# Unsteady galloping of a bridge deck with open cross section: wind tunnel tests and mathematical modeling

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ABSTRACT: Galloping instability can potentially threaten the modern launching of steel-concrete composite bridge girders, due to light weight and bluff shape of the normally first-launched steel box. A bridge deck with typical open cross section was selected and investigated in smooth flow through wind tunnel techniques. Aeroelastic tests showed that the classical instability arising from the interaction between vortex-induced vibration (VIV) and galloping may occur for a flow incidence of 4°. In contrast, a different and more complicated behavior was observed for a null wind angle of attack. Static tests further indicated that the most evident difference between the two cases is the magnitude of the vortex shedding force, which is much lower for a null angle of attack. Finally, Tamura's wake-oscillator model was implemented for the bridge deck at a flow incidence of 4°, following a recently proposed parameter identification method. The mathematical model was found to be able to give some promising predictions even for a complex bridge deck profile.

KEYWORDS: Galloping; Vortex induced vibration; Composite bridge; Open cross section; Wind tunnel tests; Mathematical modelling

## 1 INTRODUCTION

Across-wind galloping is an aeroelastic instability typical of slender structures with special cross sections, like square or D shape. Its onset and post-critical behavior can be well captured by the quasi-steady (QS) theory if high reduced wind speed is ensured [1]. Otherwise, the unsteady effects of shed vortices and fluid memory become non-negligible and both QS galloping and VIV theories fail to explain the peculiar phenomena observed during wind tunnel tests [2]. This unsteady galloping is not only physically interesting but also important in modern launching of steel-concrete composite bridges, since the first-launched steel box usually features light weight, low damping and bluff section. A bridge deck with open cross section was thus selected to conduct a wind tunnel investigation. This profile is typical during the bridge construction phase but limited attention has been paid so far to its aeroelastic stability. A rectangular prism with the same side ratio was also considered as a reference and for the sake of comparison. Finally, an attempt to model unsteady galloping with Tamura's wake-oscillator model [3-4] was carried out for this bridge deck profile.

## 2 WIND TUNNEL TESTS

The boundary layer wind tunnel at the Institute of Steel Structures of Technische Universität Braunschweig is a suction Eiffel-type facility with a cross section of 1.4 m ×1.2 m. The flow speed can be varied continuously up to 25 m/s with a free stream turbulence intensity below 1%.

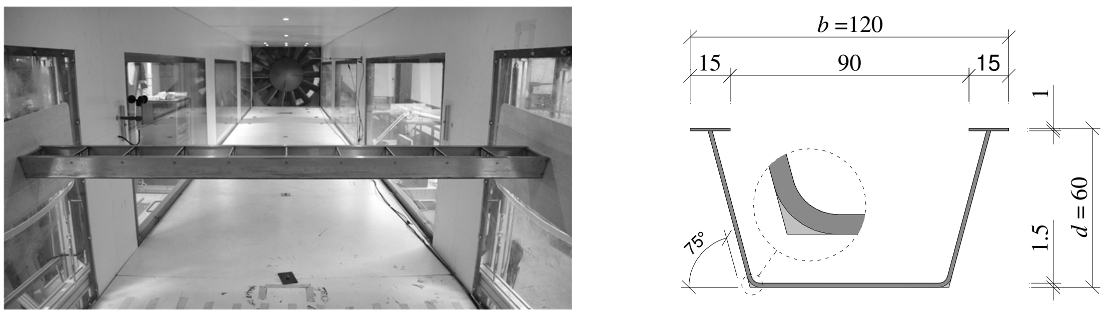


Figure1. Photo of the bridge deck model in the wind tunnel and sketch of the cross section (in mm)

