

Side-surface openings effects on the aerodynamic performance of box girders in tandem

Jiaqi Wang, Ph.D.¹; Tomomi Yagi, Ph.D.²; Jun Ushioda³; Kyohei Noguchi, Ph.D.⁴;

Naoki Nagamoto, Ph.D.⁵; Hiroyuki Uchibori⁶

¹Researcher, Dept. of Civil and Earth Resources Engineering, Kyoto Univ., Kyoto 615-8540, Japan (Corresponding author). E-mail: wang.jiaqi.44v@kyoto-u.jp

²Professor, Dept. of Civil and Earth Resources Engineering, Kyoto Univ., Kyoto 615-8540, Japan. E-mail: yagi.tomomi.7a@kyoto-u.ac.jp

³Former Graduate Student, JAL SKY CO., LTD., Japan. E-mail: ushioda.jun.r16@kyoto-u.jp

⁴Assistant Professor, Dept. of Civil and Earth Resources Engineering, Kyoto Univ., Kyoto 615-8540, Japan. E-mail: noguchi.kyohei.7z@kyoto-u.ac.jp

⁵General Manager, Structural Engineering Service Dept., Sumitomo Mitsui Construction co., ltd., Tokyo 104-0051, Japan. E-mail: nagamoton@smcon.co.jp

⁶Engineer, Structural Engineering Service Dept., Sumitomo Mitsui Construction co., ltd., Tokyo 104-0051, Japan. E-mail: uchibori@smcon.co.jp

Abstract

A butterfly web girder is a box girder with discretely distributed side-surface openings. Owing to these openings, butterfly web girders show better aerodynamic performance than conventional box girders. This study aims to investigate the effects of the side-surface openings on the aerodynamic instability of a box girder when it is placed in tandem with another girder. Another aim is to investigate whether the aerodynamic instability of one girder is affected by the side-surface openings of an adjacent girder. A series of wind tunnel tests was carried out on a butterfly web girder and conventional box girder, with another rigidly supported butterfly web girder or conventional box girder, respectively, at its upstream/downstream side. The fixed downstream

girder increased the galloping instability of the upstream girder, while the fixed upstream girder amplified the vortex-induced vibration of the downstream girder. The side-surface openings of the upstream girder stabilized its galloping and vortex-induced vibration, irrespective of the type of girder downstream. The side-surface openings of the downstream girder stabilized its vortex-induced vibration independent of the type of girder upstream.

Keywords: butterfly web bridge; vortex-induced vibration; galloping; tandem; wind tunnel test.

Introduction

One of the main concerns with the construction of long-span bridges is optimizing the balance between the girder weight and its wind resistance capability. Kasuga (2017) recently introduced the butterfly web girder, which is a box girder with discretely distributed openings on the side surface (Fig. 1). Our recent study (Wang et al., 2020a) confirmed that the side-surface openings stabilized the vortex-induced vibration and galloping in a butterfly web girder with a side ratio, B/D , of 3.24, where B is the girder width and D is the girder depth. To accommodate an increase in traffic, a new bridge is sometimes constructed adjacent to an existing bridge (Honda et al., 1990; Meng et al., 2011; Kim et al., 2013; Argentini et al., 2015). Compared with the aerodynamic performance of a single stand-alone bridge, the aerodynamic performance of two bridges in tandem is more complicated and even more unstable (Honda et al., 1990; Kimura et al., 2008; Meng et al., 2011; Kim et al., 2013; Seo et al., 2013; Argentini et al., 2015; Park and Kim, 2017a; Park et al., 2017b). This raises the question of whether butterfly web girders can exhibit good aerodynamic performance in a tandem arrangement. Furthermore, by introducing side-surface openings in the box girder, the approaching flow can access the inner space of the box girder, thereby altering the flow field (Wang et al., 2020a). Subsequently, when two girders are placed in tandem, the side-surface openings of each girder may not only affect the flow field around the

girder itself, but may also potentially affect the flow field around the adjacent girder. Therefore, this study also intends to investigate the relationship between the side-surface openings of two girders in tandem and the resulting aerodynamic performance (i.e. the vortex-induced vibration and galloping).

As reported in our previous study (Wang et al., 2020a), the $B/D = 3.24$ conventional box girder showed the motion-induced vortex vibration. Vortex-induced vibrations are divided into two types: Kármán-vortex and motion-induced types (Matsumoto et al., 2008a). Kármán-vortex vibration occurs at a reduced wind velocity of $1/St$ (St is the Strouhal number), while vertical motion-induced vortex vibration occurs at a reduced wind velocity of $1.67B/D$. The side-surface openings reduced the amplitude of the vertical motion-induced vortex vibration by 50%, but had no effect on the critical wind velocity (Wang et al., 2020a). By simplifying the $B/D = 3.24$ butterfly web girder as a $B/D = 2$ rectangular cylinder, a recent study (Wang. et al., 2020b) showed that increasing the total openings area resulted in a continuous decrease in the amplitude of the vortex-induced vibration. Furthermore, similar to the side-surface openings of the butterfly web girder, the spanwise periodic passive slits on the windward and leeward surfaces also stabilized a $B/D = 7.75$ box girder against the vortex-induced vibration (Chen et al., 2019a; Yang et al., 2020). Owing to these slits, the approaching flow passed through the box girder into the wake, reducing the “vortex strength” around the box girder (Chen et al., 2019b). This reduction in the “vortex strength” was assumed the reason for the stabilizing effect of the side-surface openings or slits on the vortex-induced vibration. When two girders were placed in a tandem arrangement, the vertical vortex-induced vibration of the upstream girder exhibited an amplified amplitude as a result of the presence of the downstream girder (Seo et al., 2013; Park et al., 2017a, b). The vertical vortex-induced vibration of the downstream girder was amplified as a result of the periodic turbulent flow

from the upstream girder (Okajima et al., 1990; Takeuchi and Matsumoto, 1992; Kimura et al., 2008; Meng et al., 2011; Park and Kim, 2017a). Free vibration tests have been widely utilized to observe these aerodynamic interferences. It has been suggested in several studies (Kimura et al., 2008; Honda et al., 1990) that both girders should be elastically supported to accurately evaluate the aerodynamic interference. However, according to Park and Kim (2017a), when two girders were elastically supported in tandem, the vertical vortex-induced vibration of the upstream girder had nearly the same magnitude regardless of whether the downstream girder vibrated or not. Conversely, the amplitude of the vertical vortex-induced vibration of the downstream girder reached a maximum value when the two girders in tandem shared a similar frequency (Park and Kim, 2017a). Compared with this maximum value, when the upstream girder was rigidly supported, the maximum amplitude of the vortex-induced vibration of the downstream girder showed a similar value. Furthermore, the aerodynamic interferences shared a similar mechanism when both girders were elastically supported and when one girder was rigidly supported while the adjacent girder was elastically supported. Therefore, for simplicity, this study intends to observe the vertical vortex-induced vibration of one girder by rigidly supporting the adjacent girder. This study also intends to investigate the effects of the side-surface openings on the vertical vortex-induced vibration of girders in a tandem arrangement.

