

Side-surface Openings Effects on Galloping Instability for a Rectangular Cylinder

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Abstract

Discretely distributed side-surface openings have a stabilizing effect on box girders against galloping. This research intends to further investigate the relationship between the size of the openings and galloping instability with respect to aerodynamic response and aerodynamic damping. An additional objective is to explain the stabilization mechanism against galloping owing to the openings. A series of wind tunnel tests was carried out on rectangular cylinders with different-sized openings that were non-dimensionalized as the Opening-area Ratio (OR), which is the ratio of the total-openings area to half of the front-surface area. At high wind velocities, increasing the OR from 0 to 0.75 increased the aerodynamic damping, and the separated shear layer gradually approached the model's trailing edge. Increasing it above 0.75 resulted in a decrease of the aerodynamic damping and the separated shear layer reattaching to the model. As OR increased, the galloping onset increased accompanied by the decrease in Strouhal number. Thus, the rectangular cylinder showed good galloping stability owing to the openings, which promoted the reattachment of the separated shear layer on the side surfaces, effectively increasing the body width-to-depth ratio. This research contributes to an innovative method to stabilize rectangular cylinder-like bluff bodies against galloping instability.

Keyword: Rectangular cylinder; Galloping; Strouhal number; Time-averaged streamline; Particle-Image Velocimetry.

1 Introduction

Long-span bridges require lightweight but strong girders with good wind-resistance capability. The butterfly web girder was recently introduced owing to its advantages in construction efficiency and structural and aerodynamic performance. It is a box girder with discretely distributed side-surface openings (Fig. 1). These openings reduced the amplitude of the vortex-induced vibration and galloping for 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 (Wang et al., 2020). Meanwhile, the side-surface openings reduced the amplitude of the vortex-induced vibration and torsional flutter for a butterfly web girder with a side ratio of 5 (Kasuga, 2017). Therefore, the side-surface openings are a practical design to make the box girder perform well aerodynamically without loss of structural stiffness or construction efficiency. However, it still lacks general conclusions regarding the relationship between the size



Fig. 1 Butterfly web bridge

of the openings and the galloping instability, e.g., vibration amplitude, critical wind velocity of galloping, aerodynamic damping, etc. Another question still remains regarding the suitable mechanism for the openings' effects against galloping stability.

Galloping is a self-excited vertical vibration that usually occurs in rectangular cylinder-like bluff bodies with a small side ratio ($0.7 < B/D < 2.8$) (Smith, 1962; Parkinson and Brooks, 1961; Parkinson and Wawzonek, 1981; Parkinson, 1989; Nakamura and Hirata, 1994; Hirata, 1993; Massai, 2016; Mannini et al., 2014). The quasi-steady theory is widely utilized to analyze galloping response and aerodynamic damping, especially for high wind velocities where the ratio of the body oscillation velocity to the approaching wind velocity is small. Through the forced vibration tests, the linear unsteady aerodynamic damping is identified and asymptotic to the aerodynamic damping predicted by the linear quasi-steady theory (Nakamura and Mizota, 1975; Obasaju, 1983; Washizu et al., 1978; Yagi et al., 2013). As the flow can pass through the inner space of the model, one of the concerns is whether the quasi-steady theory is valid in predicting the asymptotic behavior of the aerodynamic damping for the rectangular cylinder with openings. Furthermore, the relationship between the size of the openings and the aerodynamic damping at high wind velocities must be clarified.

At low wind velocities, an interesting phenomenon is observed wherein for the rectangular cylinders with the side ratios from 0.7 to 2.8, the critical wind velocity of galloping is identical to the resonance wind velocity of Kármán-vortex vibration (Parkinson, 1989; Parkinson and Wawzonek, 1981; Parkinson and Brooks, 1961). As this resonance wind velocity is characterized by the reciprocal of the Strouhal number, the critical wind velocity of galloping is controlled by the reciprocal of the Strouhal number. Meanwhile, with increase of the side ratios from 0.7 to 2.8, the critical wind velocity increased accompanied by the decrease of Strouhal number (Parkinson and Wawzonek, 1981; Nakaguchi et al, 1968; Okajima, 1983). Furthermore, as recently reported by Mannini (2018), with the increase of turbulence intensity, the critical wind velocity of galloping increased accompanied by the decrease of Strouhal number. Therefore, the current research intends to identify the effects of the openings' size on the Strouhal number and critical wind velocity of galloping, which is essential for the galloping stability.

