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AERODYNAMIC COEFFICIENTS AND PRESSURE DISTRIBUTION ON U-BEAMS WITH POROUS FLANGES

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Abstract: *This study presents the results of wind tunnel experiments on U-shaped beams with either solid flanges or flanges with 50% porosity. Aerodynamic drag and lift coefficients, along with pressure coefficient distributions on the beam surfaces, were evaluated and compared for both configurations. The findings demonstrate that flange porosity significantly affects the aerodynamic forces and flow around the U-beam. Across most angles of attack, the solid-flange beam exhibited higher drag than the porous-flange beam. However, within the range of approximately −11.5° to −5.5°, the porous configuration showed higher drag. Furthermore, at negative angles of attack, the lift force on the porous-flanged beam acted in the opposite direction to that on the solid-flanged beam. Finally, incorporating flange porosity reduced the magnitude of suction pressures on both the top and bottom surfaces of the U-beam.*

Keywords: Aerodynamic coefficients, U-shaped beam, Wind tunnel testing, Pressure coefficients, Porous flanges

1. Introduction

This paper presents the results of experimental aerodynamic analyses of a thin U-shaped beam with porous and non-porous (solid) flanges, a configuration typically found in bridge decks with wind barriers or in pedestrian footbridges with railings. A similar open U-shaped cross-section can also occur during bridge construction for example, during the launching phase, as documented in wind tunnel tests by Chen et al. (2020). Aerodynamic force coefficients are among the most important outputs of wind tunnel testing, as they are crucial for determining wind loads on structures and for analyzing the potential for aeroelastic instabilities such as galloping. In a recent study, Hračov and Macháček (2022) examined the effect of flange porosity on the aerodynamic coefficients of U-shaped beams, as well as on their galloping susceptibility. It was found that a U-beam with solid flanges exhibited galloping behavior similar to a rectangular beam with a same cross-sectional aspect ratio $B/D = 2$. Hračov and Macháček (2022) further showed that increasing the flange porosity of the U-beam significantly reduces its tendency to gallop, resulting in a more stable profile. Furthermore, other researchers have demonstrated that the detailed geometry of the openings can influence wind loading. For example, Davide et al. (2012) and Gu et al. (2020) reported notable changes in drag coefficients when the size and shape of the perforations were varied.

In this study, two U-beam section models were tested in the wind tunnel: one with porous flanges and one with solid flanges. The porous flange geometry was slightly modified compared to that in previous experiments by the authors. Each model was constructed by attaching two plywood flange plates to a wooden rectangular prism, forming a U-shaped cross-section, see Figure 1d. The porous flanges had an array of equally spaced square holes with side lengths of 5 mm, providing 50% open area. The solid-flange model had the same overall dimensions but no openings. A schematic of the fundamental geometry of the U-shaped cross-section is shown in Figure 1d. All experiments were conducted in the climatic wind tunnel at ITAM, CAS, in Telč, Czech Republic. The test section of this tunnel measures 1.9 m in width and 1.8 m

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in height. Each model was mounted vertically in the test section as shown in Figure 1a), connected to ATI Industrial Automation Mini 40 load cell sensors at its top and bottom. This setup, combined with a synchronized rotation mechanism shown in Figure 1c), allowed the angle of attack α to be varied from −15° to +15° in increments of 0.1°. At each angle, the load cells measured the forces on the model, which were used to calculate the drag and lift coefficients *Cd* and *Cl* , as illustrated in Figure 1d). For each angle, force data were recorded for 60 seconds at a sampling frequency of 1000 Hz. This measurement duration and frequency were sufficient to obtain statistically stationary and ergodic force signals. In addition to the force measurements, surface pressures were measured using a 64- channel MPS4264 micro-pressure scanner at 500 Hz, as shown in Figure 1b. It enabled the calculation of pressure coefficient distributions around the model. All tests were carried out at a wind speed of approximately 14 m/s under nearly laminar flow conditions with turbulence intensity below 1%. At this wind speed, the Reynolds number based on the cross-section width B was about 2.8 x10^5. The wind tunnel blockage ratio ranged from roughly 7.9% to 11.7%, depending on the angle of attack.

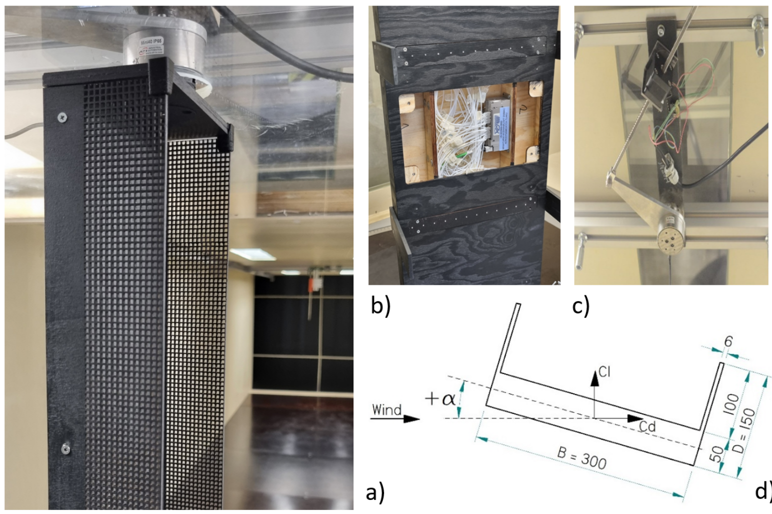

Fig. 1: a) Porous U-beam installed vertically in the wind tunnel; b) Detail of pressure taps with scanner; c) Rotational device; d) Used sign convention.

