considered. A large number of numerical analysis has been conducted in order to study the influence of different features on the comfort of both pedestrians and vehicle users. The results clearly remark the large influence of the wheel radius on the vertical accelerations when the road irregularities are large, which has a direct interest for bridge designers and for the highway maintenance. Finally, the hammering effect triggered by the initial bounce of the vehicle on its suspension when it crosses the deck joint at the abutments is also studied, considering different bearing supports for the deck.

2. The bridge, the vehicle and their interaction

2.1 Description of the bridge and its vibration modes

The bridge considered in this study is an 80m span UD-CSB with 1m depth prestressed concrete

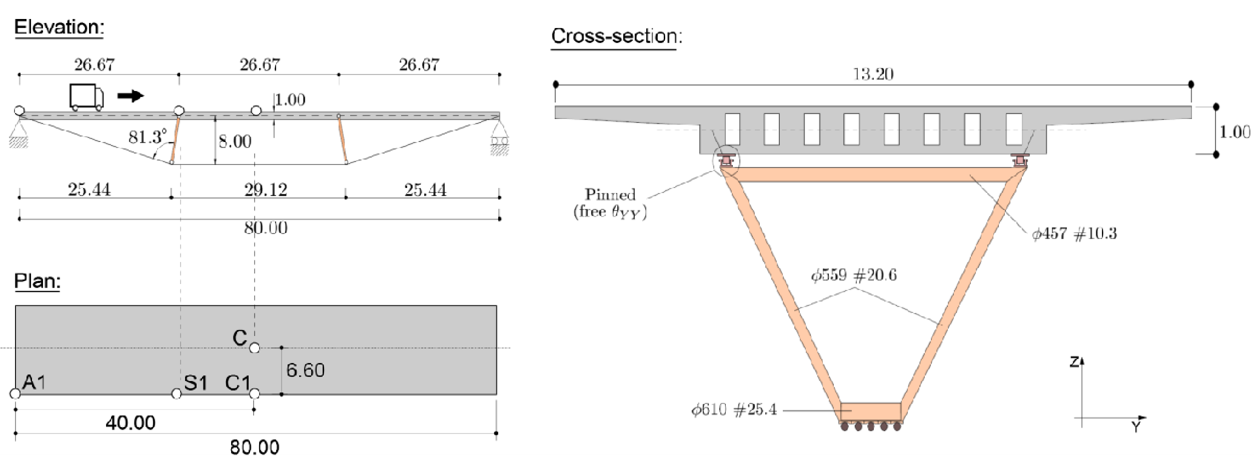


Fig. 2: Studied UD-CSB and labels at key deck positions used in the discussion. Units of the deck in metres and units of steel struts in millimetres (Φ diameter, # thickness).

deck (elastic modulus 35GPa). Two metallic struts (S355) divert the cable-system below the deck as represented in Fig. 2. The steel in the cable-system has an elastic modulus of 190 GPa. In this work two different deck bearings have been considered to study the vehicle hammering effect at the abutments. Both 500 x 600 x 70 mm Laminated Elastomeric Bearings (LEBs) and POT bearings are proposed. More details about the bridge model may be found in [3,12].

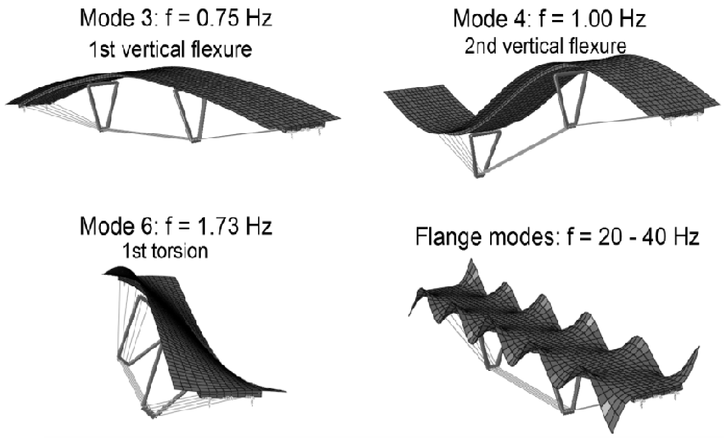


Fig. 3. Four relevant vibration modes of the bridge with LEB supports.