Gallop instability is a self-excited one degree-of-freedom vibration in the direction normal to the oncoming wind (Parkinson, 1989). The side-surface openings stabilized the galloping by increasing the critical wind velocity (Wang et al., 2020a, and b). Recent researches (Wang et al., 2020a, and b) have shown that the side-surface openings stabilized the galloping by promoting the reattachment of the separated shear layer on the upside/downside surface. When two girders were placed in tandem, the galloping of the downstream girder was stabilized by the turbulent flow from

the upstream girder regardless of whether or not the upstream girder was rigidly supported (Takeuchi and Matsumoto, 1992; Honda et al., 1990). This result coincided with past studies (Parkinson, 1989), which reported that an increase in the turbulence intensity stabilized the galloping. However, the upstream girder occasionally exhibited more unstable galloping due to the presence of the downstream girder (Takeuchi and Matsumoto, 1992; Honda et al., 1990). This coincided with previous research (Nakamura et al., 1991; Yagi et al., 2013), which reported that the galloping was more unstable if the splitter plate was located in the wake in order to suppress the vortex shedding. Thus, for simplicity, this study intends to observe the galloping of one girder while the adjacent girder is rigidly supported. Furthermore, this study intends to investigate the effects of the side-surface openings on the galloping instability of two girders in tandem.

The aerodynamic interference of two girders in tandem is dependent on their center distance (Sakamoto et al., 1987; Okajima et al., 1990a and b; Kimura et al., 2008; Liu et al., 2009, 2010 and 2015; Ma et al., 2020; Takeuchi and Matsumoto, 1992; Park et al., 2017b; Zhou et al., 2017; Núñez et al., 2018). The aerodynamic force coefficients working on the two girders in tandem varied significantly with the center distance (Okajima et al., 1990a; Liu et al., 2009 and 2015; Zhou et al., 2017). Furthermore, the Strouhal number of two girders in tandem also varied with the center distance (Sakamoto et al., 1987; Okajima et al., 1990a; Park et al., 2017). The maximum amplitude of the vertical vortex-induced vibration of the two girders in a tandem arrangement increased with their center distance, and increasing the center distance above a certain value resulted in a continuous decrease in the maximum amplitude with center distance (Okajima et al., 1990b; Kimura et al., 2008; Liu et al., 2010; Park et al., 2017b; Ma et al., 2020). However, discussions on the effect of center distance on the aerodynamic interference are out of scope for the current research. The aerodynamic performance of a box girder with a side ratio, B/D , of 3.24

is characterized by that of a $B/D = 3$ rectangular cylinder. The Strouhal number of the $B/D = 3$ rectangular cylinders in tandem decreased with the center distance, achieving an extreme value at about the center distance of twice the girder width (i.e., $2B$), and then increased with the center distance. For $B/D = 3$ rectangular cylinders in a tandem arrangement, in wake of a fixed upstream cylinder, the vertical vortex-induced vibration of the downstream cylinder was amplified most substantially at a center distance of $2B$ (Okajima et al., 1990). Therefore, the center distance between the two girders was set to $2B$.

To investigate the effects of the side-surface openings on the aforementioned aerodynamic interference, the $B/D = 3.24$ butterfly web girder used in our recent study (Wang et al., 2020a) was duplicated in the current study. By covering its openings, a conventional box girder was essentially created. As the $B/D = 3.24$ butterfly web girder was a bluff girder, this study mainly focused on the aerodynamic interference in the vertical direction, and the torsional vibration was not considered. Aerodynamic force tests, vertical one-degree-of-freedom (1DOF) free vibration tests, and vertical 1DOF forced vibration tests were carried out for one girder while the adjacent girder was rigidly supported at the upstream/downstream side. This $B/D = 3.24$ butterfly web girder was designed for the main girder of a 365 m extradosed bridge with a main span of 180 m. Even though a 365 m extradosed concrete bridge would not suffer from severe vortex-induced vibration and galloping owing to its high mass-damping parameter, for the free vibration tests, the mass-damping parameter was minimized as much as possible to facilitate the observation of the effects of side-surface openings on the vibration.

To begin, the effects of the side-surface openings on the aerodynamic forces of the stationary girders in tandem are investigated. Then, the aerodynamic performance of the upstream girder is evaluated with consideration for the effects of the downstream conventional box girder. The effects

of the side-surface openings of the upstream and downstream girders on the aerodynamic performance of the upstream girder are also evaluated. Furthermore, the effects of the upstream conventional box girder on the aerodynamic performance of the downstream girder are explained. Then, the effects of the side-surface openings of the two girders in tandem on the aerodynamic performance of the downstream girder are illustrated. This research confirms the good aerodynamic performance of butterfly web girders in a tandem arrangement and provides a new method for controlling aerodynamic instability.

Details of the wind tunnel tests

The relationship between the side-surface openings of the upstream/downstream girder and the aerodynamic interference was investigated via a series of wind tunnel tests that included aerodynamic force tests, spring-supported free vibration tests (vertical one-degree-of-freedom (1DOF)), and forced vibration tests (vertical 1DOF). These tests were carried out in a room-circuit Eiffel-type wind tunnel with a working section 1.8 m high and 1.0 m wide. The wind tunnel was located at Kyoto University, and the details of the wind tunnel tests are explained in this section.

Model details

Two sectional butterfly web girder models were evaluated in this study. The models were constructed at a geometric scale of 1:80 and had a side ratio (B/D) of 3.24, where B and D are the width and height of the girder, respectively. The cross-section and detail of the side-surface openings are shown in Fig. 2. As shown in Fig. 3, the open girder was designated as the butterfly web girder (Fig. 3 (a)), and the butterfly web girder where the side-surface openings were covered by acrylic plates (1 mm thick) was designated as the closed girder (Fig. 3 (b)).

Free vibration test

This study mainly focused on the effects of the side-surface openings on the aerodynamic interference in the vertical direction. To avoid the coupling effects between the vertical and torsional vibration, the girder was only elastically supported in the vertical 1DOF direction by eight coil springs. The vertical 1DOF displacement of the girder in smooth flow was measured by laser gages. While one girder was being measured, the other was rigidly supported (Fig. 4). A center distance of $2B$ (Fig. 4) was set to analyze the relationship between the side-surface openings and aerodynamic interference. The single $B/D = 3.24$ butterfly web girder showed the vortex-induced vibration at angles of attack of 0° , -3° , and $+3^\circ$, and the galloping instability at the angle of attack of $+3^\circ$ (Wang et al., 2020a). To further investigate the vortex-induced vibration and galloping of the girders in a tandem arrangement and the effect of side-surface openings on these aerodynamic instabilities, the angle of attack (α) of the 1DOF free vibration tests was set as 0° and $+3^\circ$ for the two girders in a tandem arrangement (Fig. 5). The characteristic parameters for the upstream and downstream girders are listed in Table 1 and Table 2, respectively. They were set equal to the characteristic parameters of the single girders (i.e., closed girder (0° , $+3^\circ$): $m = 2.40$ kg/m, $f = 4.55$ Hz, $\delta_\eta = 0.0026$, $Sc_\eta = 4.2$; open girder (0° , $+3^\circ$): $m = 2.36$ kg/m, $f = 4.60$ Hz, $\delta_\eta = 0.0029$, $Sc_\eta = 4.5$) (Wang et al., 2020a) for the convenience of comparison. The mass and structural damping were assigned low values to facilitate observation of the aerodynamic response (see Table 1 and Table 2).

