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Aerodynamic and aeroelastic characteristics of typical bridge decks equipped with wind barriers at the windward bridge-deck edge

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ABSTRACT

The present wind-tunnel study focuses on the effects of roadway wind barriers on aerodynamic and aeroelastic characteristics of bridge decks characterized by various aerodynamic shapes of the cross section. Three bridge-deck sections are studied, i.e., streamlined, semi-bluff, and bluff sections. The standard 5 m high (full-scale) wind barrier with 30% porosity is placed at the windward (leading) edge of the bridge-deck sections. Aerodynamic forces and overturning moment are determined at various wind incidence angles. Galloping stability is studied using the quasi-steady theory. Flutter derivatives are determined to evaluate flutter sensitivity of the studied bridge-deck sections with the wind barrier in comparison with the empty bridge-deck sections. The experimental results indicate some important features. In particular, the drag force coefficient is increased for all bridge-deck sections when the wind barrier is in place. This feature is particularly exhibited for the streamlined bridge-deck section. The wind barrier alters the trends and values of the lift force coefficient, while the influence of the wind barrier on the pitch moment is particularly exhibited for positive wind incidence angles, which is characteristic for all bridge-deck sections. The wind barrier does not influence the galloping sensitivity of the studied bridge-deck sections, while it deteriorates their dynamic stability with respect to torsional flutter.

1. Introduction

Long-span suspension and cable-stayed bridges are flexible slender structures characterized by relatively low natural frequency and low mechanical damping in the pitch and heave motions. Consequently, they are sensitive to self-excited oscillations, which occur due to a complex interaction between the airflow and the vibrating bridge deck. It is therefore required to carefully analyze aeroelastic behavior of long-span bridges during construction and service. Aeroelastic studies are commonly performed experimentally on small-scale bridge-deck section models in wind tunnels, e.g. Larsen [1]. In general, rigid bridge-deck section model attached to elastic springs accurately represents aeroelastic and modal properties of the bridge, Jones and Scanlan [2].

Flutter is the self-excited instability, which may cause bridges to collapse. In this case, aerodynamic forces due to the wind feed the energy into the system during each cycle of oscillation. The wind-induced self-excited forces are counteracted with the structural (mechanical) damping. When the critical flow velocity (flutter velocity) is reached, a total damping (a sum of aerodynamic and mechanical damping) at least in some of the response components is zero and the bridge deck becomes unstable (flutter onset).

In general, it is an important goal for bridge engineers to design bridges with critical flutter velocity larger than the maximum expected wind velocity, as to avoid flutter occurrence during the bridge lifetime. Bridge sensitivity to flutter is commonly studied using flutter derivatives (FDs), which are considered as indicators of the bridge dynamic stability.

The original method for extracting dimensionless FDs is proposed by Scanlan and Tomko [3]. The ARMA (Auto Regressive Moving Average) model for extraction of flutter derivatives is suggested by Shinozuka et al. [4], while the Kalman filtering method is used by Yamada and Ichikawa [5]. The free-vibration method and the time-domain method to obtain FDs is developed by Sarkar [6]. A method for extracting flutter derivatives from a system dynamic response based on the least squares theory is developed by Gu et al. [7]. This procedure is further developed with respect to stability and precision by Ding et al. [8]. The indicial functions for studying bridge dynamic stability are developed by Farsani et al. [9].

The influence of bridge-deck section model properties (i.e. mass, mass moment of inertia) on FDs extracted in wind-tunnel tests proves to be negligible, Gu et al. [10]. Dynamic response of the bridge-deck section depends on turbulence intensity in the

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freestream flow, e.g. Sarkar and Scanlan [11], as well as on the vertical wind profile, Arena et al. [12].

Aeroelastic behavior of bridge-deck sections proves to be sensitive to changes in aerodynamic design of a bridge-deck cross-section, Raggett [13], Xu et al. [14]. Wang et al. [15] suggest installing rigid central buckle to enhance flutter stability, while external dampers can reduce bridge sensitivity to flutter as well, Jain et al. [16].

As the construction of long-span cable-supported bridges is a long-lasting process, importance of studying aeroelastic stability of bridges during the construction is emphasized by Diana et al. [17], while bridges prove to have smaller critical flutter velocity in initial construction stages in comparison with the finalized bridge.

Vehicles placed on bridge decks can change aerodynamic force and moment coefficients, Xu et al. [18], as well as dynamic stability of bridge decks, Wu et al. [19]. Spacing density of vehicles placed on a bridge and wind incidence angle can impact the aeroelastic stability of bridges, Han et al. [20,21].

It is therefore anticipated that the dynamic stability of bridges is to further change when placing roadway wind barriers at the leading edge of bridge decks. In general, roadway wind barriers are commonly used to protect vehicles on bridges from adverse cross-wind effects, Chu et al. [22], Guo et al. [23], Kozmar et al. [24–26], as vehicles prove to be particularly vulnerable to wind effects when passing the bridges and viaducts, Chen et al. [27], Kozmar et al. [28,29]. Aerodynamic force coefficients of vehicles and wind barriers on bridges are reported for various test cases in Xiang et al. [30].

