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DYNAMICAL BEHAVIOUR OF AN UNDER-DECK CABLE-STAYED FOOTBRIDGE UNDER THE ACTION OF PEDESTRIAN TRANSIT

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Abstract: In recent years, the new trends in the construction of footbridges have led to the design of innovative bridge types, such as under-deck cable-stayed bridges, with slender and lighter decks. This tendency has made the serviceability limit state of vibrations relevant in the design of footbridges. The natural frequencies of these bridge types, in many occasions, fall within the range of the frequencies of the dynamic forces induced by pedestrians. Therefore, the accelerations induced by pedestrian transit are not admissible when the users' comfort has to be guaranteed. In this paper, the dynamical behaviour of an under-deck cable-stayed footbridge under pedestrian action is presented. Both vertical and lateral components of the pedestrian action have been considered. For the analysis of the vertical component, the under-deck cable-stayed footbridge is loaded with groups of pedestrians moving across the footbridge with two different velocities. For the analysis of the lateral component, the frequencies of the lateral forces induced by the pedestrians are taken from the range 0.7-1.2Hz. (Bachmann, 2002). The verification criteria for the serviceability limit state of vibrations established by Eurocode are considered, and the response of the under-deck cable-stayed footbridge was compare with these design standards.Results of the analyses carried out shows the acceleration values of the footbridge in both horizontal and vertical direction. The important of the application of a bracing system on the horizontal acceleration due to laterally induced pedestrians' action. The effect of density on the vertical and horizontal acceleration values of the footbridge due to induced pedestrians' action. Finally, the result of the effect of speed and different phase time in the induced pedestrians' action is shown.
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Keywords: Dynamic behaviour; lateral vibration; under-deck cable stayed footbridge; action of pedestrian transit.

1. Introduction.

Over the past years, new types of bridges have been developed, one of which is the under-deck cable-stayed bridges (Fig.1). This is a form of cable-stayed bridges, in which the stay cables are located under the deck. The stay cables are self anchored in the deck at the section that are supported over the abutment, and are deflected by struts working under compression. Ruiz-Teran and Aparico (2007a) have outlined the state-of-the-art of this type of bridges, and explained their structural behaviour (Ruiz-Teran and Aparicio 2008). When a load acts on the deck of a conventional bridge (without a cable-stayed system), the only response available to resist the isostatic moment is by the bending of the bridge deck.

Jumet footbridge (courtesy of Jean Marie Cremer, Bureau Greisch)

Fig.1. Truc de la Fare overpass (courtesy of Nicolas Janberg, www.structurae.de)

However, in the case of an under-deck cable-stayed bridge, this isostatic moment is resisted by two mechanisms: (1) the flexural response of the deck, which is the bending and the axial response of the cable stayed system, and (2) the axial response, consisting on tension in the stay cables and compression in the struts and the deck. (Ruiz-Teran and Aparico 2007b)

Special considerations are given to the serviceability limit states (SLS) in the design of footbridges. The comfort of pedestrians has made the SLS of deflection and vibration determinant in the design. When pedestrians induce dynamic forces with frequencies falling within the range of the natural frequency of the footbridge, significant vibration of the structure is generated. The large accelerations may not be acceptable for guaranteeing the comfort of the pedestrians crossing the footbridge.

Pedestrian loading is known to act in the vertical and horizontal direction, causing excitation of footbridge girder in these directions. Large accelerations due to pedestrians have been reported in several footbridges. This was the case of the T-bridge, a cable-stayed bridge constructed in Japan. The footbridge girder was noted to vibrate in the lateral direction when pedestrians walked on the footbridge. This happened for first time when the bridge was opened to the public (Nakamura and Kawasaki 2006). A similar situation occurred in the Millennium Bridge in London (Dallard and Fitzpatrick 2001).