The Scruton numbers for the vertical direction are defined as follows:

$$S_{c\eta} = \frac{2m\delta_\eta}{\rho D^2} \quad (1)$$

where m is the mass per unit (kg/m), δ_η is the vertical structural damping as quantified by logarithmic decrement, and ρ is the air density (kg/m³).

The reduced wind velocity, U_r , is given by:

$$U_r = \frac{U}{fD} \quad (2)$$

where f is the natural frequency of the system, and U is the approaching wind velocity (m/s).

Aerodynamic force test

The model was rigidly connected to load cells, and the aerodynamic forces were measured through the load cell. While one girder was being measured, the other model was rigidly supported at the upstream or downstream side (Fig. 5). The lift (C_{Fy}) and drag (C_{Fx}) force coefficients, fluctuating lift force coefficient (C_{Fy}'), and Strouhal number (St) are defined on the structural axis as follows:

$$C_{Fy} = \frac{F_y}{\frac{1}{2}\rho U^2 Bl} \quad (3)$$

$$C_{Fx} = \frac{F_x}{\frac{1}{2}\rho U^2 Dl} \quad (4)$$

$$C_{Fy}' = \frac{F_y'(t)_{std}}{\frac{1}{2}\rho U^2 Bl} \quad (5)$$

$$St = \frac{f_{st}D}{U} \quad (6)$$

where F_y , F_x are the lift force (N) (upward direction is positive) and drag force (N) (streamwise direction is positive) (see Fig. 6), respectively; l is the span length (m); f_{st} is the frequency (Hz) of the Kármán-vortex shedding; and $F_y'(t)_{std}$ is the standard deviation of the lift force component ($F_y'(t)$) that fluctuates in the frequency of f_{st} . The fluctuating lift force coefficient, C_{Fy}' , is the Kármán vortex shedding intensity, which indicates the strength of the vortex shedding.

Based on the quasi-steady theory, the instantaneous lift force acting on the single oscillating girder with a velocity of $\dot{\eta}$ is assumed to be equal to that acting on the single stationary girder under the relative angle of attack ($\alpha_0 = \arctan(\dot{\eta}/U)$, where U is the approaching wind velocity). However, this assumption cannot work for the oscillating girder with another adjacent stationary girder at the upstream and downstream sides. As the velocity of girder oscillation depends on the

girder position, other than the relative angle of attack, the relative position between the oscillating girder and adjacent stationary girder must be considered for measuring the lift force acting on the two stationary girders in tandem. The aerodynamic forces acting on these girders in tandem substantially depend on their relative vertical position (Zhou et al., 2017). Hence, the quasi-steady theory is difficult to be applied to the two girders in tandem, owing to the uncertainty in the relationship between the velocity of girder oscillation and the relative position between the oscillating girder and adjacent stationary girder. Therefore, the aerodynamic forces were only investigated at $\alpha = 0^\circ$ and 3° .

Forced vibration test

Vertical 1DOF forced vibration tests were carried out to identify the linear aerodynamic derivatives to evaluate the effects of the side-surface openings on the aerodynamic damping. The aerodynamic self-excited forces working on a girder are expressed by the following aerodynamic derivatives according to Scanlan and Tomko (1971):

$$L_{se} = \frac{1}{2}\rho(2b)U^2 \left\{ kH_1^* \frac{\dot{\eta}}{U} + kH_2^* \frac{b\dot{\phi}}{U} + k^2 H_3^* \varphi + k^2 H_4^* \frac{\eta}{b} \right\} \quad (7)$$

$$M_{se} = \frac{1}{2}\rho(2b^2)U^2 \left\{ kA_1^* \frac{\dot{\eta}}{U} + kA_2^* \frac{b\dot{\phi}}{U} + k^2 A_3^* \varphi + k^2 A_4^* \frac{\eta}{b} \right\} \quad (8)$$

where L_{se} is the lift force per unit span (N/m), M_{se} is the pitching moment per unit span (N·m/m), η is the vertical displacement (m), φ is the torsional displacement ($^\circ$), $(\cdot)$ indicates the time differentiation, b is the half-length of the girder width (m), k is the reduced frequency ($b\omega/U$), and ω is the angular frequency (rad/s).

The aerodynamic self-excited forces were measured by load cells rigidly connected to the model under vertical 1DOF forced vibration conditions in smooth flow. The displacement of the model was recorded by laser gages simultaneously with the self-excited forces. Based on the

displacement and aerodynamic self-excited force time series, the aerodynamic derivatives were calculated. The aerodynamic derivative H_1^* represents the linear aerodynamic damping in the vertical direction, and a positive H_1^* indicates instability in the vertical direction (Scanlan and Tomko, 1971; Matsumoto et al., 1996). While one girder was being measured, the other girder was rigidly supported at the downstream or upstream side (Fig. 5). Corresponding to the vertical 1DOF free vibration tests, the vertical 1DOF forced vibration tests were performed at $\alpha = 0^\circ$ and $+3^\circ$. To improve the accuracy of the aerodynamic derivatives, the vertical amplitude and frequency were set to 10 mm and 2 Hz, which were the same values as those of the single girders in our previous study (Wang et al., 2020a).

Aerodynamic force coefficients of stationary girders in tandem

To begin, the aerodynamic force coefficients of the upstream girder is investigated in terms of the effects of the side-surface openings on both the upstream and downstream girder. Additionally, the aerodynamic force coefficients of the upstream girder are compared with those of a single girder (Wang et al., 2020a) to explain the aerodynamic interference. Then, the effects of the side-surface openings on both girders in tandem on the aerodynamic force coefficients of the downstream girder are illustrated. Finally, the aerodynamic interference is discussed by comparing the aerodynamic force coefficients of the downstream girder and single girder.

Aerodynamic force coefficients of the upstream girder

The aerodynamic force coefficients of the upstream girders at $\alpha = 0^\circ$ and $+3^\circ$ are shown in Fig. 7, which also includes those of the single girder for a comparison. According to Fig. 7, when the downstream girder changed from a closed girder to an open girder, the values of C_{Fx} , C_{Fy} , and C_{Fy}' for the upstream closed/open girder exhibited similar values. Therefore, the values of C_{Fx} , C_{Fy} , and C_{Fy}' for the upstream girder were not affected by the side-surface openings of the downstream

girder. The upstream closed and open girders showed almost the same C_{Fx} value (Fig. 7(a)). However, the C_{Fy} value for the upstream closed girder was larger than that for the open girder (Fig. 7(b)). Even though the value of C_{Fy}' was small for all upstream girders (Fig. 7(c)), the C_{Fy}' value of the upstream closed girder was larger than that of the open girder. The smaller value of C_{Fy}' for the upstream open girder indicated that the vortex shedding from the upstream girder was suppressed owing to its side-surface openings. The reduction in the C_{Fy} and C_{Fy}' values of the upstream girder owing to the side-surface openings coincided with the result obtained for the single girder (Wang et al., 2020a). The reduction in the C_{Fy} and C_{Fy}' values was caused by the promotion of the reattachment of the separated shear layer on the girder owing to the side-surface openings (Wang et al., 2020a and b). Therefore, the side-surface openings of the upstream girder promoted the reattachment of the separated shear layer on the upstream girder and suppressed the vortex shedding from the upstream girder irrespective of the type of downstream girder.