According to previous studies (Parkinson, 1989; Massai, 2016; Nakamura and Hirata, 1989; Nakamura et al. 1991; Hu et al. 2016), galloping depends on the side ratio B/D because the afterbody, which is the part of the body downstream from the separation point, plays an important

role on galloping. For $B/D < 0.7$, the rectangular cylinder exhibits hard galloping, which requires a high initial amplitude to trigger the vibrations, because the afterbody is totally free from interfering with the separated shear layer (Parkinson, 1989; Nakamura et al., 1991). For $0.7 < B/D < 2.8$, the rectangular cylinder exhibits soft galloping, which gallops spontaneously from the rest, as the afterbody intermittently interferes with the separated shear layer (Parkinson, 1989; Nakamura et al., 1991). With the increase of side ratio from 0.7 to 2.8, the vibration amplitude at a certain wind velocity gradually decreases and the critical wind velocity gradually increases (Parkinson, 1989; Parkinson and Wawzonek, 1981; Parkinson and Brooks, 1961). For $B/D > 2.8$, galloping is stabilized owing to the complete reattachment of the separated shear layer to the afterbody. Thus, galloping is closely related to the interference between the afterbody and the separated shear layer (Parkinson, 1989; Nakamura and Hirata, 1994; Hirata, 1993). This provides an important clue for the stabilization mechanism against galloping owing to the side-surface openings. The question is what are the openings' effects on the time-averaged flow field, which qualitatively indicates the interference strength between the separated shear layer and the afterbody.

To answer these questions, a rectangular cylinder with a side ratio of 2, which is characterized by the galloping and the vortex-induced vibration, was utilized. The vertical one-degree-of-freedom (1DOF) free vibration tests of low mass-damping parameters were carried out. The aerodynamic force working on the stationary and vertically oscillating model of constant amplitude and frequency were measured. Section 2 explains the setup of the wind tunnel tests. Section 3 focuses on the relationship between the size of the openings and aerodynamic performance, i.e., the aerodynamic response and aerodynamic damping. Section 4 presents the setup of the Particle Image Velocimetry (PIV) tests and the time-averaged flow field in the inner space and wake of the model, and the time-averaged flow field around the model in the vertical plane. The mechanism of stabilization against galloping owing to the openings is qualitatively explained in this study. By increasing our understanding of how side-surface openings affect the aerodynamic performance, this research contributed to the designing of an aerodynamic rectangular cylinder-like bluff body with side-surface openings.

2 Set-up of wind tunnel tests

To investigate the relationship between the size of the openings and the aerodynamic performance, vertical one-degree-of-freedom (1DOF) free vibration tests, vertical 1DOF forced vibration tests, and aerodynamic force tests were conducted. First, the model details and case lists are explained, and then the details of the free vibration tests, aerodynamic force tests, and forced vibration tests are illustrated. The turbulence intensity of the free stream in the wind tunnel is less than 0.3% at the approaching wind velocity of 10 m/s. This free stream flow in the wind tunnel is referred to as smooth flow.

2.1. Details of the model and different case lists

The main body of the model for the wind tunnel tests is depicted in Fig. 2 (a). The model has a length (l) of 900 mm. As depicted in Fig. 2 (b), the model has a side ratio B/D of 2, where the width (B) and the depth (D) are 140 mm and 70 mm, respectively. Owing to an open space with a

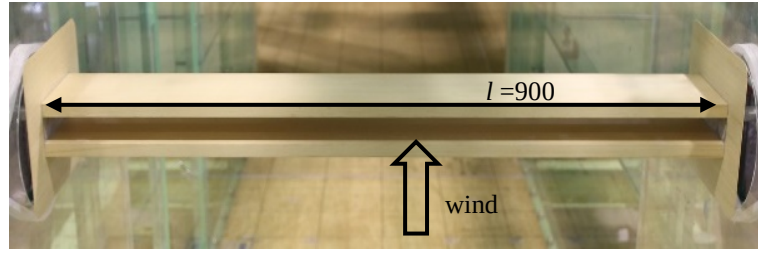
height (D_0) of 35 mm in the center of the model (Fig. 2 (b)), the flow can move through the inner space of the model. The height (D_0) of the open inner space was set as half of the model depth, to reflect the actual condition for the bridge section (Wang et al., 2020).