In this paper, the dynamical behaviour of an under-deck cable-stayed footbridge under pedestrians' action is studied. In an initial study, an MSc dissertation (Adesua, 2009), only the vertical accelerations induced by pedestrians were considerer, and planar finite element (FE) models were used. The under-deck cable-stayed footbridge was loaded with a group of pedestrians moving along the footbridge with different speeds. In this paper, subsequent research is included, considering both horizontal and vertical components, and using 3D FE models. The dynamic model proposed by Nakamura and Kawasaki (2006) is used for the analyses. Two parametric analyses have been developed in order to investigate the effects of synchronisation and density. The comfort criteria used for this study is that defined by Eurocode 1 (BS 2003). The maximum acceptable acceleration in any part of the bridge deck is equal to 0.4 and 0.7 m/s^2 for the horizontal and vertical acceleration respectively. The former limit for the lateral vibration is for an exceptional crowd condition.

2. Proposed Lateral Induced Force.

The dynamic model proposed by Nakamura and Kawasaki (2006) to define the forces induced by pedestrians is described by Equation (1). It was based on the observation of pedestrians' synchronisation with the vibrating footbridge girder. The pedestrian density, the rate of pedestrians synchronized, the rate between the lateral and vertical forces induced by pedestrians, and the pedestrians' attitude to large vibration amplitude were considered.

$$F_P(t) = K_1 \quad K_2 \quad H(X_B') \quad G(f_B) \quad M_p g$$

(1)

where F_P is the modal lateral dynamic force induced by pedestrians, $M_p g$ is the modal self-weight of pedestrians, K_1 is the ratio between the lateral and the vertical (weight) forces due to the pedestrians, K_2 is the percentage of pedestrians that synchronised with the vibrating girder, $H(X_B')$ is a function that describes the pedestrians' synchronisation nature, that is assumed to be proportional to girder velocity of X_B' at low velocities.

3. Description of the footbridge and the models used for the analysis.

3.1 The Dietersheim viaduct.

The under-deck cable-stayed bridge used in this research is a real structure located in a sewage treatment plant in Munich, Germany (Schlaich, 2004).Three identical footbridges like the one considered, connects the lift tower and three sewage tanks. The footbridge has a span of 21.6m with a deck width of 2.7m. The deck consists of 2 main beams (HEB 260), which are supported by 2 tension rods with a 56mm diameter. The tension rods are anchored to the main beams at the support sections. The cables are deviated by means of two vertical struts, being in horizontal direction at the central section of the bridge.

The strut has a triangular shape with the beams and the rods in the corners. To provide a gradual change of direction, the rods are led over a saddle made up by a half tube, which are stiffened by steel plates in longitudinal and cross direction.

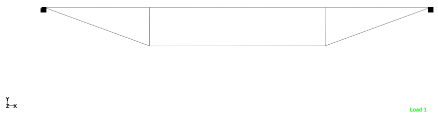
3.2 The FE models.

The FE models have been developed by means of the software package for structural analysis STAAD PRO. (STAAD Pro Intl 2004).

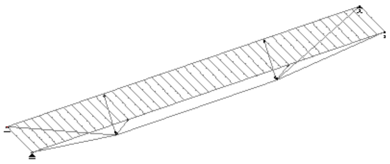
For the two-dimensional FE model of the under-deck cable-stayed footbridge, the section builder of the FEM software is used to generate prismatic properties for a single beam with a equivalent section to the 2 HEB-260. A single cable member with an equivalent section and diameter to the 2 56mm rods is used. The main beam is then divided into short members of 0.5m, in order to both achieve an appropriate accuracy and facilitate the introduction of the induced loads in the model.

In the three-dimensional FE model, the transverse beams (HE120B) were introduced at intervals of 0.5m. Because of the same reasons described above, the transverse beams were also subdivided by short transverse members of 0.25m length each.

The two- and three-dimensional models of the footbridge developed are included in Figure 2.



2-dimensional model.



3-dimensional model

Fig. (2). Models of the under-deck cable-stayed footbridge: (a) Two-dimensional and (b) three-dimensional models

The boundary conditions are a rolled connection at one side, and a pinned connection at the other, allowing rotations in both cases.

