Effects of terrain proximity on the aeroelastic response of a bridge deck

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ABSTRACT: Wind tunnel tests on sectional models are largely used to derive both aerodynamic forces and flutter derivatives of long-span bridge decks. The most common situation for this typology of bridges is to be far from the ground. Wind tunnel tests on sectional models are therefore generally carried out in a homogeneous and smooth flow. However, due to the possibility of channeling effects and a considerable turbulence intensity, the effects of terrain proximity deserve to be investigated if the bridge deck is close to the ground. The present paper reports the results of a wind tunnel test campaign aimed at the evaluation of wind actions and aeroelastic response of a bridge deck particularly close to the terrain. Wind tunnel tests are carried out both considering the classic configuration of isolated deck and simulating the terrain proximity with two different approaches. The results are compared.

KEYWORDS: Bridge deck, flutter, terrain proximity, wind-tunnel tests.

1 INTRODUCTION
The Marchetti Viaduct is a 290 m long arch bridge which will be built along the Milano – Novara highway, close to Ivrea, Italy. The bridge is composed by a single central arch with a trapezoidal section and the deck, which unusual width ($B_p = 41$ m) is coupled with a small height over the ground ($H_p = 7$ m, Fig. 1a). Such a configuration may emphasizes the aerodynamic interaction between the bridge and the terrain. Moreover, the noteworthy height of the side barriers, which is variable between 3 and 6.7 m, completes the picture of a project that is surely unconventional under the aerodynamic viewpoint.

Figure 1. The prototype bridge: cross-section (a) and full view (b).

To investigate such a situation, static and aeroelastic sectional-model tests on the deck of the bridge have been conducted in the Wind Tunnel Laboratory at the Faculty of Engineering of the University of Genova, which working section is 1.7x1.35 m. Both static and aeroelastic wind
tunnel tests have been carried out considering three different arrangements: a) the deck is isolated, far from the ground, in a uniform flow; b) a rigid plate is installed under the deck, to simulate the wind channeling effect between the deck and the ground; c) the deck is placed at the scaled distance over an artificially-rough ground that generates a boundary layer coherent with the expected velocity profile for the bridge site.

The analysis of these different conditions is not traditional for sectional model tests, and the whole of these simulations provides an overview about how the effects involved by different configurations may change the aerodynamic response of the bridge.

2 WIND TUNNEL TESTS

2.1 Experimental arrangement

Static and aeroelastic wind tunnel tests have been carried out using the same sectional model, which has been realized in aluminium with a geometric scale equal to 1:150. The model has a length $\ell = 694$ mm, and a width $B = 274$ mm ($\ell/B \approx 2.5$). Static tests have been conducted separately on the sectional model of the arch but are not reported in the present paper.

The central and side barriers of the prototype are made of perforated steel plates, whose porosity changes as a function of the height over the deck. Moreover, their height changes with continuity along the length of the bridge (Fig. 1b). In the wind tunnel tests an average value of the side barriers height has been considered. Due to the impossibility of reproducing their actual geometry respecting the Reynolds number similarity, an equivalent solidity ratio of the barriers installed on the model has been selected to reproduce the head loss measured on a portion of the full-scale barrier. The head loss has been evaluated measuring the drag force acting on a portion of the real bridge barriers and on different grids suitable to be installed on the model. The grid that has been chosen to carry out the tests develops the correct drag force in the range of the velocities of interest (Fig. 2).

As introduced in Section 1, three different arrangements have been considered for wind tunnel tests. The first dealt with the isolated deck immersed in a homogeneous flow characterized by a turbulence intensity below 0.5%. This is the typical situation for testing sectional models. However, the closeness of the terrain for the real bridge may make the isolated-deck model not truly representative of the physical reality, due to the channeling of the flow between the deck and the terrain and the presence of a boundary layer characterized by high turbulence intensity. To investigate only the consequences of the channeling effects, a second setup was obtained installing a smooth, rigid plate below the model, at a distance corresponding to the height of the deck over the terrain (about 4.5 cm at 1:150 scale, Figs. 4b-6b). In this way the creation of a thick boundary layer was avoided. The real flow conditions have then been reproduced in the last setup using a suitable surface roughness to create a wind velocity profile and turbulence characteristics (Figs. 4c-6c).

