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Sheltering efficiency of wind barriers on bridges

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ABSTRACT

Sheltering efficiency of wind barriers on viaducts was experimentally studied in a boundary layer wind tunnel. Effects of wind incidence angle on flow field characteristics in the wake of a wind barrier were reported. Mean velocity fields and vorticity fields were determined using the Particle Image Velocimetry (PIV) technique. Freestream velocities were measured using hot-wire and Pitot tube. Results indicate a possibility of wind-induced instability of high-sided vehicles at larger vertical incidence angles, especially in the traffic lane close to trailing edge of the bridge, as velocity fluctuations and mean freestream velocities approach the road surface when increasing the vertical incidence angle. Removing elements from the wind barrier causes very large local velocities immediately downstream from a barrier and strong vorticity in the entire area in the wake of a wind barrier. Variations in horizontal incidence angle do not seem to affect flow field characteristics significantly. Without a wind barrier, wind velocities on bridges reach 80% of the freestream velocity at height as low as 1 m full-scale along with very strong vorticity in the immediate vicinity of the road surface.

1. Introduction

Strong bora winds on both the Italian and the Croatian coast induce instability of vehicles, especially on viaducts and bridges, and in the past freeways have had to be closed for traffic often due to safety requirements. Recently, an extensive research program has been undertaken to develop an optimal design of wind barriers for several freeway viaducts particularly exposed to cross-winds.

Some of the first studies on aerodynamic design of wind barriers in modern times are reported by Nägeli (1941) and Jensen (1954), whereas most of the research was carried out for agricultural purposes. Kaiser (1959) was among the first researchers who made a distinction between 'mean wind reduction' and 'wind protection', emphasizing that while a less porous wind barrier may give a greater reduction in mean wind velocity, the greater turbulence in its wake may reduce its overall effectiveness for wind protection compared to a more porous wind barrier. Both Jensen (1958) and Kaiser (1959) indicated that flow characteristics in the wake of wind barriers are independent of approaching flow velocity for neutrally-stratified aerodynamically rough flow. Moreover, Raine (1974) and Raine and Stevenson (1977) pointed out that Reynolds number similarity is relatively unimportant for wind barrier aerodynamics, while turbulence in oncoming flow is very important. Arie and Rouse (1956), Good and Joubert (1968) and de Bray (1971) indicated that an increased roughness of the upstream terrain (more turbulent flow) reduces the wind-barrier drag coefficient and reattachment distance due to a larger vertical exchange of streamwise momentum resulting from higher Reynolds stress $u'w'$, which intensifies a recovery of streamwise momentum behind a wind barrier (u' and w' are fluctuating velocity components in the main wind direction and vertical direction, respectively). McNaughton (1988) reported a quiet zone of reduced turbulence and smaller eddy size immediately behind wind barriers independent of the barrier porosity. Further downwind an extended wake region of increased turbulence with eddy sizes recovering to upwind length scales was observed.

Wind barriers generally reduce turbulent eddy length, thus increasing the peak frequency of turbulent velocity fluctuations (Heisler and DeWalle, 1988), while peak frequency of velocity fluctuations close to wind barriers tends to increase with barrier wall porosity. Several studies reported that for some windbreak configurations the wind-protected area is larger for consecutively arranged windbreaks compared to a single windbreak (e.g. McAneney and Judd, 1991; Judd et al., 1996; Dierickx et al., 2001; Frank and Ruck, 2005). Wind-tunnel experiments by Cornelis and Gabriels (2005) indicated that porosity from 20% to 35% (ratio between open area and entire barrier wall) could be optimal in terms of wind velocity reduction, while Jensen (1954) and Blenk and Trienes (1956) showed a maximum sheltering efficiency to be associated with porosities from 35% to 50%. Dong et al. (2007) indicated that the optimal porosity could be between 20% and 30%

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suggesting that for porosity higher than 30% the bleed flow dominates and for porosity lower than 20% the reversed flow becomes significant. As the discrepancy between these results is quite large, it seems that the sheltering efficiency strongly depends even on small details of wind barrier design and oncoming wind turbulence. Cornelis and Gabriels (2005) reported that an evenly distributed porosity in the barrier wall generated the longest protected area, noting that the optimal design of wind barrier wall depends strongly on their purpose. Dierickx et al. (2003) showed that windbreaks are less effective for rough than for smooth turbulent flow, although differences depend on the open area of the windbreak. Moreover, they indicated that inclination of wind screens may influence their efficiency, in agreement with Nord (1991). Plate (1971) showed that separation from the top of the shelterbelt gives rise to a separation streamline which divides the low velocity flow below from the high velocity flow aloft. The blending of the flow across this streamline, which determines the recovery of the wind profile and the reduction in sheltering efficiency, is caused by the gradient in velocity across the streamline, while its location is determined by the drag on the shelter and the pressure distribution behind it.

Several researchers attempted to quantify aerodynamic characteristics of wind barriers in a form of a sheltering coefficient. Miller et al. (1975) suggested a shelterbelt drag, characterized by the integrated wind reduction curve or a drag coefficient, as a practical basis for comparison of the effectiveness of different field shelterbelts. Gandemer (1979, 1981) suggested a shelter parameter based on the generally accepted critical level of discomfort, and the corresponding discomfort wind frequencies. Schwartz et al. (1995) developed an equation to describe the near ground horizontal distribution of mean relative velocity in the vicinity of the barrier.