Figure 1 shows the aluminum bridge deck model and the details of the cross section. It has a general side ratio $b/d$ = 2.0 and a length $L$ = 1300 mm between two 480 mm×240 mm×5 mm end-plates. Two-component epoxy adhesive was used to sharpen the section lower corners. The 1290 mm long rectangular cylinder has the same side ratio and depth, and was equipped with the same end-plates. It was made of 5 mm thick balsawood, with an aluminum square tube inside to provide stiffness. The static setup consisted of three strain-gauge load cells and specially designed connecting rods at each side of the wind tunnel. The flow incidence of the models was manually adjusted with an electronic inclinometer. The aeroelastic setup was composed by eight coil springs suspending the sectional models from outside the wind tunnel. The horizontal motion was restricted with anti-drag cables. The dynamic response of the model was measured with four laser displacement sensors, and additional damping was provided by two or four electromagnetic dampers with a strength controlled by the input electric power. The bridge deck model had a natural frequency $n_0$ = 9.53 to 9.63 Hz and an oscillating mass $M$ = 3.6 to 3.67 kg, depending on the number of dampers used. The lowest damping ratio $\zeta_0$ in this setup was smaller than 0.1%. The blockage ratio was 5%, defined here as the ratio of model depth to wind tunnel height. The mean wind speed was monitored by a Prandtl tube. Flow maps were prepared prior to the installation of the model to obtain more precise estimates of the wind speed at the location of the model.

The 2:1 rectangular prism was tested first. The obtained value of the drag coefficient $c_D$ = 1.50 (normalized with the length $d$) and Strouhal number St = 0.079 at 0° flow incidence agree well with the literature [5], thus suggesting the validity of the test setup and the end-plates. Figure 2 shows some static test results for the bridge deck model, where $c_D$ and $c_L$ are mean drag and lift coefficients, $c_{\mathrm{lat},0}$ denotes the root-mean-square (RMS) value of fluctuating lift coefficient, and a positive α means a nose-up rotation of the model. The negative slope of $c_L$ is clear for -5° < α < 12°, implying the possible galloping instability.

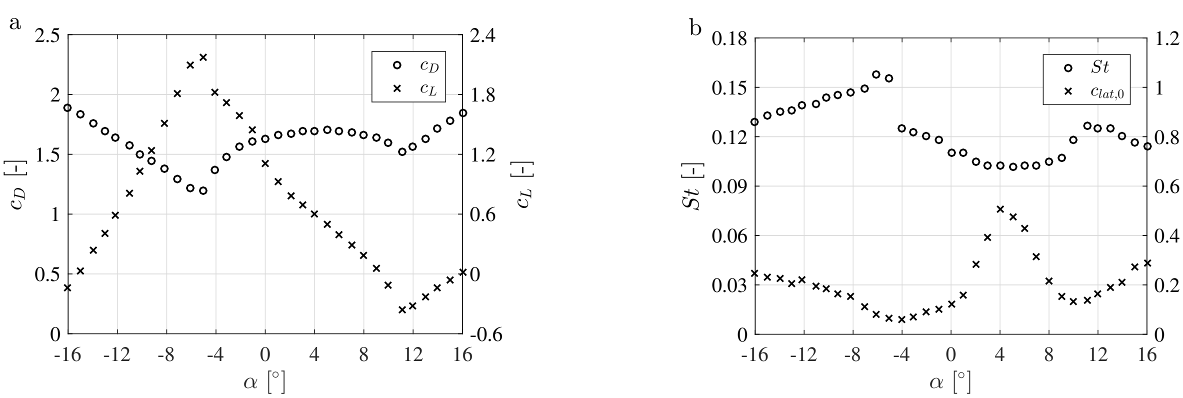


Figure 2. $c_D$ and $c_L$ at Re = 6.0·10$^4$ (a); St and $c_{\mathrm{lat},0}$ at Re = 2.0·10$^4$ (b). $c_D$ and $c_L$ are normalized with section depth $d$

Figure 3a shows the effect of flow incidence $\alpha_0$ on the aeroelastic response for the lowest Scruton number Sc considered. The galloping onset velocity $U_g$ predicted by the quasi-steady theory is lower than the Kármán-vortex-resonance wind speed $U_r$ for all of the investigated $\alpha_0$. In case of $\alpha_0$ = 4° or 2°, galloping oscillations occur at $U_r$, as is typical for the combined instability of VIV and galloping [2]. For $\alpha_0$ = 0° or -2°, the instability appears neither at $U_r$ nor at the threshold predicted by the quasi-steady theory ($U_g < U_r$), but clearly after $U_r$. Interestingly, a similar behavior has already been observed for a 3:2 rectangular cylinder in turbulent flow [6]. Figure 2 shows that the magnitude of the vortex shedding force $c_{lat,0}$ is significantly smaller in these cases.