The reproduced turbulent boundary layer is such that the mean wind velocity profile can be approximated by a power law with exponent $\alpha=0.27$ (Fig. 3). Assuming a reference height equal to 10 m, corresponding to the average bridge deck height on the ground, the wind profile corresponds to a logarithmic law with roughness length equal to $0.2\div0.25$ m, suitable for the site of prototype (i.e. countryside).
2.2 Static tests

Static tests, aimed at the evaluation of the aerodynamic coefficients and wake parameters, have been carried out, with and without barriers, for a range of angles of attack between -10° and 10° in step of 1° (setups with and without plate) and with barriers between -5° and 5° in step of 1° (setup with boundary layer). Figure 4 shows the three different setups.

The drag, lift and torque aerodynamic coefficients are here defined based on the well-known expressions:
\[ C_D = \frac{F_D}{0.5pU^2B\ell}; \quad C_L = \frac{F_L}{0.5pU^2B\ell}; \quad C_M = \frac{M}{0.5pU^2B^2\ell} \]  

(1)

where \( F \) and \( M \) are the total force and the torque evaluated by measurements, \( \rho \) is the air density, \( U \) is the reference wind speed and the subscripts \( D, L, M \) stand for drag, lift and moment, respectively. The aerodynamic coefficients are constant for all practical purposes in the range of Reynolds numbers investigated during tests, i.e. \( 1.4 \cdot 10^5 \leq Re \leq 2.5 \cdot 10^5 \) (based on the bridge width \( B \)).

Figure 4. Setups for static tests: isolated deck (a), deck close to plate (b), deck immersed in a boundary layer (c).

Figure 5 shows the drag, lift (positive upwards) and moment coefficients (positive nose up) for all the investigated configurations. From Figure 5 it is possible to infer that the barriers, the plate and the presence of a boundary layer influence significantly the aerodynamic coefficients. In particular, for the isolated deck, the introduction of the barriers enhances the dependency of the drag coefficient on the angle of attack, and tends to significantly reduce the values and the slope of both lift and moment coefficients; it also produces a stall at \(-5^\circ\).

Figure 5 Static drag, lift (positive upwards) and torsional moment (positive nose up) coefficients.

The introduction of the plate to simulate the channeling effect due to the terrain mainly produces an increment of the drag coefficient for large angles of attack, and a shift of lift and moment coefficients (upwards for lift and nose-up for moment). The introduction of the plate
also anticipates the torsional stall for positive angle of incidence. The aerodynamic coefficients evaluated in presence of the turbulent boundary are obtained assuming as reference wind speed the averaged value where the deck is positioned (Fig. 3). The values of the actions evaluated in such a configuration are in between those evaluated in isolated conditions and with the plate. In particular, at zero angle of attack, the lift force becomes negligible as in the case with plate but without barriers.

2.3 Aeroelastic tests

Wind tunnel tests on the aeroelastic model have been carried out aimed at the evaluation of the flutter derivatives in the same configurations of static tests, but without changing the angle of attack. A classic 2 d.o.f. arrangement (i.e. heaving and pitching motion) has been considered. Figure 6 illustrates the wind tunnel setups. The aerelastic derivatives have been extracted from the records of the free-decaying oscillatory motion from imposed initial conditions [1]. For each experimental setup and each wind velocity at least four repetitions have been carried out. Moreover, two sets of springs of different stiffness have been used to better explore different ranges of the reduced wind velocity. Table 1 shows the values of the spring stiffness $k_s$, the model mass and its moment of inertia, $M$ and $I$ respectively, the heaving and pitching natural frequencies $f_h$ and $f_\alpha$, and the corresponding damping ratios $\xi_h$ and $\xi_\alpha$.

Table 1. Mechanical parameters for aeroelastic models.