The effects of the downstream girder on the aerodynamic force coefficients of the upstream girder were also evaluated. The upstream closed/open girder showed smaller C_{Fx} and C_{Fy}' values than those of the single closed/open girder at $\alpha = 0^\circ$ and $+3^\circ$, respectively (Fig. 7). This coincided with the previously reported results (Matsumoto et al., 2006) that the splitter plate in wake of the rectangular cylinder reduced its C_{Fx} and C_{Fy}' values. Further, extant research (Okajima et al., 1990a) indicates that the adjacent girder in wake of the upstream girder resulted in recovery in the base pressure of the upstream girder, and subsequently, reduced the C_{Fx} values of the upstream girder. The splitter plate or the downstream girder disturbed the flow entrainment in wake of the upstream girder and promoted the detachment of the separated shear layer from the upstream girder (Okajima et al., 1990a; Matsumoto et al., 2006). Probably owing to the detachment of the separated

shear layer from the upstream girder, the upstream closed/open girder showed larger C_{Fy} values than those of the single closed/open girder (Fig. 7(b)).

The Strouhal number (St) of the upstream girder was also analyzed. According to Table 3, the upstream closed girder displayed almost the same St irrespective of the type of downstream girder. Meanwhile, the St of the upstream closed girder was slightly smaller than that of the upstream open girder. Subsequently, the side-surface openings of both the upstream and downstream girders did not affect the St of the upstream girder. Furthermore, the St of a single girder (Wang et al., 2020a) is shown in Table 4. By comparing Table 3 and 4, it can be seen that the St of the upstream girder was smaller than that of the single girder. The vortex-shedding frequency from the upstream girder was reduced as a result of the presence of the downstream girder, which blocked the vortex formation in the wake of the upstream girder and led to a longer distance for the vortex formation (Gerrard, 1966; Bearman and Trueman, 1972; Sakamoto et al., 1987). Consequently, the downstream girder reduced the St of the upstream girder. However, it was not affected by the side-surface openings of the two girders in tandem.

In summary, the side-surface openings of the downstream girder did not affect the aerodynamic force coefficients of the upstream girder. However, as indicated by the aerodynamic force coefficients, the downstream girder and side-surface openings of the upstream girder both altered the time-averaged flow around the upstream girder and suppressed its vortex shedding. The downstream girder blocked the flow entrainment in the near wake of the upstream girder, thereby directly suppressing the vortex shedding and, subsequently, promoting the detachment of the separated shear layer from the upstream girder. The blockage also potentially reduced the frequency of the vortex shedding from the upstream girder. On the other hand, the side-surface openings promoted the reattachment of the separated shear layer on the upstream girder and

effectively reduced its bluffness, which was a direct result of the flow through the inner space of the box girder (Wang et al., 2020a and b).

Aerodynamic force coefficients of the downstream girder

The relationship between the side-surface openings (of both the upstream and downstream girders) and aerodynamic force coefficients of the downstream girder (Fig. 8) at $\alpha = 0^\circ$ and $+3^\circ$ was evaluated first. The aerodynamic force coefficients of the single girder are also included in Fig. 8. According to the figure, in wake of the closed girder, the C_{Fx} , C_{Fy} , and C_{Fy}' values for the closed girder were almost the same as those of the open girder. In wake of the open girder, the C_{Fx} , C_{Fy} , and C_{Fy}' values for the closed girder were almost the same as those of the open girder. Therefore, the side-surface openings of the downstream girder did not affect its time-averaged flow and vortex shedding. They were affected, however, by the turbulent flow from the upstream girder. The values of C_{Fx} , absolute C_{Fy} , and C_{Fy}' for the downstream girder decreased when the upstream girder was changed from a closed girder to an open girder at $\alpha = 0^\circ$ (e.g., the C_{Fx} of the downstream closed girder was reduced by 25% when the upstream girder was changed from a closed girder to an open girder). Consequently, the flow field around the downstream girder was affected by the side-surface openings of the upstream girder.

The effects of the upstream girder on the aerodynamic force coefficients of the downstream girder were analyzed next. The C_{Fx} values of the downstream closed/open girder were smaller than those of the single closed/open girder at $\alpha = 0^\circ$ and $+3^\circ$ (Fig. 8). The reduction in the C_{Fx} values of the downstream girder resulted from the small wind velocities of the wake flow of the upstream girder (Wang et al., 2020a) and the subsequent reduction in the windward-surface pressure of the downstream girder (Okajima et al., 1990a). Furthermore, extant research (Okajima et al., 1990a) indicates that the turbulent flow from the $B/D = 2$ rectangular cylinder promoted the reattachment

of the separated shear layer on the downstream $B/D = 2$ rectangular cylinder. Probably owing to the promotion of the reattachment of the separated shear layer on the downstream girder, the lift force of the downstream girder was in the downward direction, while the single girder showed an upward lift force at $\alpha = 0^\circ$. Additionally, according to the past researches (Chen et al., 2014; Ma et al., 2020), the pressure fluctuation coefficients of the upside/downside surface of the downstream girder were significantly larger than those of the upstream girder. Probably owing to the increase in the pressure fluctuation of the upside/downside surface of the downstream girder, the C_{Fy} ' value of the downstream girder was larger than that of the single girder (Fig. 8(c)).

Finally, the St of the downstream girder (Table 5) was assessed. According to Table 5, the closed girder and open girder had almost the same St in the wake of the closed girder and in the wake of the open girder at $\alpha = 0^\circ$. The St of the girders in the wake of the closed girder was slightly smaller than that of the girders in the wake of the open girder. By comparing Table 3 and Table 5, it can be seen that the St of the downstream and upstream girder was almost the same for the same arrangement. A comparison of Table 4 and Table 5 revealed that the St of the downstream girder was slightly smaller than that of the single girder. According to Sakamoto (1987), the same vortex-shedding frequency of the downstream girder and upstream girder was related to the synchronization between the vortex shedding from the upstream girder and the vortex formation of the downstream girder.

In summary, the flow around the downstream girder was significantly affected by the turbulent flow from the upstream girder. The synchronization between the vortex shedding from the upstream girder and the vortex formation of the downstream girder led to their having the same St . The aerodynamic force coefficients of the downstream girder were not affected by its side-surface openings, but were slightly affected by the side-surface openings of the upstream girder.

Aerodynamic instability of the upstream girder

In this section, the effects of a stationary downstream closed girder on the aerodynamic performance of the upstream girder are discussed by comparing the results of the upstream girder with that of the single girder presented in our past research (Wang et al., 2020a). Then, the effects of the side-surface openings (in both the upstream and downstream girders) on the aerodynamic instability of the upstream girder are discussed.