Two different three-dimensional models have been considered, one with cross-bracing located along the deck, and one without cross-bracing. These two models have been developed in order to investigate the influence of the cross-bracing in the lateral vibrations.

4. Description of the loading included in the model.

The static vertical load induced by one pedestrian, i.e. the weight of a pedestrian, is assumed to be equal to 750N. Eq. (2) is used to calculate the lateral pedestrian load as proposed by Nakamura. (Nakamura and Kawasaki 2006) The diagram included in Figure 3 illustrates how a vertical load moving across the bridge with a uniform speed is included in the model through a time-history. The general principle of the load-time function is, the load acts at designated nodal points at a given time

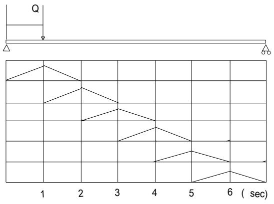


Fig (3): Illustration of moving load

Different models of loading are considered for this analysis to investigate the effects of the number of pedestrians (single pedestrian versus groups of pedestrians), the effect different speeds (walking, and running), and the effect of synchronisation of the groups of pedestrians in different walking pattern. A speed 0.5m/s is used for the walking pedestrians, while 1m/s for running pedestrians. The models considered are as stated below

Model 1: In this model the dynamical forces are represented as a single pedestrian walking along the deck of the under-deck cable-stayed footbridge. As the deck of the under-deck cable-stayed is divided by nodes at interval of 0.5m, the arrival time for the load model is equal to values between 0 to 44 seconds, which is the total time to cover the span of the bridge.

Model 2: This model represents the dynamical forces of a group of 22 pedestrians walking along the deck of the under-deck cable-stayed footbridge. The induced forces act on the nodes of the model. In this case, the group is walking on a straight line, one pedestrian after another with a time interval of one second between pedestrians with the effect of synchronisation with the lateral movement of the footbridge deck. A diagram to illustrate the walking pedestrians is shown in Figure 4.

Figure.4: Plan View of Model 2

Model 3: This model (Figure 5) is a more realistic model, as it is model to represent the dynamical forces of group of 22 pedestrians with some walking side by side along the transverse beams, with load-time function of one second and out of phase. The effect of synchronisation is also considered for this model.

Figure.5: Plane View of Model 3

Model 4: This model is similar to model 3, but with few pedestrians running while others walk along the under-deck cable-stayed footbridge. The synchronisation effect is still considered. The speed for those pedestrians running along the deck is taken equal to 1m/s, while the speed for those remaining pedestrian walking is equal to the ordinary 0.5m/s. The arrival time for the running pedestrians was between 0 and 22 seconds, which is still under the arrival time for the walking pedestrians. An illustration of this loading case is shown in Figure 6.

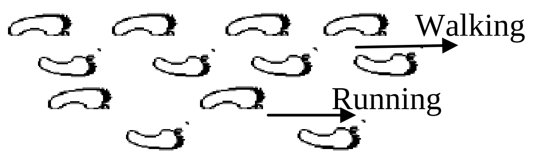


Figure.6: Plan View of Model 4

5. Results and discussion.

The maximum accelerations at mid span section for the first loading case, that simulates a single pedestrian on the deck of the under-deck cable-stayed footbridge, are provided in Table 1. In all of the cases, the maximum acceleration is under the design limit given by Eurocode 1 (BS, 2003).

Maximum acceleration (m/s^2)	Loading model 1	
	Braced	Un-braced
Vertical	0.055	0.047
Lateral	0.004	0.026

Table1: Maximum acceleration values at mid-span section due to the loading model 1

For the second loading model (Table 2), the maximum accelerations at mid-span section are found to be under the design value given by Eurocode in most of the cases, with the exception of those vertical accelerations when the footbridge was braced.