<table>
<thead>
<tr>
<th>Setup</th>
<th>$k_s$ (kN/m)</th>
<th>$M$ (kg)</th>
<th>$I$ (kg m²)</th>
<th>$f_h$ (Hz)</th>
<th>$f_\alpha$ (Hz)</th>
<th>$\xi_h$ (10^{-3})</th>
<th>$\xi_\alpha$ (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>no barriers</td>
<td>1.21</td>
<td>5.52</td>
<td>$6.41 \times 10^2$</td>
<td>6.66</td>
<td>11.63</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>7.54</td>
<td>5.99</td>
<td>$6.92 \times 10^2$</td>
<td>15.94</td>
<td>29.94</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>with barriers</td>
<td>1.21</td>
<td>5.60</td>
<td>$6.49 \times 10^2$</td>
<td>6.62</td>
<td>11.55</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>7.54</td>
<td>6.08</td>
<td>$7.03 \times 10^2$</td>
<td>15.85</td>
<td>27.77</td>
<td>0.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The estimation of the mechanical parameters during the tests has been made applying the algorithm proposed in [2]. The subsequent evaluation of the flutter derivatives has been made applying the model proposed in [3], and considering $b = B/2$ as reference dimension.

The aeroelastic derivatives have been evaluated for reduced wind velocities up to $U/(fB) = 16$ and 9 (heaving motion and pitching motion respectively). As an example, Figure 7 shows, for the isolated deck without barriers, the aeroelastic derivatives $H_1$, $A_1$ and $A_2$ that plays an important role for torsional flutter (the direct derivative $A_2$) as well as for the coupled flutter ($H_1$, $A_1$ and $A_2$) [4]. Small markers indicate the values obtained from single trials, large markers the mean values and lines the interpolating splines used for the subsequent stability analyses.
Figure 7. Flutter derivatives $H^*$, $A^*$ and $A''$ for the isolated deck (without barriers).

Figure 8 shows the standard deviation $\sigma$ of the steady vibrations amplitude measured on the aeroelastic model (with barriers) as a function of the reduced velocity. It can be observed that the introduction of the plate deeply changed the torsional aeroelastic response of the model.

Figure 8. Amplitude of displacement of the bridge deck with barriers.
In particular, a significant vortex-induced vibration appeared at a reduced velocity roughly equal to 1, and the occurrence of diverging motion was anticipated at a reduced velocity equal to 5.5. On the other hand, the simulation of the terrain through a turbulent boundary layer reduced the torsional aeroelastic response, but significantly enhanced the heaving motion at lower reduced velocities.

3 DATA ANALYSIS AND DISCUSSION OF RESULTS

The aeroelastic derivatives obtained from wind tunnel tests have been used to carry out the stability analysis of the prototype bridge considering three modes of vibrations, namely the mode 2 (heaving, antisymmetric, 0.48 Hz) and the modes 6 and 7 (pitching, almost antisymmetric, 0.96 and 0.99 Hz, respectively). The introduction of a third mode, with respect to the classic formulation, has been made necessary due to the noteworthy similarity (both in mode shape and frequency) existing between modes 6 and 7. The other natural modes do not provide any significant contribution to the flutter mechanism.

Figure 9 shows the dependency on wind speed of the natural frequencies and damping ratios for the aforementioned prototype modes, considering the deck in isolated conditions, with and without the side barriers, and close to the plate (with barriers). From Figure 9 it can be inferred that the presence of the barriers does not affect significantly the evolution of the eigenfrequencies, but it anticipates the critical velocity from 233 to 217 m/s, as well as it shift the instability from the mode 2 (plunge, without wind) to the mode 6 (torsion, without wind).

The use of the plate to simulate channeling effects causes a significant reduction of the critical velocity for flutter, which is initiated by mode 6 as in the previous case. On the contrary, when simulating the terrain with a turbulent boundary layer (case not reported in Figure 9), no negative damping regions were found in the examined range of velocities.

Figure 9 also shows a region characterized by negative damping on pitching modes around 40 m/s. Such a region is due to a positive value of the aerodynamic derivative $A_c^2$ (e.g. Fig. 7). This phenomenon, as already pointed out in [4], is characterized by an onset wind velocity nearly equal to the resonance velocity of Karman vortex shedding on the torsional mode, but in the present contest the response amplitude was limited as in classic vortex shedding, and such a region does not contribute to flutter instability. Confirmation of this fact is found in positive values of $H_1^c$ in a range of reduced velocities for heaving motion corresponding to those of pitching motion (Fig. 7).