Effects of a fixed downstream girder

A comparison of the aerodynamic response of the upstream girder and single girder at $\alpha = +3^\circ$ is shown in Fig. 9. According to Fig. 9 (a), at $4 < Ur < 8$, the motion-induced vortex vibration of the upstream closed girder exhibited almost the same maximum magnitude as that of a single closed girder. The upstream open girder and single open girder also displayed almost the same maximum amplitude of motion-induced vortex vibration (Fig. 9 (b)). Therefore, with a center distance of $2B$, the motion-induced vortex vibration of the upstream girder was not affected by the downstream girder. According to Fig. 9, another noticeable result was that the reduced critical wind velocity for galloping (U_{rc0}) of the upstream girder was smaller than for the single girder. According to Fig. 9 (a), the value of U_{rc0} ($= 25$) for the upstream closed girder was smaller than that ($U_{rc0} = 47$) for the single closed girder. According to Fig. 9 (b), the upstream open girder showed galloping from $U_{rc0} = 40$, whereas the single open girder did not show galloping until $U_r = 70$. Therefore, the downstream closed girder caused the upstream girder to be more unstable from the perspective of galloping. This conclusion was supported by a comparison between the aerodynamic derivative, H_1^* , of the upstream girder and single girder (Fig. 10). The H_1^* based on the quasi-steady theory is also included in Fig. 10. The H_1^* based on the quasi-steady theory is calculated as

$$H_1^* = -\frac{1}{k} \frac{dC_{Fy}}{d\alpha} \quad (9)$$

where $dC_{Fy}/d\alpha$ is the lift slope. The H_1^* identified from the forced vibration gradually approached that calculated based on the quasi-steady theory for the single girder at high wind velocities (Fig. 10). Hence, H_1^* can provide sufficient information, such as the value of aerodynamic damping and corroborative evidence of critical wind velocity of galloping, to discuss the galloping instability. The value of H_1^* for the upstream closed/open girder was larger than the value for the single closed/open girder at $U_r > 30$ (Fig. 10), which indicated that the upstream girder had a larger aerodynamic damping than the single girder. In addition, H_1^* turned positive at $U_{rc_for} = 40$ for the upstream closed girder, and $U_{rc_for} = 60$ for the single closed girder (Fig. 10 (a)). The value of U_{rc_for} (= 52) for the upstream open girder was smaller than the value of U_{rc_for} (= 80) for the single open girder (Fig. 10(b)). This also supports conclusion that the critical wind velocity for galloping in the upstream girder was smaller than for the single girder. According to past studies (Matsumoto et al., 2008b; Yagi et al., 2013), the galloping of the upstream girder was more unstable owing to the suppression of the vortex shedding, which was indicated by the small fluctuating lift coefficients of the upstream girder (Fig. 7 (c)). Therefore, the motion-induced vortex vibration of the upstream girder was unaffected by the downstream closed girder. However, the downstream girder made the upstream girder more unstable in galloping by reducing its critical wind velocity.

Effects of the side-surface openings

The aerodynamic response of the upstream girders at $\alpha = +3^\circ$ is summarized in Fig. 11, and the aerodynamic derivative, H_1^* , at $\alpha = +3^\circ$ is summarized in Fig. 12. First, the side-surface opening effects of the downstream and upstream girders on the motion-induced vortex vibration of the

upstream girder are discussed. Then, the side-surface opening effects of the downstream and upstream girders on the galloping are discussed.

According to Fig. 11, the upstream girders displayed motion-induced vortex vibration at $4 < U_r < 8$. According to Fig. 11 (a), the largest reduced double amplitude of the motion-induced vortex vibration ($2A\eta_{\max}/D$) was 0.42 irrespective of the type of girder downstream (i.e., closed girder or open girder). In addition, the value of $2A\eta_{\max}/D$ for the upstream open girder was 0.28 irrespective of the type of girder downstream (Fig. 11 (b)). Consequently, the value of $2A\eta_{\max}/D (= 0.42)$ for the upstream closed girder was approximately 1.5 times as much as that ($2A\eta_{\max}/D = 0.28$) of the upstream open girder. Therefore, introducing side-surface openings to the downstream girder did not affect the motion-induced vortex vibration of the upstream girder. However, the side-surface openings of the upstream girder stabilized its motion-induced vortex vibration by reducing the largest amplitude by 33%.

The effects of the side-surface openings in the downstream girder on the galloping instability of the upstream girder were further evaluated based on the aerodynamic response (Fig. 11) and H_1^* (Fig. 12). According to Fig. 11 (a), when the downstream girder changed from a closed girder to an open girder, the upstream closed girder exhibited almost the same vibration amplitude for each wind velocity. The upstream closed girder showed galloping at the reduced critical wind velocity (U_{rc0}) of 25. According to Fig. 11 (b), the upstream open girder showed galloping at $U_{rc0} = 40$ with a closed girder at the downstream side and at $U_{rc0} = 50$ with an open girder at the downstream side. Despite the difference between the U_{rc0} value for these two cases (Fig. 11 (b)), the upstream open girder in both cases achieved a reduced double amplitude larger than 45 at $U_r = 55$. Therefore, the galloping instability of the upstream girder was not obviously affected by the side-surface openings of the downstream girder. This conclusion was also supported by the H_1^*

values of the upstream girder (Fig. 12). The H_1^* values of the upstream closed girder were nearly identical irrespective of the type of girder downstream (Fig. 12 (a)). According to Fig. 12 (b), the same conclusion was reached for the H_1^* values of the upstream open girder. In summary, the side-surface openings of the downstream girder did not obviously affect the galloping instability of the upstream girder.

A comparison of Fig. 11 (a) and (b) revealed that the upstream closed girder exhibited a smaller reduced critical wind velocity for the galloping ($U_{rc0} = 25$) than the upstream open girder ($U_{rc0} = 40/50$). Furthermore, according to Fig. 12, the H_1^* of the upstream closed girder turned positive at $U_{rc_for} = 40$, which was smaller than the $U_{rc_for} (= 52/56)$ of the upstream open girder. Therefore, the side-surface openings of the upstream girder stabilized its galloping instability by increasing the critical wind velocity.

In summary, the side-surface openings of the downstream girder had almost no effect on the aerodynamic performance of the upstream girder. However, the side-surface openings of the upstream girder stabilized it against motion-induced vortex vibration and galloping.

Aerodynamic instability of the downstream girder

The effects of the turbulence from the upstream closed girder on the aerodynamic performance of the downstream girder were evaluated by comparing the results of the downstream girder with a single girder. The data for the single girder were from our recent study (Wang et al., 2020a). Then, the effects of the side-surface openings in both the upstream and downstream girders on the aerodynamic instability of the downstream girder were analyzed.