Four relevant vibration modes are included in Fig. 3 in the model with LEB supports. In this structure, the first two vibration modes correspond to horizontal movements of the supports and do not contribute to the vertical accelerations caused by the passing vehicles. The first mode with vertical flexure of the deck has a frequency of 0.75Hz and presents a single symmetric wave that governs the vibration at midspan (point C in Fig. 2). The second vertical flexural mode is antisymmetric and has a relevant importance for the vertical vibration recorded in the strut-deck connection (point S1 in Fig. 2). These two vibration modes contribute equally to the structural response regardless the eccentricity of the vehicle. However, the 1st torsion mode (1.73 Hz) is clearly activated when the vehicles cross the bridge eccentrically, as in Load Cases II and III represented in Fig. 1. Finally, Fourier amplitude spectrum analysis of the vertical acceleration demonstrated that there is a very important a group of local flange modes that are closely spaced and have frequencies ranging from 20 to 40 Hz (Fig. 3). These modes are very significant for the vertical vibration recorded at the flanges of the deck, which is relevant as footways are located at the flanges and pedestrians are especially sensitive to vertical accelerations. The model with POT supports present similar vibration modes, avoiding those related with the LEB deformation. From this initial analysis of the vibration modes it becomes obvious that the SLS of vibrations in this type of bridges cannot be studied accurately by simply considering the first vibration mode, as traditional displacement-based methods inherently accept. This is especially true the closer to the abutment and to the flanges of the deck, and the larger the eccentricity of the vehicles.

2.2 Vehicle model and interaction with the bridge

The multi-degree-of-freedom H20-44 truck (18.6t) shown in Fig. 4 is employed in this study. It has 7 degrees of freedom and the following fundamental vibration modes and associated damping ratios ξ: (1) body roll, f = 0.92Hz, ξ = 34%; (2) body pitch, f = 0.93Hz, ξ = 52%; (3) body pitch and heave (vertical motion), f = 1.14Hz, ξ = 29%. The detailed description of the mechanical properties of this vehicle model is reported elsewhere [4].
The roughness profile, *r(x)*, is an imposed displacement defined as [5]:

$$r(x) = \sum_{k=1}^{N} \sqrt{2\varphi(n_k)\Delta n}\cos(2\pi n_k x + \theta_k) \quad (1)$$

where x is the position of the point (Fig. 4); n_k is the spatial frequency, n_1 = 0.01 and n_N = 10 cycle/m are respectively the lower and upper cut-off frequencies; Δn represents the increment between consecutive frequencies; θ_k is a random phase angle between 0 and 2π that allows for the definition of independent profiles, 10 profiles have been considered in this study and the average and the standard deviation of the analysis conducted with these are presented in the each case; finally, $\varphi(n_k)$ is the Power Spectral Density (PSD) function ISO 8608:1995 [13]:

$$\varphi(n_k) = a\left(\frac{n_k}{0.1}\right)^{-2} \quad (2)$$

a being the spectral roughness coefficient [m3/cycle] that depends on the quality of the road pavement. The following values are considered in this work according to [13]: very good (road A) *a* = 16E-6; good (road B) *a* = 64E-6, regular (road C) *a* = 256E-6, bad (road D) *a* = 1024E-6. Highways and major roads typically have good maintenance and can be classified as roads A – B. Two innovative features have been included in this work by modifying the conventional pavement roughness definition in Eq. (1); the real wheel dimensions and the cross slope of the road:

$$\bar{r}(x) = r(x_P) + \sqrt{R^2 - d^2} + r_0 \quad (3)$$

This modified roughness profile adds two new terms to the original profile defined at the contact point between the wheel and the road (P), $r(x_P)$. The term '$\sqrt{R^2 - d^2}$' takes into account the 'deep valleys' in which the lower part of the wheel does not contact the profile generated by Eq. (1). In Eq. (3) *d* is the horizontal distance between the contact point of the wheel with the road roughness profile and the wheel center; *R* is the wheel radius. On the other hand, the parameter r_0 considers the 2% cross slope of the road. It is a constant shift added only to road profile associated with the wheels which are closer to the bridge centerline if the vehicle is eccentric ($\bar{r}^2_{r,f}(x)$ in Fig. 4). The resulting profile is filtered from the original one and is obtained with Eq. (3) in the 80m long deck and the external platforms, with a length of 30 m each at both sides of the deck.