Figure 3b shows the effect of varying the Scruton number on the aeroelastic response for $\alpha_0$ = 4°. Test cases #0 to #5 show a full interaction of VIV and galloping [2], the actual galloping onset being fixed at $U_r$ for Sc smaller than 83. When Sc is higher than 83, VIV and galloping begin to separate, and a clear lock-in range reappears around $U_r$. Spontaneous galloping onset were not reached in test cases #6 to #8 not to risk to destroy the model, but a higher amplitude branch was found beyond the lock-in wind speed range by releasing the model from a higher position. Finally, it is worth noting that the typical value of Sc for this kind of bridge deck in the launching phase normally ranges from 10 to 30.

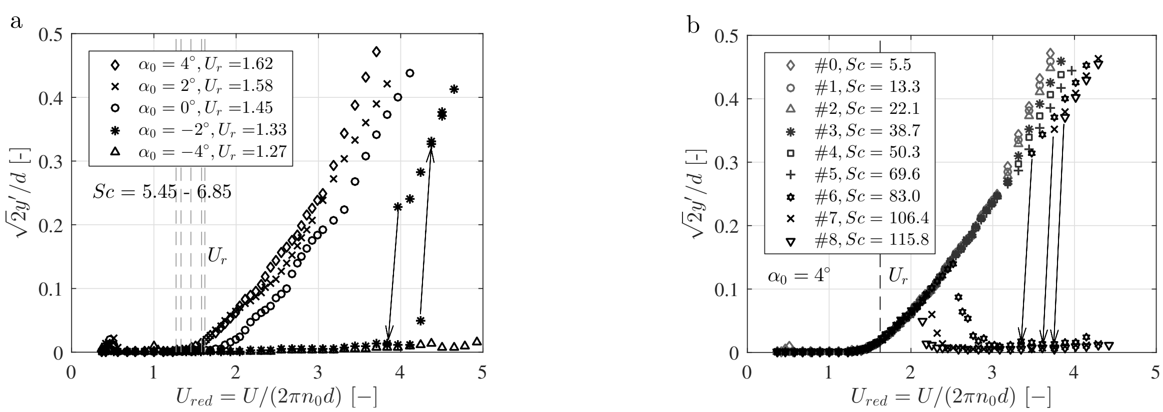


Figure 3. Effect of flow incidence on bridge model response curves for a low Sc (a), and effect of Sc at $\alpha_0$ = 4° (b). The Scruton number is defined as $Sc = 4\pi M\zeta_0/\rho d^2 L$, $U_r = 1/2\pi St$ denotes the VIV onset velocity, $y'$ represents the RMS value of displacement response, $U$ is the mean flow velocity, and positive $\alpha_0$ implies a nose-up rotation of the model.

## 3 MATHEMATICAL MODELING

The wake-oscillator nonlinear model proposed by Tamura & Shimada [3] was selected to simulate the VIV-galloping interaction for this bridge deck at 4° flow incidence. Equations (1) and (2) describe respectively the motion of the body and the rotation of the wake. The wake lamina is supposed to pivot about the centroid of the bridge deck, and $c_{L0} = \sqrt{2}c_{lat,0}$. Adopting the method proposed by Mannini *et al*. [4], the key parameter $f$ =17 was calibrated from the lock-in amplitude of test case #8 after setting $h^*$= 1.6, which represents the nondimensional wake width. Quasi-steady transverse force coefficient $C_{Fy}^{QS}(\alpha) = -\sec(\alpha)[c_L(\alpha) + c_D(\alpha)\tan(\alpha)]$ measured at Re = $6.0 \cdot 10^4$, and St = 0.098 at Re = $2.0 \cdot 10^4$ were used. The dependence of $c_{L0}$ on Re was considered by interpolating the experimental data. Detailed parameter definition can be found in [4]. The following two differential equations were simultaneously solved by numerical integration.

