Comparisons between wind tunnel tests on a full aerelastic model and numerical results of the Izmit Bay Bridge

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ABSTRACT

This paper presents a comparison between experimental and numerical analysis of the aeroelastic stability of the Izmit Bay Bridge, a record span suspended bridge that will be built in Turkey crossing the homonymous bay. Wind tunnel tests were performed on a 1:220 scale aeroelastic model. Experimental records show a double instability involving symmetrical and anti-symmetrical mode shapes at the same wind speed of 82 m/s. To analyze this phenomenon a numerical multi-modal aeroelastic model has been used. Numerical results confirm that this double instability occurs at the same wind speed if the side spans modes are included in the analysis.

Keywords: long span suspended bridge, aeroelastic model, flutter instability, modal coupling, bimodal approach, double flutter.

1 INTRODUCTION

The Izmit Bay Bridge (IBB) is going to be a part of the 420 km Gebze-Orhangazi-Bursa-Izmir motorway at a mouth of the Bay of Izmit in Turkey under construction. With an east-west deck direction, it is characterized by a three-lane dual carriageway and no railway arrangement. The structure is a three-span suspension bridge with a main span of 1550 m and two side spans of 566 m, it has two towers 235 m high; it will become the world’s fourth longest suspension bridge at the completion. The deck is a classical streamed line single box, 30.1 m wide and 4.75m thick [1], with 2.92m wide inspection walkways at the both sides. For a long span bridge aerodynamic stability is always a critical issue both for in-service condition and during the construction stages. In order to assess the aerodynamic stability of the bridge an extensive wind tunnel test campaign with aeroelastic bridge models has been conducted for the in-service and construction stages. In both cases, a flutter and buffeting analysis [1] has been done.

In this article an experimental and numerical analysis of the flutter instability is presented, with a specific focus on the modes involved in terms of modal shapes and modal frequencies. In bridge design, it is commonly well-known that a flutter prediction with a multimode analysis is the most accurate approach [2], however bimodal schemes are preferred [3, 4, 5, 6]. As a matter of fact, for standard long span bridge, the velocity flutter estimation with the two approaches typically leads to very similar results. Tests performed highlight how the alike simplifying bimodal approaches could involve to a considerable error in flutter velocity estimation, depending on modal shapes of the bridge. The presented analysis focuses on the importance of considering different modal shapes in the flutter velocity prediction, in particular on the necessity of considering more than two modes for describing the flutter instability shape. In addition, the experience highlighted the co-presence of two flutter instabilities which participate at the same critical wind velocity.
The numerical multimodal results demonstrate that these simplified bimodal approaches are inadequate and that lead to inaccurate critical velocity prediction; in particular, the IBB bridge requires a tri-modal approach at least to assure acceptable correspondence between experimental evidences and numerical results.

2 EXPERIMENTAL TESTS

2.1 The aeroelastic model, deck aerodynamic and structural properties

Tests were performed on the 1:220 aeroelastic model of the Izmit Bay Bridge (Figure 2), scaled according to Froude similarity, in the Boundary Layer Wind Tunnel of Politecnico di Milano. All data are reported in full scale values.

The aeroelastic stability of the bridge has been studied in smooth flow condition with a residual along wind turbulence intensity \(I_u< 2\%\); in this condition the integral length scale along the main direction is \(L_u=0.15\) m. Tests were carried out increasing wind speed step by step and keeping it constant for a certain period (~120 s) since the critical speed was reached and the instability occurred. In Figure 2 the IBB full bridge aeroelastic model tested.

The aerodynamics of the deck was tuned to account for Reynolds effects, using dedicated wind tunnel tests performed on a sectional model in smooth flow, at 0° yaw angle. The sectional model was in the same scale of the aeroelastic bridge (1:220), in order to verify the aerodynamic coefficients that are used. Target coefficients were measured in previous tests on a 1:65 sectional model.

With reference to Figure 1, the aerodynamic coefficients \(C_D, C_L\) and \(C_M\), for drag force \(F_D\), lift force \(F_L\), and pitching moment \(M\) of the IBB deck, are defined according to following formulation:

\[
C_D = \frac{F_D}{qBL} ; \quad C_L = \frac{F_L}{qBL} ; \quad C_M = \frac{M}{qB^2L}
\]

where \(B\) is the overall deck chord (36.4 m full scale), \(L\) is the length of the considered deck, and \(q=0.5\rho U^2\) is the mean dynamic pressure at the height of the leading edge of the deck. In Figure 3 the IBB deck static aerodynamic coefficients are reported, while Figure 3 shows bridge main structural modal shapes (bending and torsional).