2. Aerodynamic coefficients

The mean values of aerodynamic drag and lift coefficients presented in this section are normalized by the cross-sectional height, D. No correction for the blockage effect was applied in the calculation of either aerodynamic coefficients or the pressure coefficients. Figure 2a shows the aerodynamic lift coefficient as a function of the angle of attack α, while Figure 2b presents the corresponding drag coefficient. The red lines represent the data for the U-beam with solid flanges, and the blue lines represent the data for the U- beam with porous flanges. Porous flanges significantly alter the character of the flow around the U-beam. Notably, at negative angles of attack, the lift force acts in the opposite direction compared to the case with solid flanges. At an angle of 8°, the lift coefficient reaches 1.25 for the solid-flange configuration, whereas for the porous flanges, it is −0.75. A reduction in drag is observed across a broad range of wind attack angles, approximately from −5° to 15°. This reduction is attributed to the ability of the porous flanges to allow airflow to pass through, thereby decreasing drag. However, between angles of −11.5° and −5.5°, the presence of holes in the flanges results in the opposite effect, that is, an increase in drag relative to the solid configuration.

The negative slope of the lift coefficient near zero angle of attack is smaller for the porous-flange configuration compared to the solid-flange case. A smaller negative slope of the lift coefficient corresponds to a higher critical wind speed for the onset of transversal galloping instability. The range of the negative slope is broader for the U-beam with solid flanges, which may lead to a more pronounced dynamic response during galloping instability.

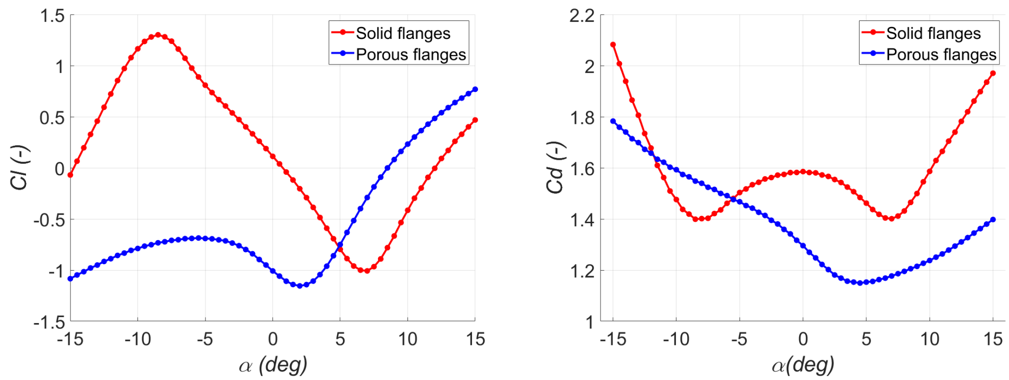

Fig. 2: Aerodynamic coefficients of U-beams: lift coefficient (left); drag coefficient (right)

3. Pressure coefficients

The distribution of the mean aerodynamic pressure on the surface of the U-beam cross-section is presented for selected angles of attack in Figures 3-5. The positions of the pressure taps are indicated by small black dots on the cross-section. Pressure values located outside the cross-section denote suction, while values inside indicate positive pressure.

The left side of Figure 3 shows the distribution for a wind attack angle of −15°, and the right side of this figure corresponds to an angle of -8°. It is evident that the use of porous flanges leads to a substantial reduction in suction within the interior of the U-beam. This results in a negative aerodynamic lift force at negative angles of attack. As the angle of attack increases, the suction effect within the U-beam diminishes further due to the influence of flange porosity. The presence of porous flanges also leads to a reduction in suction on the bottom surface of the cross-section for most angles of wind attack. Interestingly, at an angle of −8°, the suction at the bottom is nearly identical for both the solid and porous flange configurations. The difference in positive pressure on the windward face of the U-beam is relatively small between the two cases, indicating that flange porosity does not significantly affect the pressure distribution on the windward side across the examined range of angles. In contrast, the suction on the leeward side is strongly influenced by the presence of porous flanges. In general, flange porosity results in a marked reduction of suction on the leeward side of the U-beam.

