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POST-CRITICAL FLUTTER MODE AT THE ONSET OF INSTABILITY IN A FOOTBRIDGE DECK SECTION MODEL WITH AERODYNAMIC MODIFICATIONS

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Abstract: *This study investigates the post-critical flutter mode of a footbridge deck section model at the onset of instability. Wind tunnel tests were performed on a two-degree-of-freedom model, and the response was evaluated from limit cycle oscillations immediately following flutter onset. The analysis focused on the amplitude ratio and phase relationship between heave and pitch, as well as the flutter frequency and critical wind speed. The results show that aerodynamic modifications significantly affect not only the critical flutter velocity, but also the character of the flutter mode. The modified leading edge promotes torsion-dominated oscillations, while longitudinal ribbons result in a predominantly heave-dominated response.*

Keywords: Flutter, Post-critical response, Aeroelastic instability, Footbridge deck, Wind tunnel testing

1. Introduction

The aeroelastic stability of slender pedestrian bridges is an important issue in modern bridge engineering. Due to their low mass and limited structural damping, such structures are highly susceptible to wind-induced instabilities, particularly flutter, which may lead to rapidly growing oscillations and potential structural failure. The aerodynamic behavior of bridge decks is strongly influenced by their cross-sectional geometry. Previous studies have shown that relatively small geometric modifications, such as deck edge shaping or the addition of aerodynamic devices, can significantly affect flow separation and improve aeroelastic stability, as demonstrated by Macháček et al. (2025). The self-excited aerodynamic forces are commonly described using the flutter derivative formulation introduced by Scanlan and Tomko (1971). These derivatives are typically identified from wind tunnel experiments using free-decay or forced vibration methods, as shown, for example, by Bartoli et al. (2009), Buljac et al. (2017), and Král et al. (2016). In previous work by the authors, the aeroelastic stability of a footbridge deck was investigated experimentally, focusing on the identification of flutter derivatives and the determination of critical wind velocities for several modified configurations. The results demonstrated that aerodynamic modifications can significantly delay the onset of flutter. However, less attention is usually devoted to the structural response at and immediately beyond the onset of instability. In this regime, the character of the oscillatory motion, including the relative contribution of vertical and torsional components and their phase relationship, may vary depending on the aerodynamic configuration of the deck. The present study therefore focuses on the post-critical flutter behavior at the onset of instability. Using experimental data obtained from a sectional model with two degrees of freedom, the modal characteristics of the response are evaluated in terms of amplitude ratio and phase shift between heave and pitch motion, with particular emphasis on the effect of aerodynamic modifications.

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2. Experimental setup

The investigated configurations of the footbridge deck are illustrated in Fig. 1. Three cross-section variants were considered, including the original deck geometry and two modified configurations incorporating aerodynamic measures. These modifications were designed to alter flow separation and improve the aeroelastic performance of the structure. The right part of the figure shows the sectional aeroelastic model installed in the aerodynamic wind tunnel in Telč. The model was mounted to allow coupled vertical and torsional motion, enabling the investigation of flutter behavior under controlled aerodynamic conditions. The experimental setup corresponds to that used in the authors' previous study, ensuring consistency in the comparison of aerodynamic characteristics across the investigated configurations. The sectional model was characterized by a heave natural frequency of 2.26 Hz with a damping ratio of 1.18%, and a pitch natural frequency of 3.49 Hz with a damping ratio of 0.94%. The mass per unit length was 4.933 kg/m, the mass moment of inertia was 0.0376 kg·m²/m, and the deck width and model length were 0.30 m and 1.00 m, respectively. The aeroelastic response of the sectional model was investigated using the free-decay method. The model was initially displaced and released, and the resulting oscillations were recorded over a range of wind velocities. Based on these measurements, the flutter derivatives were identified following the same procedure as in the authors' previous study. As the wind velocity approached the critical condition, the onset of flutter was observed. Immediately beyond this point, the model exhibited sustained oscillations in the form of limit cycle motion. These post-critical responses were subsequently recorded and evaluated.