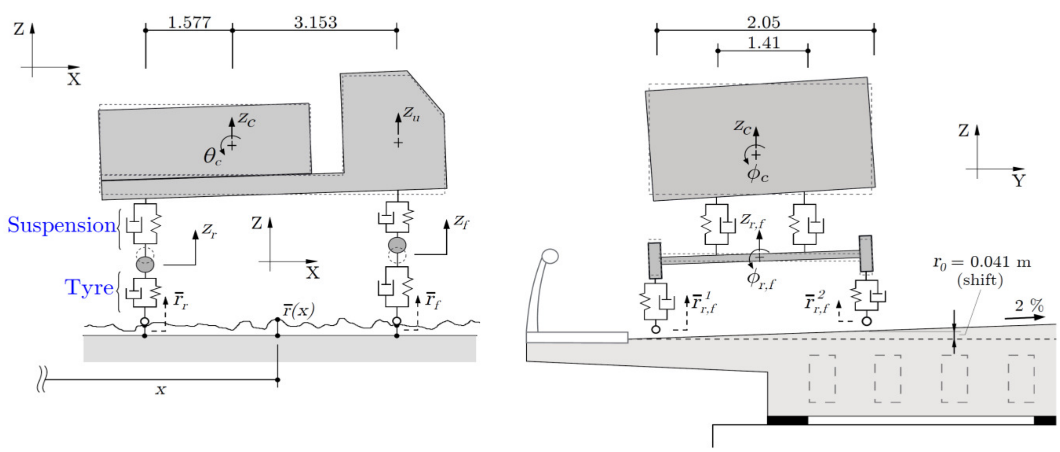


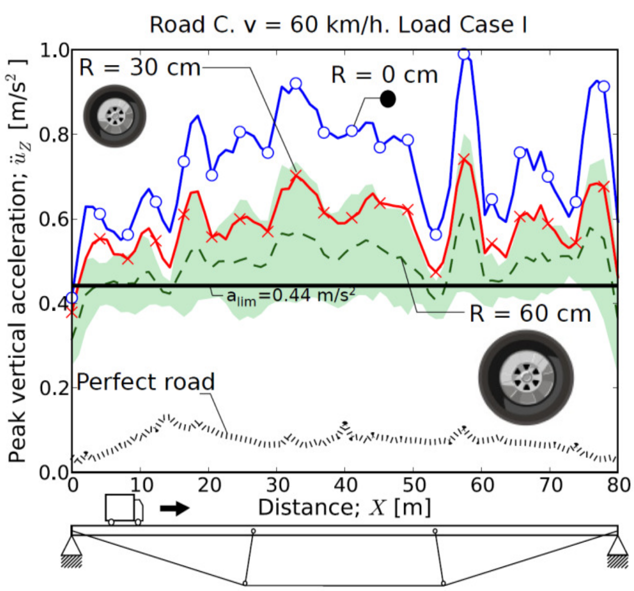
Fig. 4. Multi-degree-of-freedom model of the vehicle and pavement roughness definition.

The numerical analysis is divided in two steps; (1) the self-weight of the structure and the vehicle is statically applied; (2) a constant velocity is imposed to the vehicle. The vehicle is initially 30 m away from the left abutment to ensure that when it accesses the deck the bouncing caused by the initial deformation of the suspension and tyres is negligible. The second step involves a nonlinear dynamic analysis in which the loads transmitted by the contact between the tyre and the pavement are functions of the bridge deflection and the dynamic response of the vehicle, requiring an iterative procedure solved by the HHT implicit integration algorithm [14]. The Rayleigh damping in the structure is 2% in both the fundamental mode (0.75Hz, see Fig. 3) and that corresponding to the maximum frequency of interest: 45Hz [4]. Apart from the structural damping, additional energy is dissipated through the rigorous definition of the damping in the vehicle.

3. Impact of the road and the vehicle on the users comfort

3.1 Vehicle wheel size

Different wheel radii have been considered in the analysis. Fig. 5 presents the peak vertical acceleration (absolute value averaged for 10 road profiles) along the deck centreline when the vehicle is not eccentric (Load Case I) and its velocity is 60km/h. The peak acceleration recorded in the deck is compared with the maximum value that would be admissible by pedestrians according to BS5400 [15]: $a_{\lim} = 0.5\sqrt{f} = 0.44\text{m/s}^2$, where f is the fundamental frequency of the bridge (f = 0.75Hz in this case). Two types of road have been considered in order to highlight the importance of the wheel size; a completely perfect road ($\bar{r}(x) = 0\,\text{m}$) and a regular road (C) with different wheel radii (0, 30 and 60cm). The coloured band centred on the averaged value represents the mean plus and minus one standard deviation at each point, it was only included for R = 60cm.



From Fig. 5 it is evident the importance of the road quality on the pedestrian's comfort. Although this will be studied in detail in the next section, it is worth start mentioning that the accelerations are far beyond the admissible levels when the road quality is not very good.