The aerodynamic coefficients derived through static tests have been used to evaluate the buffeting response of the bridge through a quasi-steady formulation, which is not reported in the present paper, and to check the applicability to the present case of the quasi-steady theory at high reduced velocities. Since the quasi-steady formulations can be referred to as a special case of unsteady forces when the frequency-dependent fluid memory effect is negligible, it is possible to correlate the static aerodynamic coefficients to the aeroelastic derivatives when the reduced frequencies tend to zero (i.e. high reduced wind velocities).

Based on the correlations between aeroelastic derivatives and quasi-steady aerodynamic force coefficients proposed in [5], Figure 10 shows the 6 aeroelastic derivatives that can be correlated to quasi-steady theory assuming a 2 d.o.f. heaving-pitching motion model. In Figure 10 the bridge deck is considered with barriers in the three different setups. The aeroelastic derivatives are plotted versus the reduced velocity; markers indicate results of aeroelastic tests, while values derived from aerodynamic coefficients (not dependent on frequency) are represented with horizontal lines of the same color.

It is necessary to point out that correlations between the flutter derivatives and the aerodynamic coefficients involves also an arbitrary length, often called characteristic radius,
whose definition is related to the contribution of the angular velocity of the body to the effective angle of incidence of the flow. The use the characteristic radius, hereinafter referred to as $R_0$, has been inspired by the use of the three-quarter chord point in airfoil flutter analysis, and several values have been proposed in the literature based on the shape of the body, see [6] and [7] for references.

![Graph](image)

Figure 9. Isolated deck with and without barriers and deck with barriers close to plate: eigenfrequencies and damping ratios versus velocity.

The choice of the value of the characteristic radius is not obvious. In the present context, the linkage between the aeroelastic derivatives and the aerodynamic coefficients has been used to derive it, being involved in the relationships between $H_2^*$ and $C_D + C_{D}'$ and between $A_2^*$ and $C_M'$. Specifically, it has been evaluated by imposing the equivalence at higher reduced velocities on the term $A_2^*$. For the setups with installed barriers (Fig. 8), $R_0$ has been found always negative, varying from $-0.3B$ to $-2B$ (i.e. the reference point for velocity induced by the angular
velocity is aft of the pivot). Such a case is not common, but can be found in the literature (e.g. [8]).

To apply the quasi-steady theory, points represented in Figure 10 should tend to lines when the reduced velocity tends to the highest values. On the contrary, the comparison between experimental values of aeroelastic derivatives and values obtained from aerodynamic coefficients is far from being satisfactory in any case, confirming that the application of the quasi-steady theory to cases where torsional motion plays a fundamental role is questionable (e.g. [9]).

![Figure 10. Aeroelastic derivatives derived from aeroelastic setups (markers) and based on aerodynamic coefficients from static tests (lines). The same color identifies the same experimental arrangement.](image_url)

4 CONCLUSIONS AND PERSPECTIVES

Static and aeroelastic sectional wind tunnel tests have been carried out aimed at investigating the aerodynamic characteristics of a long-span bridge deck very close to the ground. Besides the classic configuration of isolated deck in uniform flow, the terrain proximity has been simulated with two different approaches, also considering the effects due to the barriers installed on the
bridge. The results highlight that the presence of the terrain and its modeling, as the presence of the barriers, implies deeply different aerodynamic behaviors.

It has been observed that the stability analyses carried out based on data derived considering the isolated deck do not lead to conservative values of the onset velocity for aeroelastic phenomena. Such an aspect points out that when channeling effects and the presence of a relevant boundary layer are not negligible, as for bridge decks close to the terrain, an investigation of the aerodynamic characteristics including the modeling of the boundary conditions is appropriate. Further researches are necessary to understand if some general trend can be derived, though.

Experimental results also confirm that the application of the quasi-steady theory to estimate the onset of instability is more than questionable for elongated bluff shapes.

5 REFERENCES