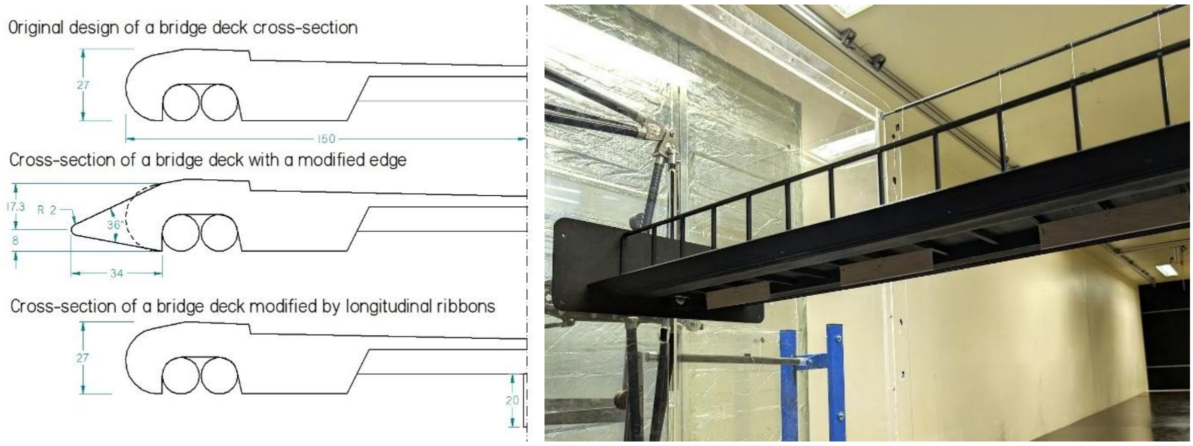

Fig. 1: Three cross-section variants of the footbridge (left); view of the experimental section model of the footbridge with longitudinal ribbons (right).

3. Results

The analysis focused on the modal characteristics of the motion, including the phase shift between vertical displacement and torsional rotation, the amplitude ratio, and the oscillation frequency at the onset of flutter. In addition, the critical wind velocity was determined in model scale. The post-critical aeroelastic response of the sectional model was evaluated at the onset of instability for all three investigated configurations. The results are summarized in Table 1. The ratio P/H denotes the ratio of torsional (pitch) to vertical (heave) oscillation amplitudes at flutter onset, while the phase shift P vs H represents the phase difference between torsional and vertical motion. The flutter wind speed corresponds to the critical wind velocity in model scale, and the flutter frequency is defined as the coupled frequency of the heave and pitch modes at flutter onset. The pitch and heave frequency changes represent the relative changes in torsional and vertical natural frequencies with respect to the zero-wind condition. A significant influence of aerodynamic modifications on the modal character of the flutter response was observed. For the original deck configuration, the amplitude ratio was 0.629, indicating a response dominated by vertical motion with a moderate torsional contribution. The modified leading edge resulted in a substantial increase in the amplitude ratio to 1.299, indicating a clear shift towards torsion-dominated oscillations. In contrast, the configuration with longitudinal ribbons exhibited a reduced amplitude ratio of 0.326, corresponding to a predominantly heave-dominated mode with a significantly diminished torsional contribution. These results demonstrate that aerodynamic modifications affect not only the critical flutter velocity, but also fundamentally alter the character of the post-critical flutter mode. In particular, the leading edge modification promotes torsional dominance, while the application of aerodynamic ribbons shifts the response towards a heave-dominated regime. The phase shift between vertical and torsional motion remains close to 180° for all configurations, with values of 167°, 171°, and 165° for the original, modified edge, and ribbon configurations, respectively. This confirms that the observed instability corresponds to a classical coupled flutter mode with nearly anti-phase motion between heave and pitch. The critical wind velocity increases significantly with aerodynamic modifications, from 6.3 m/s for the original configuration to 7.17 m/s and 9.13 m/s for the modified edge and ribbon configurations, respectively, confirming the stabilizing effect of the applied measures.

Tab. 1: Post-critical limit cycle oscillation characteristics

	Original design	Modified edge	Longitudinal ribbons
P/H (°/mm)	0.629	1.299	0.326
Phase shift P vs H (°)	167	171	165
Flutter wind speed (m/s)	6.3	7.17	9.13
Flutter frequency (Hz)	2.95	3.11	2.71
Pitch frequency change (%)	-15.5	-10.9	-22.3
Heave frequency change (%)	30.5	37.6	19.9

The flutter frequency, defined as the common frequency at which the heave and pitch modes coalesce, varies between the investigated configurations. The highest value of 3.11 Hz is observed for the modified edge, while the ribbon configuration exhibits the lowest value of 2.71 Hz. The changes in modal frequencies further support the observed differences in flutter behavior. The torsional frequency decreases in all cases, with reductions of −15.5%, −10.9%, and −22.3% for the original, modified edge, and ribbon configurations, respectively. At the same time, the heave frequency increases by 30.5%, 37.6%, and 19.9%, indicating a convergence of the two modes at the onset of flutter. The most pronounced torsional softening occurs for the ribbon configuration, which is consistent with its reduced torsional contribution to the resulting oscillation mode.