For the loading model 3, which simulate the group of pedestrians walking side by side and with different phase time, Table 2 shows that the value of the maximum vertical acceleration of the deck is above the design limit in both cases of braced and un-braced footbridge. These higher values are due to fact that the density of the pedestrians in an area is higher in the loading model 3 than in the loading model 2. It is noticed that the values of the lateral acceleration in the loading model 3 were lower than those in the loading model 2, which highlights the effect of density of the pedestrian. The reduced lateral acceleration in this model was due to the fact that pedestrians were moving out of phase, leading to induced lateral forces acting in opposite directions. Therefore, the lateral forces were balanced and almost cancelled.

For the loading model 4, which simulate the pedestrian induced forces for running and walking, Table 2 shows that for both braced and un-braced under-deck cable-stayed the acceleration in both directions is under the design limit.

Two time registers of accelerations at mid-span section are included in Figure 7.

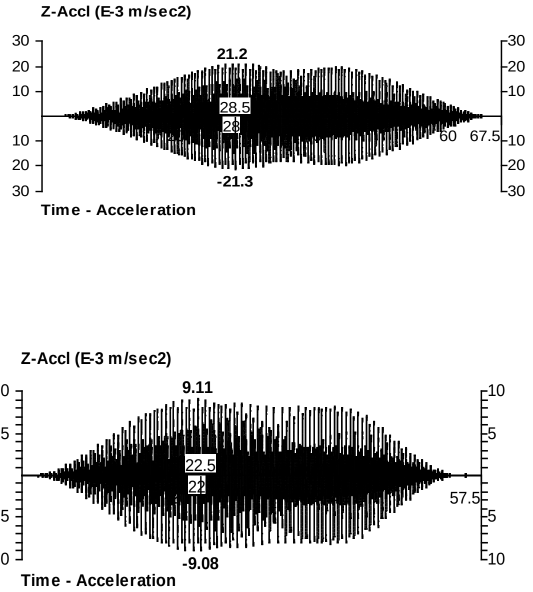


Figure 7: Lateral acceleration at mid-span section for the braced under-deck cable-stayed bridge due to the loading models (a) 2 and (b) 3.

The maximum acceleration at the mid-span section for the loading model 1 and model 2 on the deck of under-deck cable-stayed footbridge in the 2-dimensional model, are under the design limits given by Eurocode 1. The acceleration values are shown in Table 3 to compare with the values of the models on the 3-dimensional model.

6. Conclusions.

Several relevant conclusions can be drawn on the basis of this research:

- The horizontal accelerations at mid-span section of the under-deck cable-stayed footbridge due to pedestrian transit are smaller than the vertical accelerations.
- The horizontal or lateral accelerations of the under-deck cable- stayed footbridge under pedestrian transit can be negligible as long as a bracing system providing lateral stiffness is included. However, the provision of cross-bracing could lead to an increase in the vertical accelerations.
- The pedestrian density is directly related to the vertical accelerations induced on the under-deck cable-stayed footbridge. Increase of the vertical accelerations by 21% and 13% have been respectively observed in un-braced and braced models by comparing the loading models 2 and 3.
- The lateral accelerations are significantly reduced when the pedestrians are walking out of phase. Reductions of accelerations to 62% and 57% have been respectively observed in the un-braced and braced models by comparing the loading models 2 and 3
- The larger the velocity of the pedestrians, the larger the maximum accelerations, provided it is in the same phase time

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Maximum acceleration (m/s^2)	Model 2		Model 3		Model 4		Design limit (m/s^2)
	Braced	Un-braced	Braced	Un-braced	Braced	Un-braced	
Vertical	0.915	0.674	1.030	0.819	0.550	0.424	0.7
Lateral	0.021	0.295	0.009	0.111	0.014	0.175	0.4

Table 2: Maximum acceleration values at mid-span section due to the loading models 2, 3 and 4

		2-D	3-D
Maximum mid-span acceleration (m/s^2)	1 pedestrian	0.030	0.047
	22 pedestrian	0.512	0.067

Table 3: maximum acceleration values at mid-span section for loading model 1 and 2 in the 2-dimension and 3-dimension