![Figure 1 - Deck aerodynamic forces convention and static coefficients.](image1)

![Figure 2 - The Izmit Bay full bridge aeroelastic model (1:220).](image2)
Mode: main span, 1st Bending (1v) – 0.0885 Hz

Mode: main span, 2nd Bending (2v) – 0.0864 Hz

Mode: main span, 3rd Bending (3v) – 0.1173 Hz

Mode: side span, 1st Bending (1s) – 0.1301 Hz

Mode: main span, 4th Bending (4v) – 0.1818 Hz

Mode: main span, 5th Bending (5v) – 0.1934 Hz

Mode: main span, 6th Bending (6v) – 0.2366 Hz

Mode: main span, 1st Torsional (1t) – 0.2592 Hz

Mode: side span, 2nd Bending (2s) – 0.2661 Hz

Mode: side span, 3rd Bending (3s) – 0.2663 Hz

Mode: main span, 2nd Torsional (2t) – 0.2757 Hz

Figure 3 - Principal IBB vertical bending and torsional mode shape.

2.2 Flutter instability

The critical wind speed identified was about 81.6 m/s. In Figure 4 some frames referring to the evolution of instability are shown, while in Figure 5a accelerometric time histories related to the incipient instability are reported; they refer to the vertical bending and torsional accelerometric signal measured in the ½ and ¼ main span of the bridge. Torsional acceleration is reported in terms of “Equivalent torsional acceleration”, $\ddot{\theta}_{eq} = \frac{E}{I} \ddot{\theta}$ [m/s²]. Figure 5b shows the Fourier spectra of the proposed time histories and two main frequencies are clearly visible (0.173 Hz and 0.214 Hz).
The experimental analysis highlights some peculiarities of the bending-torsional flutter instability:

- Two flutter instabilities appear simultaneously at the same wind velocity equal to 81.6 m/s. They are characterized by two different frequencies equal to 0.173 Hz and 0.214 Hz (Figure 5b).
- Instabilities shapes are related to first symmetrical and anti-symmetrical modes respectively.
  - The first instability shape (Figure 5a – 0.173 Hz) can be mainly described referring to the first torsional modal shape (0.2592 Hz) and to the main span first bending one (Figure 3, 0.0885 Hz).
  - The second instability shape (Figure 5b – 0.214 Hz), can be mostly described by the second torsional mode (0.2757 Hz) and, limited to its vertical component, by a pair of vertical structural modes: the main span second one (0.0864 Hz) and the side span first one (Figure 3, 0.1301 Hz).

Figure 4 - Some frames of the flutter instability at 81.6 m/s (full scale value).

Figure 5 - Flutter instability: (a) time histories and (b) Fourier spectra of ½ and ¼ Main Span.
Figure 6 - Instabilities modal shapes (bending and torsional components): (a) 0.173 Hz and (b) 0.214 Hz.

The frequency ratios and the reduced velocities of the two instabilities are respectively equal to:

\[
\frac{f_{1t}}{f_{2v}} = \frac{0.2592}{0.0885} = 2.93 \quad;\quad \frac{f_{1t}}{f_{2v}} = \frac{0.2757}{0.0864} = 3.19
\]

\[
U_{0.17}^* = \frac{81.6 \, \text{m/s}}{36.4 \, \text{m/s} + 0.173 \, \text{Hz}} = 13.0 \quad;\quad U_{0.21}^* = \frac{81.6 \, \text{m/s}}{36.4 \, \text{m/s} + 0.214 \, \text{Hz}} = 10.5
\]

By a first experimental data analysis, higher bending modes, in frequencies closer to the two torsional ones, are not interested in instability; bending-torsional frequencies ratio is not a binding parameter in flutter phenomenon [7]; otherwise, it is obvious the importance covered by the side span vertical mode which, properly phased with the second main span mode, strongly contributes in the energy introduction as it will be shown in the next section.

3 NUMERICAL RESULTS

To investigate this unusual phenomenon of a double coupled flutter, a numerical analysis was carried out in order to highlight the importance of each structural mode for the instability. A multi-modal approach, using the flutter derivative coefficients [8], has been used to study the aeroelastic stability of the system as a function of the incoming wind speed. The algorithm, based on multi-modal equation, solves the following complex eigenvalue problem:

\[
\left( [M_s^*(\omega_r)]\lambda^2 + [R_s^*(\omega_r)]\lambda_r + [K_s^*(\omega_r)] \right)q_0^{(r)} = 0 \quad \text{with} \quad r = 1, 2, \ldots, N_{\text{modes}}
\]

Where \(M^*, R^*, K^*\) are generalized structural \((s)\) and aerodynamic \((a)\) mass, damping and stiffness modal matrices, respectively, depending on \(\omega \) (\(\lambda = \alpha + i\omega\) is the complex eigenvalue) and, on the structural modes considered and on the aerodynamic deck coefficients (which depend on the wind attack angle) and \(q_0^{(r)}\) is the principal coordinate. The flutter condition is determined by seeking the minimum velocity that corresponds to zero damping [9]. The peculiarity of a modal approach is the possibility to select each mode individually one-by-one. In this way it is possible to conduct analyses involving different combinations of structural modes in order to isolate only the modes that are the mainly involved in the flutter instability.
As reference result a 50 dof simulation is taken and all the others simulations with less modes are compared with this one. The results of the 50 dof simulation are in agreement with the experimental results showing a double instability at the same velocity of 80 m/s (Table 1). This assumption is quite reasonable since the 50 dof model well reproduces frequencies and phases between torsional and vertical components.

