J. Wind Eng. Ind. Aerodyn. 151 (2016) 25–36

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

A case-study of double multi-modal bridge flutter: Experimental result and numerical analysis

T. Argentini*, G. Diana, D. Rocchi, C. Somaschini

Politecnico di Milano, Department of Mechanical Engineering, via La Masa 1, 20156 Milano, Italy

ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form
18 January 2016
Accepted 18 January 2016
Available online 8 February 2016

Keywords:
Flutter instability
Multi-mode coupling
Eigenvalue analysis
Full aeroelastic model
Long span bridge
Wind tunnel testing

ABSTRACT

An experimental double multi-modal flutter instability was recorded during wind tunnel tests on a full bridge aero elastic model. The analysis of this instability is presented in this paper, and it is studied with a multi-modal eigenvalue approach.

It is shown that two different coupling mechanisms, one involving the symmetric modes and the other involving the anti-symmetric modes, lead to two different instabilities that occur at the same wind speed.

The numerical analysis shows that a multi-modal framework and a complete set of aerodynamic coefficients are necessary to correctly estimate the flutter onset. The effect on flutter of structural and aerodynamic characteristics is discussed thoroughly, with a focus on structural modes and on the dependence of the aerodynamic coefficients upon the reduced velocity and upon the angle of attack.

1. Introduction

The prediction of flutter instability is a fundamental aspect in the design of long span bridges. It usually relies on the numerical estimation of the natural frequencies and modal shapes of the bridge, and on the experimental measurement of steady and unsteady aerodynamic coefficients. Indeed, with these inputs, a multi-mode analysis framework allows one to achieve accurate estimates of the aeroelastic coupling and instability onset. To this end, Chen and Kareem (2008) outlined a procedure to identify the critical structural modes and flutter derivatives for predicting coupled bridge flutter. In fact, it is well-known that simpler approaches, relying only on bi-modal flutter, are representative of the aeroelastic coupling of standard long-span bridges only, when the first torsional and vertical modes are close in frequency, homologous in shape, and well separated from other modes (e.g. Chen, 2007; Zasso et al., 2013).

From a theoretical point of view, the outcome of the multi-modal analysis is important to understand the underlying physics of the phenomenon. From a practical point of view, this procedure offers a valuable guidance for the design and interpretation of wind tunnel studies using aeroelastic models of the full bridges.

As a matter of fact, often the final design of the bridge is tested in wind tunnel with full aeroelastic models to double-check the solution (e.g. Argentini et al., 2013; Diana et al., 2013b; Zasso et al., 2014; Katsuchi et al., 1999; Zhang and Ge, 2014). This is also done to check if the sectional approach adopted for the numerical modeling, with aerodynamic forces acting only on the deck, does not introduce inaccuracies in the flutter estimation.

However, also aeroelastic models have some limitations. Indeed, full aeroelastic models can reproduce only a selected number of modes, due to difficulties in model fabrication. The most limiting aspect is the small geometrical scale λ that, for long span bridges, typically ranges between 1:100 and 1:250. The small geometrical scale (limited by the wind tunnel dimensions) comes along with some critical issues in the design and in construction of the model, related to both structural and aerodynamic aspects.

From a structural point of view, the constraints and the stiffness elements of the deck must be carefully designed and realized, to correctly reproduce the target modal shapes: constraints should be effective and should not introduce damping, while the structural part of the deck should reproduce the stiffness variations along the bridge axis.

From an aerodynamic point of view, since in the model the Reynolds number is not scaled correctly ($\lambda_{Re} = \lambda^{3/2}$, with Froude similarity and atmospheric wind tunnel), and geometrical details are usually simplified, the effects on the steady and unsteady aerodynamic force coefficients should be verified with dedicated tests.

If all these aspects are taken into account, the experimental results can be used to validate numerical models for flutter

---

* Corresponding author.
E-mail address: tommaso.argentini@polimi.it (T. Argentini).

http://dx.doi.org/10.1016/j.jweia.2016.01.004
0167-6105/© 2016 Elsevier Ltd. All rights reserved.

prediction using as input the FEM model of the bridge and the aerodynamic coefficients that are usually measured in wind tunnel on section model with larger scale (e.g. Diana et al., 2014, 2013a).

Within this analysis framework, the focus of this paper is to present an outstanding experimental test-case of multi-mode flutter instability on an aeroelastic model, and to compare the result with numerical predictions obtained applying different numerical procedures.

Specifically, the presented test-case shows a peculiar flutter instability for a long-span suspension bridge: the singularity consists in the fact that two different instabilities, associated with two different flutter mechanisms, occur at the same wind speed, as it will be discussed in detail throughout the paper.

Starting from the analysis of the experimental records, a numerical analysis is performed using an iterative multi-modal eigenvalue procedure for the solution of the aeroelastic problem. Using the FEM model of the structure and the aerodynamic coefficients measured in wind tunnel as input data, several simulations were run to investigate the effect of the different vibration modes on the critical speeds, and to assess how much the dependencies upon the reduced velocity and upon the mean angle of attack of the aerodynamic coefficients affect the flutter onset.