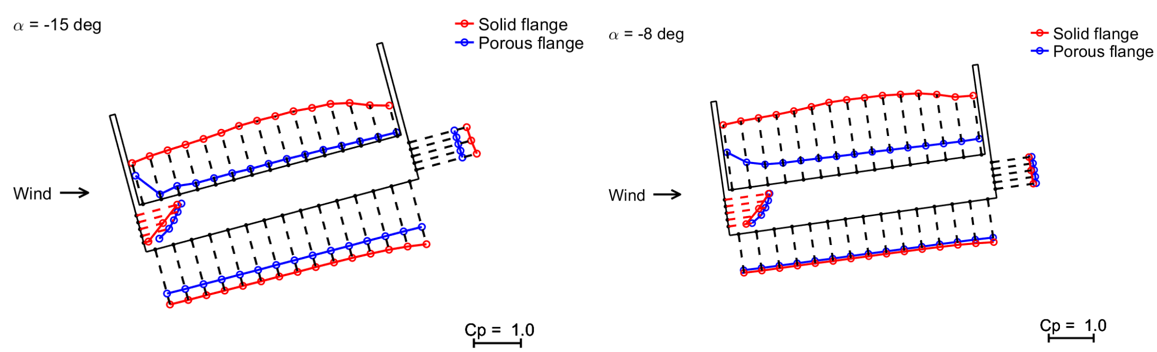

Fig. 3: Mean aerodynamic pressure coefficient on surface of U-beam for angle -15° (left) and -8° (right).

An inclination angle of 5° represents the case at which the lift forces are equal for both the solid and porous flange configurations, as shown in Figure 2 (left). The corresponding pressure distribution on the surface of the U-beam is illustrated in Figure 4 (top right). It can be observed that the pressure distributions for the two flange configurations are quite similar, particularly in the lower part of the cross-section. Other selected examples for positive angles of wind attack are also presented in Figure 4. As the inclination increases toward more positive values, the differences in pressure distribution between the solid and porous flange configurations become progressively smaller.

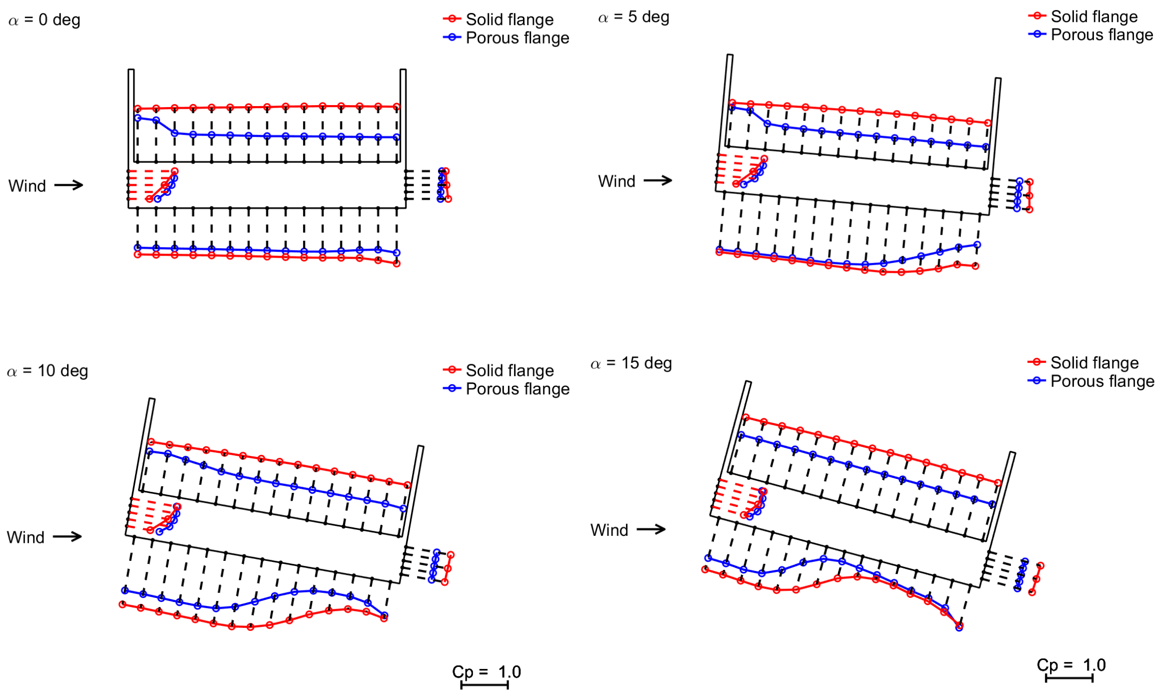

Fig. 4: Mean aerodynamic pressure coefficient on surface of U-beam for angle 0° (top left), 5° (top right), 10° (bottom left) and 15° (bottom right).

4. Conclusions

Experimental measurements of U-beams with porous and solid flanges have demonstrated the significant influence of flange porosity on aerodynamic and pressure coefficients. Overall, the usage of porous flanges leads to a reduction in suction on the top, bottom, and leeward sides of the U-beam. In contrast, the positive pressure on the windward side remains largely unaffected by flange porosity. The most pronounced differences occur at negative angles of attack, where the aerodynamic lift forces act in opposite directions for the two tested flange configurations. For the porous-flange U-beam, the negative slope of the lift coefficient near zero angle of attack is smaller than that observed for the solid-flange configuration. As a result, the susceptibility to galloping instability is reduced in U-beams with porous flanges compared to those with solid flanges.

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