<table>
<thead>
<tr>
<th>50 modes simulation</th>
<th>Symmetric instability</th>
<th>Anti-symmetric instability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Numerical</td>
</tr>
<tr>
<td>Critical velocity $U$ [m/s]</td>
<td>81.6</td>
<td>80</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>0.173</td>
<td>0.171</td>
</tr>
<tr>
<td>Phase ($\theta, z$) [deg]</td>
<td>148</td>
<td>145.3</td>
</tr>
</tbody>
</table>

Table 1 - 50 modes simulation numerical results.

At first, two bi-modal systems were examined using the first bending and torsional modes (symmetrical) and the second bending and torsional modes (anti-symmetrical) respectively. The result, shown in Table 2, points out the inaccuracy of a bi-modal approach to evaluate critical flutter velocity: in the first case the velocity is underestimated at 72 m/s while in the second one it is overestimated at 106 m/s. Therefore it was necessary to use others modes in addition to the fundamental ones. For this purpose it is useful to introduce a coefficient representative of the shape affinity between bending modes and torsional modes ($l_{ij}$), defined as:

$$l_{ij} = \frac{\phi^T_{zi} \phi_{\theta j}}{\left\|\phi_{zi}\right\| \left\|\phi_{\theta j}\right\|}$$

Where the eigenvector $\phi_{zi}$ is the vertical component of the the $i$-th mode, while $\phi_{\theta j}$ is the torsional component of the $j$-th mode. Figure 7 shows the $l_{ij}$ values considering the first and the second torsional modes ($1t, 2t$) and all the bending modes with frequencies smaller than the second torsional one (main span ones: $1v, 2v, 3v, 4v, 5v, 6v$ and side span ones: $1s, 2s, 3s$).

According to these results, the first bending mode of side spans was added to the anti-symmetrical system obtaining a tri-modal system, since it shows high affinity value with the second torsional mode. The critical velocity obtained in this case is 81 m/s (Table 2) which is very closed to the value of 80 m/s calculated considering the first 50 modes. Regarding the symmetrical system, it is instead necessary to add also the 5th and 6th bending modes to reach a critical velocity of 79 m/s as reported in Table 2. In Figure 8, the structural modes mainly involved in the instabilities are presented in terms of amplitudes and phases: for example in the symmetric instability the first torsional mode has an amplitude of 0.7 and a phase of 145 degree relatively to the first vertical bending mode.
Similar results can be shown evaluating the evolution of the torsional mode damping as a function of the wind velocity. As an example, in a comparison for both instabilities between different simulations is reported: assuming the 50 modes simulation (solid line) as reference, the two modes simulations (dashed lines) lead clearly to inaccurate critical velocity prediction, while the results obtained using all the modes with affinity $I_{ij}$ higher than 0.2 describe very well the phenomenology of the instability.

<table>
<thead>
<tr>
<th>Simulations with the 1st TORSIONAL mode</th>
<th>Symmetrical Instability</th>
<th>Anti-symmetrical Instability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending modes considered</td>
<td>$Iv$</td>
<td>$Iv,5v,6v$</td>
</tr>
<tr>
<td>$U_{CR1}$ (m/s)</td>
<td>72</td>
<td>79</td>
</tr>
<tr>
<td>Simulations with the 2nd TORSIONAL mode</td>
<td>Symmetrical Instability</td>
<td>Anti-symmetrical Instability</td>
</tr>
<tr>
<td>(anti-symmetric flutter instability)</td>
<td>$2v$</td>
<td>$2v,Is$</td>
</tr>
<tr>
<td>Bending modes considered</td>
<td>106</td>
<td>81</td>
</tr>
</tbody>
</table>

Table 2 – Numerical result: summary of different simulations
4 CONCLUSIONS

Experimental wind tunnel tests on the aeroelastic model of the Izmit Bay Bridge allowed to assess flutter instability and to validate a numerical multimodal aeroelastic model. Both experimental evidences and numerical analysis highlight some important aspects:

- There are two different instabilities which appear at the same wind velocity;
- The higher frequency instability cannot be described by a bimodal approach but it is necessary to consider an additional bending mode.
- The side span modes are not negligible and they are strongly involved in wind energy introduction into the aeroelastic system.
- A linear multi-modal aeroelastic approach describes accurately the behavior of a bridge at instability onset.

In the IBB case flutter instability can be described using seven modes: 2 torsional and 5 vertical bending ones.

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6 REFERENCES