Even though the above mentioned studies provide valuable information on aerodynamic features of wind barriers placed on ground surface, their results are not sufficient to properly design wind barriers on bridges, as the aerodynamics of agricultural wind barriers immersed in the atmospheric boundary layer differs significantly from aerodynamics of wind barriers on bridges. Moreover, very different designs of bridges resulting in significantly different flow features require the aerodynamics of wind barriers to be investigated for each object as a separate study. Previously, Štrukelj et al. (2005) numerically studied effects of wind barrier geometry on wind forces experienced by vehicles on the Črni Kal viaduct in Slovenia. Wang et al. (2007) designed a wind barrier to reduce wind velocities on the bridge deck of the Hangzhou Bay Bridge in China based on wind-tunnel experiments and numerical simulations using the Random Vortex Method (RVM). Results reported in Procino et al. (2008) indicate a decrease in velocities on the bridge with reduced barrier porosity and increased barrier wall height. Flow field characteristics on the Bukovo viaduct proved to be significantly improved using a 4 m high wind barrier compared to the configuration without a wind barrier, Kozmar et al. (2009a).

In this paper, effects of wind incidence angle on flow field characteristics in the wake of wind barriers are reported for two viaducts on the A6 Rijeka–Zagreb motorway in Croatia. Furthermore, effects of an opening in the lower portion of the wind barrier wall were investigated and results for bridges without the wind barrier in place were reported as well. Some preliminary results were previously presented in Kozmar et al. (2009b).

2. Wind tunnel experiments

Experiments were carried out in the CRIACIV boundary layer wind tunnel described in detail in Augusti et al. (1995) following standard wind-tunnel procedures (Simiu and Scanlan, 1996). This wind tunnel was designed as an open-return (Eiffel) suction-type wind tunnel with a closed test section. Wind velocity through the test section can be regulated between 0 m/s and 35 m/s by both adjusting the pitch blade angle and regulating the speed of the fan powered by a 160 kW engine, where the fan is placed at the outlet of the test section. The total length of the wind-tunnel test section (from the nozzle outlet to diffuser inlet) is approximately 22 m. The test section is 1.6 m high and 2.2 m wide at the outlet of the nozzle, i.e. at the inlet to the test section. Due to diverging side walls in the longitudinal direction to avoid pressure gradients, the test section width at the center of the turntable is 2.4 m. In some wind-tunnel studies it is required to reproduce the atmospheric boundary layer (ABL) flow. In the CRIACIV boundary layer wind tunnel, the ABL simulation can be generated along the first 11 m of the test section (8 m long fetch and 3 m at the turntable, where horizontal incidence angle of the flow can be varied). In this study, the full-scale height of the bridge together with the wind barrier is approximately 7 m and it can be assumed that differences in flow characteristics of the undisturbed flow do not change significantly with height within these 7 m. Thus, the flow was taken to be uniform and the ABL velocity profile was not reproduced.

2D Particle Image Velocimetry (PIV) measurements were taken on two wind-tunnel bridge models (Hreljin and Bukovo) in the wake of a wind barrier to study the effects of horizontal and vertical angles of attack on mean velocity and vorticity flow field characteristics. A Dantec 2100 PIV system was employed together with two Quantel Big Sky lasers (power output 220 mJ per light impulse), a CCD Kodak Megaplus camera with Nikon optics (60 mm, resolution 1 MPx and frequency filter), a Le Maitre smoke generator, and a Dantec PIV processor with Flowmap 3.61 software for data measurements and analysis. In this study, the time interval between two light impulses within one frame was 60 μs and the total number of frames for one configuration was 200. The final result is a velocity and vorticity map calculated as an average out of 200 frames. Vorticity is the measure which has been chosen to evaluate the turbulence structure of the flow behind the barrier; due to the possibility of high variations of the flow velocity, vorticity is more suitable to show the intensity and the structure of the turbulence with respect to other possible mapping of the flow (e.g. rms values). Simultaneously with PIV measurements, velocities in the undisturbed flow well upwind from the bridge models were taken by using a Dantec single hot-wire and a Prandtl–Pitot tube.

Wind-tunnel models of the Hreljin and Bukovo viaducts were made out of wood for the length scale factor 1:66 and they are presented in full-scale dimensions in Fig. 1 with a wind barrier already in place. The simulation length scale was chosen to satisfy two contradictory demands, i.e. blockage of the test section and the critical Reynolds number. In particular, wind-tunnel models were manufactured as large as possible to obtain larger Reynolds numbers. However, increasing the model size inevitably increases the blockage of the wind-tunnel test section; in wind-tunnel tests a maximum tolerable blockage between 5% and 6% should not be exceeded (e.g. Simiu and Scanlan, 1996). The freestream velocity in all tests was kept at approximately 12 m/s, as bridge model vibrations were observed at larger velocities. Reynolds number calculated using the height of the model bridge section without the barrier (7.5 cm) and average freestream velocity (12 m/s) was approximately 6×10^4. In all tests, the blockage was less than 6%, including structural models and measuring equipment placed in the wind-tunnel test section, indicating the air flow around structural models and their aerodynamic behavior in the wind tunnel is a good representation of prototype conditions, as suggested in Hucho (2002) and Holmes (2001). The Reynolds