Effects of a fixed upstream girder

A comparison of the aerodynamic response of the downstream and single girders at $\alpha = +3^\circ$ is shown in Fig. 13, while a comparison between their aerodynamic derivative, H_1^* , at $\alpha = +3^\circ$ is

shown in Fig. 14. As shown in Fig. 13 (a), the downstream closed girder did not show galloping instability, whereas the single closed girder showed galloping at $U_{rc0} > 47$. Furthermore, as shown in Fig. 14 (a), the H_1^* of the downstream closed girder was negative until $U_r = 100$, while the single closed girder turned positive at $U_{rc_for} = 60$. The H_1^* of the downstream open girder was negative until $U_r = 100$, while the single open girder turned positive at $U_{rc_for} = 80$ (Fig. 14 (b)). Therefore, the turbulent flow from the upstream closed girder stabilized the galloping of the downstream girder. This phenomenon was attributed to the fact that the turbulent flow from the upstream girder caused intermittent reattachment of the separated flow on the side surface of the downstream girder (Takeuchi and Matsumoto, 1992; Parkinson, 1989).

According to Fig. 13, another noticeable characteristic was the larger amplitude of the vortex-induced vibration of the downstream girder compared to the single girder. This was further analyzed based on Fig. 15, which provides a comparison of the vortex-induced vibration of the downstream girder and single girder at $\alpha = 0^\circ$. The largest reduced double amplitude of the vortex-induced vibration ($2A\eta_{\max}/D = 0.75$) of the downstream closed girder was larger than the $2A\eta_{\max}/D$ ($= 0.40$) of the single closed girder (Fig. 15 (a)). The $2A\eta_{\max}/D$ ($= 0.59$) of the downstream open girder was larger than the $2A\eta_{\max}/D$ ($= 0.22$) of the single open girder (Fig. 15 (b)). Therefore, owing to the presence of the upstream closed girder, the amplitude of the vortex-induced vibration of the downstream girder was amplified by a factor of almost two. According to Fig. 15, the reduced critical wind velocity of the vortex-induced vibration of the downstream girder was approximately 6, which was larger than that of the single girder (approximately 4). This difference may have been caused by the increase of $1/St$ in the downstream girder from that of the single girder (Table 4 and Table 5). Furthermore, the $1/St$ value for the upstream and downstream girders in the same arrangement were nearly the same (Table 3 and Table 5). The amplification of the

vortex-induced vibration may have been related to the synchronization between the vortex shedding from the upstream girder and the vortex formation of the downstream girder (Sakamoto et al., 1987; Meng et al., 2011; Argentini et al., 2015; Park and Kim, 2017a). As previously discussed, the fluctuating lift force coefficients of the downstream girder were obviously larger than those of the single girder (Fig. 8 (c)). Therefore, the vortex-induced vibration of the downstream girder could be regarded as a ‘forced vibration’ or ‘resonance buffeting’ owing to the periodic turbulent flow from the upstream girder (Takeuchi and Matsumoto, 1992; Argentini et al., 2015).

In summary, the turbulent flow from the upstream closed girder stabilized the galloping of the downstream girder and amplified the amplitude of the vortex-induced vibration by approximately two times. The vortex-induced vibration of the downstream girder was regarded as a ‘forced vibration’ or ‘resonance buffeting’.

Effects of the side-surface openings

The effects of the side-surface openings on the vortex-induced vibration of the downstream girder were evaluated based on the aerodynamic response at $\alpha = +3^\circ$ (Fig. 16). As shown in Fig. 16 (a), for the downstream closed girder, the largest reduced double amplitude of the vortex-induced vibration ($2A\eta_{\max}/D$) was 0.7, independent of the type of girder upstream (i.e., a closed girder or open girder). As shown in Fig. 16 (b), the $2A\eta_{\max}/D$ of the downstream open girder was the same as for the different upstream girders. Furthermore, the $2A\eta_{\max}/D$ ($= 0.7$) of the downstream closed girder was approximately 1.3 times as much as the $2A\eta_{\max}/D$ ($= 0.55$) of the downstream open girder (Fig. 16). Therefore, the side-surface openings of the downstream girders stabilized its vortex-induced vibration by reducing the largest amplitude by approximately 21%, irrespective of the type of girder upstream.

According to Fig. 16, the downstream girders did not show galloping. According to Fig. 17, H_1^* showed a continually negative magnitude at $U_r < 100$, indicating that the galloping of the downstream girder was stabilized. In addition, all cases showed almost the same H_1^* value at high wind velocities, indicating that the side-surface openings of both the upstream and downstream girders did not affect the aerodynamic damping of the downstream girder at high wind velocities.

In summary, the side-surface openings of the upstream girder did not affect the vortex-induced vibration of the downstream girder. However, the side-surface openings of the downstream girder stabilized its vortex-induced vibration by reducing the largest amplitude by approximately 21%.

Conclusion

To investigate the effects of side-surface openings on the aerodynamic interference of two box girders in tandem, two butterfly web girders with a side ratio, B/D , of 3.24, where B is the girder width and D is the girder depth, were evaluated through a series of wind tunnel tests. The following conclusions were drawn:

(1) The presence of the fixed downstream girder increased the lift force coefficient (C_{Fy}) and reduced the drag force coefficient (C_{Fx}), the fluctuating lift force coefficient (C_{Fy}') and Strouhal number (St) of the upstream girder. The side-surface openings of the fixed downstream girder did not affect the C_{Fx} , C_{Fy} , and C_{Fy}' values of the upstream girder. In contrast, the side-surface openings of the upstream girder minimized its C_{Fy} and C_{Fy}' values.

(2) The C_{Fx} , C_{Fy} , and C_{Fy}' values of the downstream girder were substantially affected by the turbulent flow from the fixed upstream girder. The upstream and downstream girders showed the same St value. While the C_{Fx} , C_{Fy} , and C_{Fy}' values of the downstream girder were not affected by its openings, they were slightly affected by the side-surface openings of the fixed upstream girder.

(3) The fixed downstream closed girder did not affect the motion-induced vortex vibration of the upstream girder, but did make it more unstable in terms of the galloping instability. The side-surface openings of the fixed downstream girder did not affect the vibration amplitude or aerodynamic damping (H_1^*) of the upstream girder. In contrast, the side-surface openings of the upstream girder stabilized its motion-induced vortex vibration and galloping instability.

(4) The turbulent flow from the fixed upstream girder amplified the amplitude of the vortex-induced vibration of the downstream girder, which was regarded as a “forced vibration”, and completely stabilized the downstream girder against galloping instability. The side-surface openings of the fixed upstream girder did not affect the aerodynamic response of the downstream girder, while those of the downstream girder stabilized its vortex-induced vibration.

The incorporation of side-surface openings is a promising method for achieving a light box girder with suitable aerodynamic performance. However, questions still remain regarding the effects of side-surface openings on the aerodynamic interference between two elastically supported box girders in tandem. As this study was based on the center distance of $2B$, further investigation of the effects of side-surface openings on the aerodynamic interference of two adjacent girders with different center distances is required. Additionally, a careful examination of the flow field around two girders in tandem is necessary to further reveal the mechanism related to the effects of side-surface openings on the aerodynamic interference of two girders in tandem.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. (Available data: select data from testing)

Reference

517 Argentini, T., Rocchi, D., and Zasso, A. 2015. "Aerodynamic interference and vortex-induced
 518 vibrations on parallel bridges: The Ewijk bridge during different stages of refurbishment." *J. Wind
 519 Eng. Ind. Aerodyn.*, 147, 276–282.