The present study focuses on effects of the roadway wind barrier on aerodynamic and aeroelastic characteristics of three typical types of bridge decks, i.e., streamlined, semi-bluff, and bluff bridge deck. A standard wind barrier is placed at the leading edge of these bridge-deck sections. This arrangement is common in practice, as the wind predominantly blows on bridges from one direction, and wind barriers are commonly placed at the bridge leading edge from that direction, e.g., Kozmar et al. [25,26]. Aerodynamic force and moment coefficients are determined at various wind incidence angles for bridge decks with and without the wind barrier. Galloping and flutter sensitivity is analyzed with particular emphasis on a role of aerodynamic shape of bridge-deck sections with respect to experienced aerodynamic and aeroelastic loads.

2. Experimental setup

2.1. Wind tunnel and experimental models

Wind-tunnel experiments are conducted in the closed-circuit boundary-layer climatic wind tunnel of the Institute of Theoretical and Applied Mechanics in Prague, Czech Republic. It is designed for experiments with respect to wind effects on structures, aeroelastic structural response, atmospheric boundary layer modeling, and general civil, environmental and mechanical engineering applications. The aerodynamic section of the wind tunnel is 1.9 m wide and 1.8 m high rectangular cross-section with a possibility to regulate wind velocity from 0.5 m/s to 35 m/s. The flow is uniform across the aerodynamic test section along with turbulence intensity less than 2%.

As the focus of this study is on influence of roadway wind barriers on aerodynamics and aeroelasticity of various aerodynamically profiled bridge decks, three different bridge-deck sections are studied: (a) bridge deck with streamlined shape of the cross-section (B_1) based on the Great Belt Bridge in Denmark, (b) bridge deck with a semi-bluff shape of the cross-section (B_2) based on the Kao-Pin Hsi Bridge in Taiwan, (c) bridge deck with a bluff shape of the cross-section (B_3) based on the Golden Gate Bridge in USA.

All three bridge-deck section models are manufactured in the 1:100 geometrical scale, while the length of all models (laterally to the main flow direction) is $L = 1000$ mm. The ratio between the width of bridge-deck sections (measured in the main flow direction) and span (laterally to the main flow direction) is smaller than 1:3.

The 50 mm high (in model-scale) wind barrier with 30% porosity is manufactured in the identical 1:100 geometrical scale as the bridge-deck section models using the 3D printing technology. The wind-barrier model consists of nine triangular shape profiles placed between the pillars. The distance between two supporting pillars is 45 mm. The wind-barrier porosity is calculated as a ratio between the cavities within the triangular shape profiles and the entire frontal surface of the barrier including the supporting pillars. This type of wind barrier is considered to optimally shelter vehicles from cross winds on bridges and viaducts, Kozmar et al. [26]. The details and dimensions of the bridge-deck section models with the wind barrier model in place are presented in Fig. 1(a)–(c), while the geometrical characteristics of the wind barrier are presented in Fig. 1d).

In all experiments, the wind barrier is placed at the windward bridge-deck edge only, as strong cross winds commonly blow on bridges from one major direction, e.g. Kozmar et al. [25,26]. In particular, in case the wind barriers are placed at both the windward and leeward bridge-deck edges, the shear layer separated from the top of the windward wind barrier is likely to be captured on the road surface of the bridge deck between the windward and leeward wind barriers, as the leeward wind barrier will prevent this vortex to be blown away from the bridge deck. This physical phenomenon (vortex captured on the road surface of the bridge deck due to leeward wind barrier) is reported in Avila-Sanchez et al. [31]. This 'captured vortex' is considered to be an important source of wind-induced instability of vehicles passing the bridge.

Maximum blockage of the wind–tunnel aerodynamic test section is less than 7%, thus no correction factors are applied on the obtained experimental results, in agreement with West and Apelt [32]. The mass and mass moment of inertia of studied bridge-deck sections are measured with and without the wind barrier, Table 1. The results include mass and mass moment of inertia of the moving parts of the supporting stand mechanism and represent the distributed mass and mass moment of inertia.

2.2. Aerodynamic force and moment coefficients

Aerodynamic lift and drag forces, as well as the pitch moment are measured in static conditions without the movement of bridge-deck sections. These forces and the moment are important for the structural stability of bridge decks, as they can be used to predict across-wind galloping dynamic instability, e.g. Xu [33]. Mean aerodynamic lift and drag force coefficients of bridge-deck sections are used to calculate susceptibility to across-wind galloping instability using the Glauert-Den Hartog procedure based on a quasi-steady approach, Den Hartog [34]. The static aerodynamic coefficients are determined at various wind incidence angles using the following equations:

$$C_D(\alpha) = \frac{2F_D(\alpha)}{\rho v_\infty^2 HL}, \quad C_L(\alpha) = \frac{2F_L(\alpha)}{\rho v_\infty^2 BL}, \quad C_M(\alpha) = \frac{2M(\alpha)}{\rho v_\infty^2 B^2 L}, \tag{1}$$

where F_D and F_L are aerodynamic drag and lift force, respectively, M is aerodynamic pitch moment. C_D, C_L, and C_M are aerodynamic drag force, lift force and pitch moment coefficients, respectively. Average freestream wind velocity is denoted as v_∞, ρ is air density, while α