$$Y'' + 2\zeta_0 Y' + Y = U_{red}^2/m^* \cdot f \cdot (\vartheta - Y'/U_{red}) + U_{red}^2/m^* \cdot C_{Fy}^{QS}(Y'/U_{red}) \tag{1}$$

$$\vartheta'' - 2\beta\upsilon\vartheta'(1 - 4f^2/C_{L0}^2 \cdot \vartheta^2) + \upsilon^2\vartheta = \lambda Y'' + \upsilon^2 Y'/U_{red} \tag{2}$$

Figure 4 shows some selected numerical results of model equations. The same value of *f* was used for the test cases at any Sc. Nonlinear quasi-steady galloping results are also given here for the sake of comparison. For the lowest Sc (test case #0), the mathematical model successfully predicts the delay of the galloping instability up to the critical wind speed for VIV, although the post-critical amplitude is overestimated. For test case #8, with a considerably higher Sc, the model well predicts the lock-in range and VIV amplitude. A second solution branch with a higher amplitude is also found by imposing a larger initial condition.

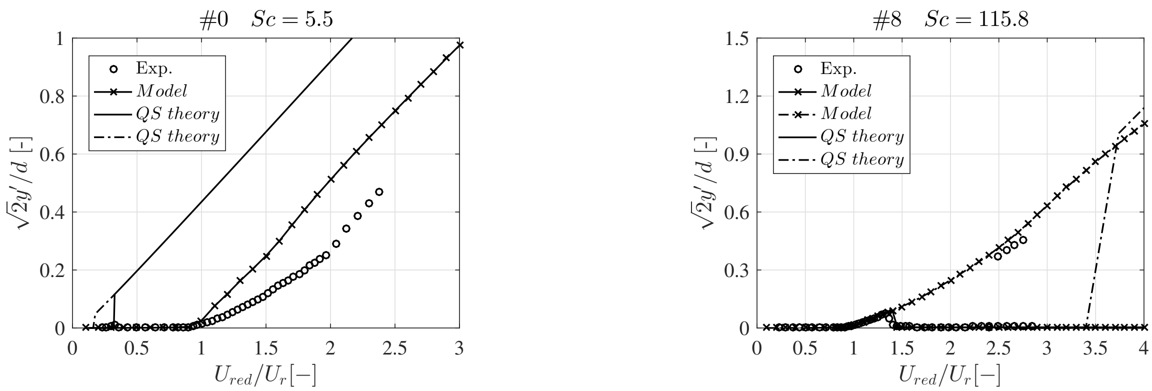


Figure 4. Selected results of mathematical modeling. Dashed lines denote the upper-branch amplitude solutions

## 4 CONCLUDING REMARKS

Wind tunnel tests showed that the studied bridge deck is prone to unsteady galloping instability, given that a low Scruton number is expected during the launching phase of steel-concrete composite bridges. The sensitivity of unsteady galloping instability to flow incidence is highlighted for this bridge deck section. In particular, strong interaction between VIV and galloping was observed at 4° flow incidence, the actual galloping onset being fixed at the Kármán-vortex-resonance wind speed $U_r$ when Sc is lower than 83. In contrast, for the 0° flow incidence, the galloping instability arises at a flow speed higher than $U_r$ even for very low Sc. Static tests suggest that the very different magnitude of the vortex shedding force at different flow incidences might play a role. Finally, Tamura's mathematical model [3] provided some satisfactory predictions of the aeroelastic behavior of this bridge deck at 4° flow incidence, identifying the key parameter *f* as suggested in [4].

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