520 Bearman, P. and Trueman, D. 1972. "An Investigation of the Flow around Rectangular
 521 Cylinders." *Aeronautical Quarterly.*, 23(3), 229-237.

522 Chen, W., Yang, W., Li, H., 2019a. "Self-issuing jets for suppression of vortex-induced
 523 vibration of a single box girder." *Journal of Fluids and Structures* 86, 213–235.

524 Chen, G., Zhang, L., Chen, W., Gao, D., Yang, W., Li, H., 2019b. "Self-Suction-and-Jet
 525 Control in Flow Regime and Unsteady Force for a Single Box Girder." *J. Bridge Eng.* 24, 1–11.

526 Gerrard, J.H. 1966. "The mechanics of the formation region of vortices behind bluff bodies."
 527 *J. Fluid Mech.*, 25, 401–413.

528 Honda, A., Shiraishi, N., and Motoyama S. 1990. "Aerodynamic stability of Kansai
 529 International Airport Access Bridge." *J. Wind Eng. Ind. Aerodyn.*, 33, 369-376.

530 Kasuga, A. 2017. "Effects of butterfly web design on bridge construction." *Struct. Concr.*,
 531 18(a), 128–142.

532 Kimura, K., Shima, K., Sano, K., Kubo, Y., Kato, K., and Ukon, H. 2008. "Effects of separation
 533 distance on wind-induced response of parallel box girders." *J. Wind Eng. Ind. Aerodyn.*, 96, 954–
 534 962.

535 Kim, S. J., Kim, H. K., Calmer, R., Park, J., Kim, G. S., and Lee, D. K. 2013. "Operational
 536 field monitoring of interactive vortex-induced vibrations between two parallel cable-stayed
 537 bridges." *J. Wind Eng. Ind. Aerodyn.*, 123, 143–154.

- Liu, Z., Chen, Z., Liu, G., Shao, X., 2009. "Experimental study of aerodynamic interference effects on aerostatic coefficients of twin deck bridges." *Front. Archit. Civ. Eng. China*, 3(3), 292–298. <https://doi.org/10.1007/s11709-009-0048-8>
- Liu, Z., Chen, Z., Cai, S.C.S., Li, X., 2010. "Experimental Study of Aerodynamic Interference on VIV of Two Rectangular Cylinders in Tandem." *Fifth International Symposium on Computational Wind Engineering (CWE2010)*. USA: North Carolina.
- Liu, Z., Chen, Z., 2015. "Aerodynamic interference effects on aerostatic coefficients of typical sections in tandem arrangement." [In Chinese.] *Journal of vibration and shock*, 34(5), 6-13.
- Ma, K., Hu, C., Yuan, W., Zhou, Z., Dang, X., 2020. "Aerodynamic interferences in vortex-induced vibration of dual-rectangular sections based on wind tunnel tests and numerical simulation." [In Chinese.] *Journal of vibration and shock* 39, 157–168.
- Matsumoto, M., Kobayashi, Y., Shirato, H., 1996. "The influence of aerodynamic derivatives on flutter." *J. Wind Eng. Ind. Aerodyn.*, 60, 227–239.
- Matsumoto, M., Yagi, T., Lee, J., Hori, K., Kawashima, Y., 2006. "Karman Vortex Effect on the Aerodynamic Forces to Rectangular Cylinders." *Pressure Vessels and Piping Division Conference, ASME* 307–316. Canada: Vancouver.
- Matsumoto, M., Yagi, T., Tamaki, H., and Tsubota, T. 2008a. "Vortex-induced vibration and its effect on torsional flutter instability in the case of $B/D = 4$ rectangular cylinder." *J. Wind Eng. Ind. Aerodyn.*, 96(6–7), 971–983.
- Matsumoto, M., Hashimoto, M., Yagi, T., Nakase, T., and Maeta, K. 2008b. "Steady galloping/unsteady galloping and vortex-induced vibration of bluff bodies associated with mitigation of Kármán vortex." In *Proc., 6th Int. Colloquium on Bluff Body Aerodynamics and Applications*. Italy: Ansaldo Breda.

561 Meng, X. L., Zhu, L. D., and Guo, Z. S. 2011. "Aerodynamic interference effects and
 562 mitigation measures on vortex induced vibrations of two adjacent parallel bridges." *Front. Archit.*
 563 *Civ. Eng. China.*, 5(4), 510–517.

564 Nakamura, Y., Hirata, K., Urabe, T., 1991. "Gallopings of rectangular cylinders in the presence
 565 of a splitter plate." *J. Fluids Struct.* 5(5), 521–549.

566 Núñez, G.J.Z., Loredó-Souza, A.M., Rocha, M.M., Bagatini-Cachuço, F., 2018. "Aerodynamic
 567 behavior of a cable-stayed bridge section composed by inclined parallel decks." *Journal of Wind*
 568 *Engineering and Industrial Aerodynamics* 173, 156–170.

569 Okajima, A., Kitawa, T., 1990a. "Aerodynamic characteristics of two rectangular cylinders in
 570 a tandem arrangement." [In Japanese.] *Journal of Structural Engineering A, JSCE*, 36, 849–857.

571 Okajima, A., Abe, A., and Kiwata, T. 1990b. "Aeroelastic instability of two rectangular
 572 cylinders in a tandem arrangement." [In Japanese.] *Journal of Structural Engineering A, JSCE*, 36,
 573 859-864.

574 Park, J. and Kim, H. K. 2017a. "Effect of the relative differences in the natural frequencies of
 575 parallel cable-stayed bridges during interactive vortex-induced vibration." *J. Wind Eng. Ind.*
 576 *Aerodyn.*, 171, 330–341.

577 Park, J., Kim, S., and Kim, H. K. 2017b. "Effect of gap distance on vortex-induced vibration
 578 in two parallel cable-stayed bridges." *J. Wind Eng. Ind. Aerodyn.*, 162, 35–44.

579 Parkinson, G. V., 1989. Phenomena and modelling of flow-induced vibrations of bluff bodies.
 580 *Prog. Aerosp. Sci.* 26, 169–224.

581 Seo, J. W., Kim, H. K., Park, J., Kim, K. T., and Kim, G. N. 2013. "Interference effect on
 582 vortex-induced vibration in parallel twin cable-stayed bridge." *J. Wind Eng. Ind. Aerodyn.*, 116,
 583 7-20.

Scanlan, R. H. and Tomko, J. 1971. "Air foil and bridge deck flutter derivatives." J. Eng. Mech., 97 (6), 1717–1737.

Sakamoto, H., Hainu, H., and Obata, Y. 1987. "Fluctuating forces acting on two square prisms in a tandem arrangement." J. Wind Eng. Ind. Aerodyn., 26, 85–103.

Takeuchi, T. and Matsumoto, M. 1992. "Aerodynamic response characteristics of rectangular cylinders in tandem arrangement." J. Wind Eng. Ind. Aerodyn., 41, 565–575.