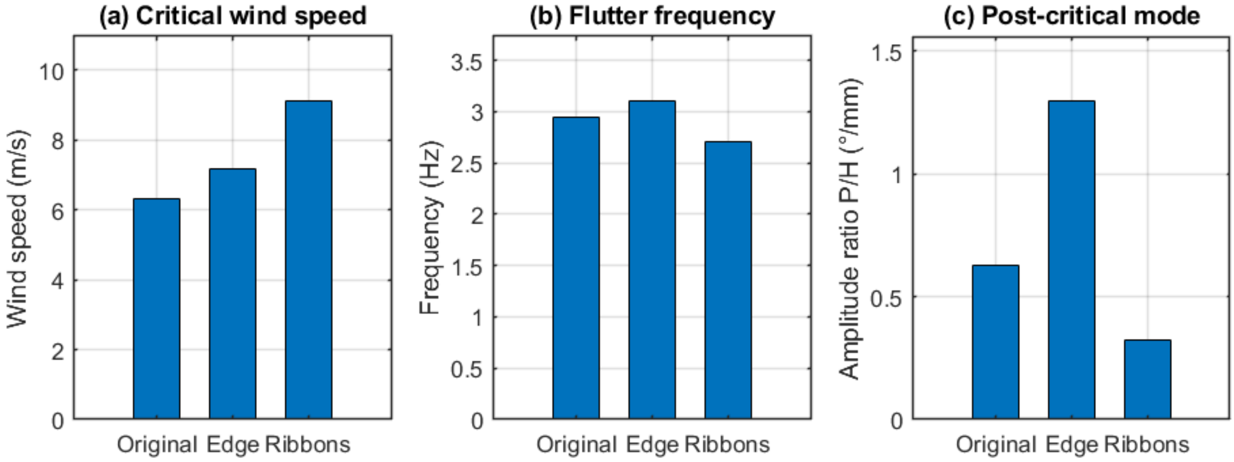

Fig. 2: (a) Critical wind speed, (b) flutter frequency, and (c) post-critical flutter mode characterized by the amplitude ratio of torsional to vertical motion.

The results are further illustrated in Fig. 2. Fig. 2(a) shows the critical wind speed, highlighting the increase in flutter onset velocity for the modified configurations. Fig. 2(b) presents the corresponding flutter frequency, while Fig. 2(c) illustrates the post-critical flutter mode expressed by the amplitude ratio between torsional and vertical motion. A clear shift in modal character is observed, with the modified leading edge promoting torsion-dominated behavior, whereas the ribbon configuration leads to a predominantly heave-dominated response.

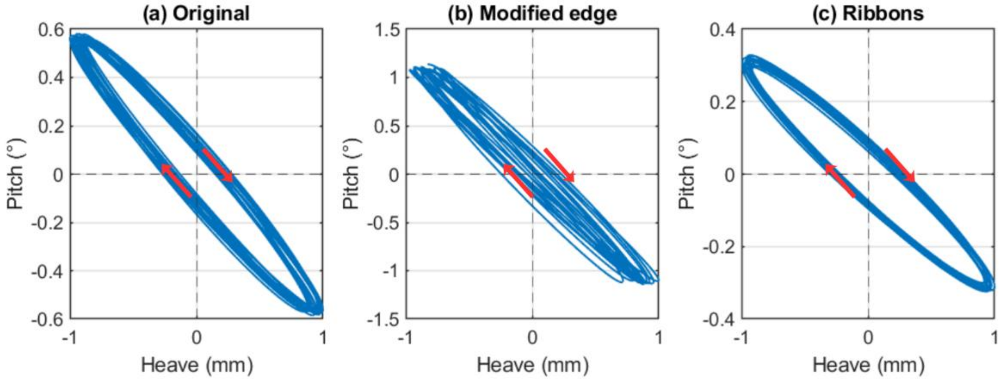

Fig. 3: Normalized phase-plane plots of post-critical oscillations at flutter onset

The post-critical response is further illustrated in Fig. 3 using phase-plane plots of heave and pitch motion. The trajectories form closed curves corresponding to limit cycle oscillations established immediately after flutter onset. The plots are normalized with respect to the heave amplitude, allowing direct comparison of the modal character between the investigated configurations while preserving the relative contribution of torsional motion. A clear change in the shape of the trajectories is observed. The modified leading edge exhibits an elongated trajectory in the pitch direction, indicating a torsion-dominated response. In contrast, the configuration with longitudinal ribbons shows a flatter trajectory, corresponding to a predominantly heave-dominated mode, while the original configuration exhibits an intermediate behavior with a mixed contribution of both components. The direction of motion, indicated by arrows, confirms a nearly anti-phase relationship between heave and pitch, consistent with the classical coupled flutter mechanism.

4. Conclusions

The presented study investigated the post-critical flutter behavior of a footbridge deck section model at the onset of instability, with particular emphasis on the influence of aerodynamic modifications. The results confirm that such modifications significantly increase the critical wind velocity, with the highest improvement observed for the configuration equipped with aerodynamic ribbons. In addition to this stabilizing effect, substantial changes in the character of the flutter mode were identified. The amplitude ratio analysis revealed a shift from a mixed or heave-dominated response in the original configuration to a torsion-dominated mode for the modified leading edge, while the ribbon configuration promoted a predominantly heave-dominated response. The phase relationship between heave and pitch remained close to anti-phase for all cases, confirming a classical coupled flutter mechanism. The findings demonstrate that aerodynamic modifications affect not only the stability limit, but also the modal structure of the flutter response. This highlights the importance of considering the character of oscillations at the onset of instability, in addition to the critical wind velocity, when evaluating the aeroelastic performance of footbridge decks.

Acknowledgement

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