The effect of the wheel radius has been also observed to be relevant when the road quality is not very good. The larger the wheel dimensions of the truck the smaller the vertical acceleration recorded in the deck. The reason is that larger wheel radii filter more the original road roughness profile in Eq. (3). The impact of this result is very relevant as normally Vehicle-Bridge Interaction (VBI) models conducted in previous research works ignore the wheel size: Fig 5 clearly demonstrates that the vertical acceleration recorded in that case (*R* = 0cm) is unrealistically large. This work will continue in the following sections with the wheel radius *R* = 30cm.

3.2 Road roughness

From the analysis point of view, the only way to consider the road roughness is through VBI models. On the contrary, Point Load (PL) models describe the vehicle action as moving loads, thus ignoring the vehicle vibration and its interaction with the bridge. The roughness profile cannot be directly considered in PL analysis and this has a major impact on the accelerations recorded in the deck. Figure 6(a) compares the peak vertical deck acceleration with the VBI and PL models for different road qualities, Load Cases and vehicle velocities. It may be observed that the larger the spectral roughness coefficient, i.e. the worse the road quality, the larger the difference between both analysis. This clearly explains the importance of the road quality from the point of view of the pedestrians' comfort. If the road maintenance does not ensure a good road quality, the pavement roughness will induce large accelerations in the deck that will reduce in turn the comfort of the users. This effect can only be observed with VBI models. For typical pavement conditions in highways (roads A-B), the average peak acceleration in the deck with the VBI model is around 2-5 times higher in than that recorded with the PL analysis. The difference between these two vehicle models is slightly higher if the vehicle is eccentric. On the other hand, if the road pavement is perfect (a = 0m^3/cycle) the VBI model still leads to higher accelerations (about 80% larger) because of the vehicle vibration and its interaction with the bridge, ignored in PL analyses.

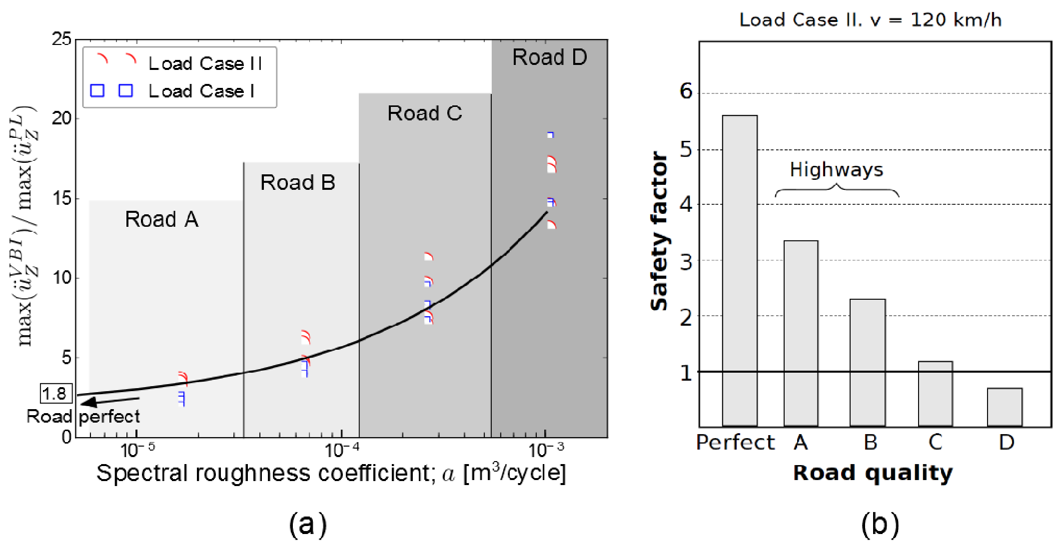


Fig. 6. (a) ratio between the peak deck acceleration with VBI and PL models. (b) vehicle users' comfort.

The great majority of the comfort studies conducted in research works so far are focused on the pedestrians, as they are the most sensitive bridge users. However, the comfort of vehicle users is also important as in many highway bridges they are they only possible users of the bridge. The only way to study in the numerical analysis the vibrations that are sensed by persons in the vehicle cabin is by means of VBI models. Fig. 6(b) presents as a safety factor the ratio between the peak cabin acceleration and the maximum admissible value according to ISO 2631: 1m/s^2 (r.m.s.) [16]. The peak cabin acceleration is weighted by a factor of 0.48 to consider the higher admissible acceleration when seated [16]. In this figure it is confirmed that the vehicle users' comfort is less critical than that of pedestrians. For typical pavement conditions in highways the vibrations in the vehicle cabin are not of a concern, even if the truck crosses the bridge with the maximum possible eccentricity and hence triggers the torsion modes. However, the vibrations in the vehicle are uncomfortable if the road quality is poor (D).