2. The test-case

2.1. The Izmit Bay Bridge: geometry and structural modes

The Izmit Bay Bridge (IBB) is going to be part of the Gebze–Orhangazi–Bursa–Izmir motorway in Turkey that will connect Istanbul to Bursa. With a north–south deck direction, it is characterized by a three-lane dual carriageway. 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 bridge at the completion (planned in 2017). The deck is a classical streamlined single box, 31.5 m wide and 4.75 m deep. Fig. 1 shows the deck cross-section and the general arrangement of the bridge.

Due to its arrangement, with relevant side spans, the first dynamic structural modes of the bridge involve also these parts of

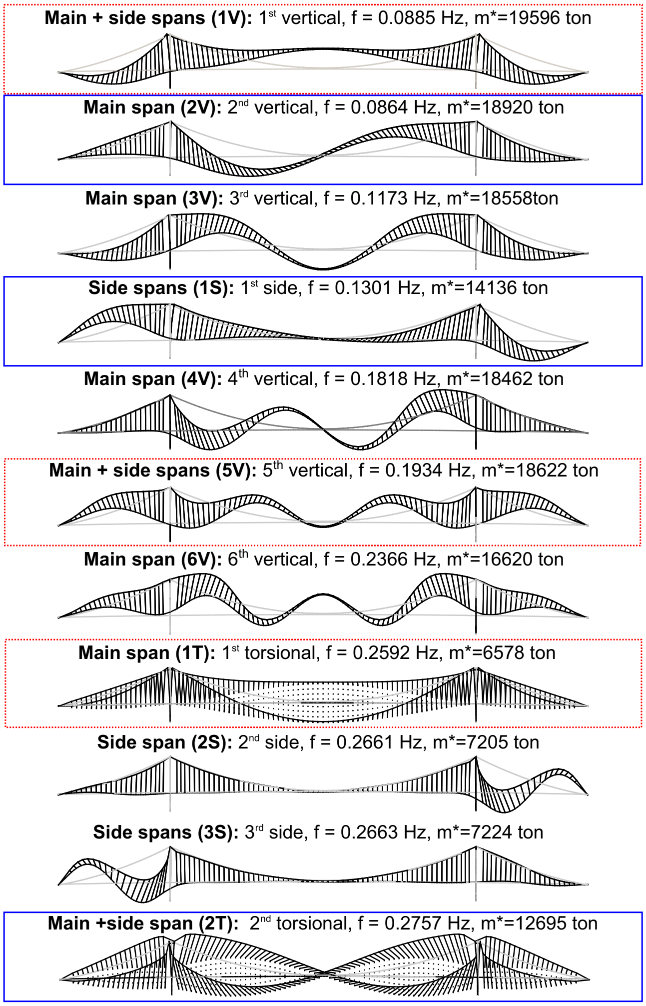

Fig. 2. Main vertical bending and torsional mode shapes: natural frequency, and modal mass (red dotted-line box: modes involved in the symmetric instability; blue solid-line box: modes involved in the anti-symmetric instability). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

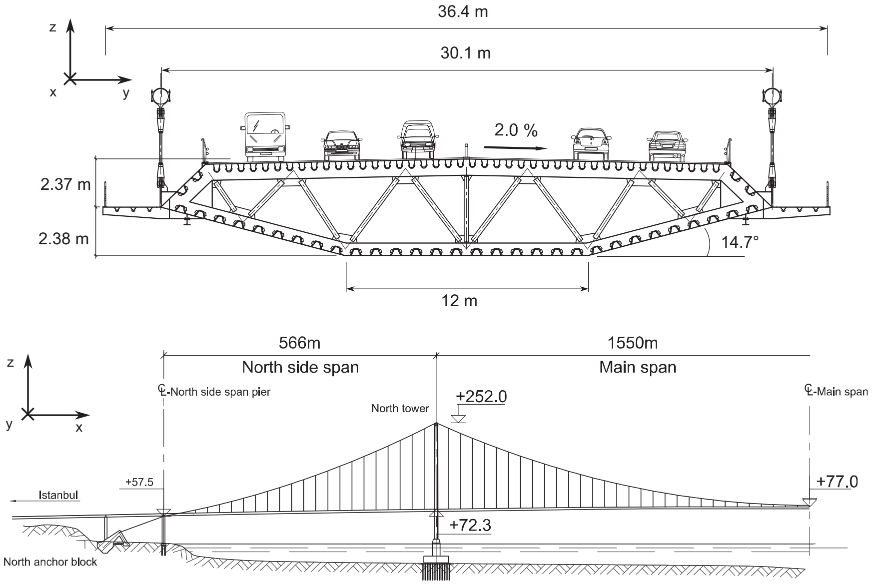

Fig. 1. Deck cross-section and general arrangement of the bridge.