Wang, J., Yagi, T., Ushioda, J., Noguchi K., Nagamoto, N., Uchibori, H., 2020a. "Experimental studies on the aerodynamic performance of two box girders with side-surface openings." Wind and Structures, an International Journal. 30(2), 119-131.

Wang, J., Yagi, T., Ushioda, J., Ichikawa, H., Yamamoto, S., 2020b. "Side-surface openings effects on galloping instability for a rectangular cylinder." J. Wind Eng. Ind. Aerodyn.. 206, 1-18.

Yagi, T., Shinjo, K., Narita, S., Nakase, T., and Shirato, H. 2013. "Interferences of vortex sheddings in galloping instability of rectangular cylinders." [In Japanese.] Journal of Structural Engineering A, JSCE, 59A, 552–561.

Yang, W., Chen, W., Li, H., 2020. "Suppression of vortex-induced vibration of single-box girder with various angles of attack by self-issuing jet method." Journal of Fluids and Structures 96, 103017.

Zhou, R., Yang, Y., Zhang, L., Ge, Y., 2017. "Interference effect on stationary aerodynamic performance between parallel bridges." International Journal of Structural Stability and Dynamics, 17(02), 1750017.

Table 1. Characteristic parameters for the upstream girder used in the free vibration experiments
(vertical 1DOF, smooth flow)

Upstream girder	Downstream girder (fixed)	α (°)	m (kg/m)	f (Hz)	δ_η	$Sc\eta$
Closed girder	Closed girder	0°	2.40	4.57	0.0027	4.3
Closed girder	Open girder		2.36	4.61	0.0027	4.2
Open girder	Closed girder		2.40	4.57	0.0027	4.4
Open girder	Open girder		2.36	4.61	0.0027	4.3
Closed girder	Closed girder	+3°	2.40	4.57	0.0027	4.4
Closed girder	Open girder		2.36	4.61	0.0027	4.2
Open girder	Closed girder		2.40	4.57	0.0027	4.3
Open girder	Open girder		2.36	4.61	0.0027	4.3

Table 2. Characteristic parameters for the downstream girder used in the free vibration experiments (vertical 1DOF, smooth flow)

Upstream girder (fixed)	Downstream girder	α (°)	m (kg/m)	f (Hz)	δ_η	$Sc\eta$
Closed girder	Closed girder	0°	2.40	4.57	0.0027	4.4
Closed girder	Open girder		2.36	4.61	0.0029	4.5
Open girder	Closed girder		2.40	4.57	0.0027	4.4
Open girder	Open girder		2.36	4.61	0.0027	4.4
Closed girder	Closed girder	+3°	2.40	4.57	0.0027	4.3
Closed girder	Open girder		2.36	4.61	0.0027	4.4
Open girder	Closed girder		2.40	4.57	0.0026	4.3
Open girder	Open girder		2.36	4.61	0.0028	4.4

Table 3. St of the upstream girder ($\alpha = 0^\circ$, $U = 6$ m/s)

Upstream girder	Downstream girder	St	$1/St$
Closed girder	Closed girder	0.129	7.77
Closed girder	Open girder	0.130	7.71
Open girder	Closed girder	0.142	7.03
Open girder	Open girder	0.147	6.80

611 **Table 4.** *St* of the single girder (Data is from Wang et al., 2020a, $\alpha = 0^\circ$, $U = 6$ m/s)

Single girder	<i>St</i>	1/ <i>St</i>
Closed girder	0.165	6.07
Open girder	0.164	6.10

612

613 **Table 5.** *St* of the downstream girder ($\alpha = 0^\circ$, $U = 6$ m/s)

Upstream girder	Downstream girder	Strouhal number	1/ <i>St</i>
Closed girder	Closed girder	0.131	7.65
Closed girder	Open girder	0.129	7.76
Open girder	Closed girder	0.146	6.83
Open girder	Open girder	0.148	6.78

614

615 **Fig. 1.** Butterfly web bridge

616 **Fig. 2.** Model section and side-surface opening detail (mm)

617 **Fig. 3.** Models used in the experiment: (a) open girder, and (b) closed girder

618 **Fig. 4.** Free vibration system for: (a) upstream girder, and (b) downstream girder

619 **Fig. 5.** Dispositions of the two girders: (a) upstream girder is under measurement, and (b)

620 downstream girder is under measurement

621 **Fig. 6.** Definitions of the aerodynamic forces on the structural axis

622 **Fig. 7.** Aerodynamic force coefficients of the upstream girder ($U = 6$ m/s, smooth flow) for (a)

623 drag force C_{Fx} , (b) lift force C_{Fy} , and (c) fluctuating lift force C_{Fy}' .

624 **Fig. 8.** Aerodynamic force coefficients of the downstream girder ($U = 6$ m/s, smooth flow) for (a)

625 drag force C_{Fx} , (b) lift force C_{Fy} , and (c) fluctuating lift force C_{Fy}' .

626 **Fig. 9.** Comparison of the aerodynamic response of the (vertical one degree-of-freedom [1DOF],

627 $\alpha = 3^\circ$, smooth flow): (a) upstream and single closed girders, and (b) upstream and single open

628 girders

629 **Fig. 10.** Comparison of H_1^* of the (vertical 1DOF, $\alpha = 3^\circ$, $f = 2.0$ Hz, $2A\eta = 20$ mm, smooth flow)

630 (a) upstream and single closed girders and (b) upstream and single open girders.

631 **Fig. 11.** Aerodynamic response of the (vertical 1DOF, $\alpha = +3^\circ$, smooth flow): (a) upstream closed

632 girder with fixed downstream closed and open girders, and (b) upstream open girder with fixed

633 downstream closed and open girders

634 **Fig. 12.** H_1^* of the (vertical 1DOF, $\alpha = 3^\circ$, $f = 2.0$ Hz, amplitude = 10 mm, smooth flow): (a)

635 upstream closed girder with fixed downstream closed and open girders, and (b) upstream open

636 girder with fixed downstream closed and open girders

Fig. 13. Comparison of the aerodynamic response of the (vertical 1DOF, $\alpha = 3^\circ$, smooth flow): (a) downstream and single closed girders, and (b) downstream and single open girders

Fig. 14. Comparison of H_1^* of the (vertical 1DOF, $\alpha = 3^\circ$, $f = 2.0$ Hz, $2A\eta = 20$ mm, smooth flow) (a) downstream and single closed girders and (b) downstream and single open girders.

Fig. 15. Comparison of the vortex-induced vibration of the (vertical 1DOF, $\alpha = 0^\circ$, smooth flow): (a) downstream and single closed girders, and (b) downstream and single open girders

Fig. 16. Aerodynamic response of the (vertical 1DOF, $\alpha = +3^\circ$, smooth flow): (a) downstream closed girder with fixed upstream closed and open girders, and (b) downstream open girder with fixed upstream closed and open girders

Fig. 17. H_1^* of the (vertical 1DOF, $\alpha = 3^\circ$, $f = 2.0$ Hz, amplitude = 10 mm, smooth flow): (a) downstream closed girder with fixed upstream closed and open girders, and (b) downstream open girder with fixed upstream closed and open girders

































