4. Hammering effect

Finally, the response of the bridge and the vehicle hammering effect with different support conditions is explored. From the comparison of the peak vertical acceleration along the deck in the model with two concentrated struts and very good road quality (road A), it is observed that the influence of support conditions is only appreciable close to the abutments, provided that both LEB and POT bearings are very stiff in vertical direction.

The support device technology only affects to the hammering effect of the vehicle when the wheels first contact the deck surface at the left abutment and when they leave the bridge at the right abutment. Due to the vertical deformation of the supports (only if LEB supports are employed) and the rotation of the deck at the abutments after the self-weight is applied to the model, an initial movement between the platforms and the deck appears. This relative vertical displacement is typically below 1 mm but triggers the bouncing of the truck when it accesses the bridge. It is also affected by the differential vertical stiffness of the external platform and the deck. Fig. 7 compares the vertical acceleration recorded at the left abutment (on the right sidewalk according to the vehicle direction) when different support conditions are employed. A perfect road surface is considered in this section in order to isolate the initial bounce of the truck.

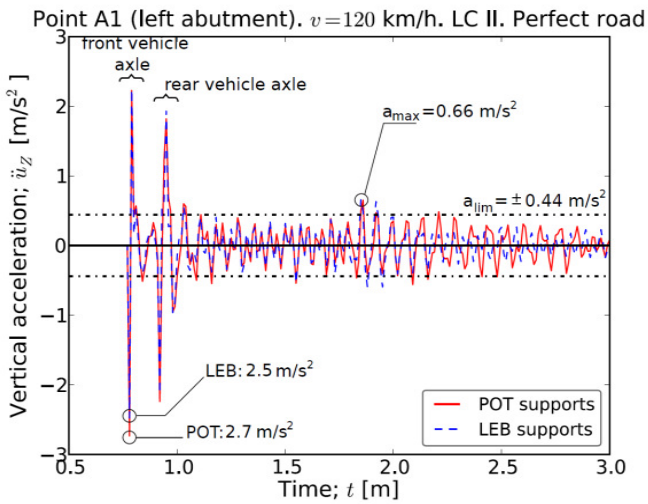


Fig. 7: Record of the vertical acceleration at the left abutment (sidewalk, point A1 in Fig. 2. Load Case II. v=120 km/h. Perfect road.

It is verified that the hammering effect of the vehicle is slightly higher (up to 10%) when supports with certain vertical flexibility (LEB) are substituted by infinitely stiff devices (POT). After this initial pulse, the response at the abutments is similar in both cases, but the stationary vibration seems to be larger in the model with POT supports once the peak acceleration a_{max} (apart from the hammering effect) is achieved. The hammering effect caused by the initial bounce of vehicle on its suspension when crossing the deck joint at the abutments is the source of the high vertical acceleration peak at the deck, nearby the abutment. Such peak acceleration would far exceed any admissible limit in the SLS of vibrations (a_{lim}). However, limiting the structure comfort in light of this local effect is questionable because it is a single pulse in the acceleration record associated to a high-order frequency.

5. Conclusions

This work addresses the Serviceability Limit State of vibrations in a very slander bridge, which is of maximum importance as it can easily govern the design. An innovative Vehicle-Bridge Interaction model has been employed and a large number of time-history analyses have been conducted to obtain the following relevant conclusions:

a. The importance of high-order vibration modes in the vibration of Under-Deck Cable-Stayed bridges has been observed. Displacement-based procedures are not recommended to study the SLS of vibrations in slender bridges. Instead, Vehicle-Bridge Interaction procedures and three-dimensional Finite Element models should be employed.
b. The definition of the pavement roughness in this work accounts for the filtering effect of the real wheel dimensions and the cross-slope of the road. The importance of the wheel size in the model has been clearly observed and should be considered in the analysis, especially if the road quality is poor.
c. The pavement roughness is of paramount importance for the vibrations sensed by the users of the bridge. It should be always included in the numerical model. Adequate road maintenance should be foreseen as the accelerations can easily exceed the admissible levels for pedestrians if the road quality is not very good. The comfort of vehicle users has been

also studied and it was concluded that, although less critical than in the case of pedestrians, it should be considered.

d. The impact of the vehicle in the bridge due to the hammering effect is very important in terms of the peak acceleration recorded close to the abutments. However, the duration if this pulse is short and the comfort limits proposed by normative are not clearly applicable. The type of support is not very relevant for the hammering effect, provided that they are properly designed to provide enough vertical stiffness.

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