According to Fig. 3, the discretely distributed openings were realized by attaching the plastic plates to the front/rear surface in constant intervals. The opening size is decided by two parameters, i.e. Opening-area Ratio (OR) and Repeating Element-size Ratio (RER). The OR and RER are defined as follows (Fig. 3):

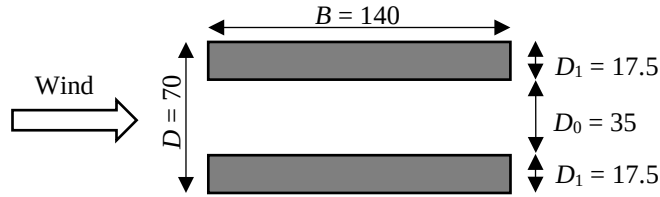
$$OR = S_1/(S_1 + S_2) = l_1/(l_1 + l_2) \quad (1)$$

$$RER = (l_1 + l_2)/D_0 \quad (2)$$

where l_1 and l_2 are the widths of the opening and plastic plate, respectively; D_0 is the height of the openings. OR represents the ratio of the total-openings area to half of the front-surface area. For a certain OR , RER represents the ratio of the width of a repeating element (consisting of one plate and one opening) to the inner-space height. The models with openings of different OR and RER were listed in Table 1. RER was set 1.07 and 2.14 to reflect the actual condition for the bridge section (Wang et al., 2020). $OR = 0$ represents the rectangular cylinder without openings, and $OR = 1$ represents the case that the inner space is totally opened without any cover.



(a)



(b)

Fig. 2 Model information: (a) main body; (b) model section (unit: mm).

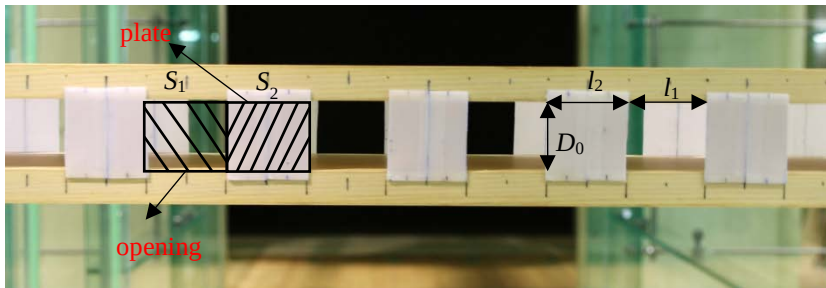
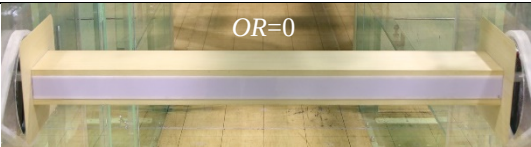
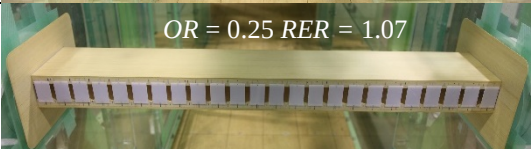
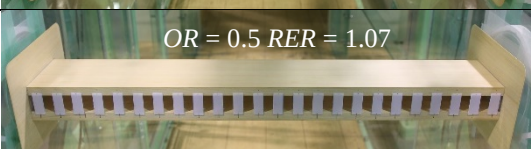
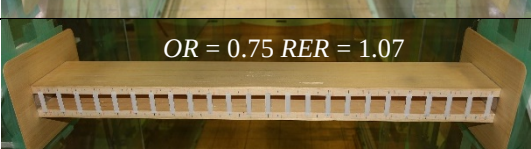
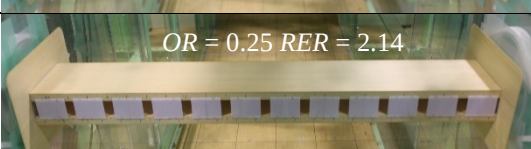
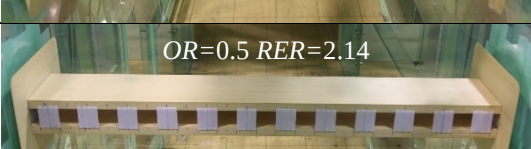
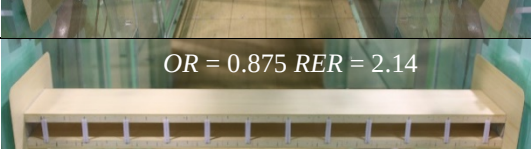
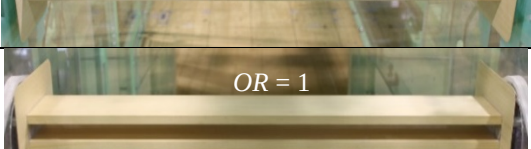


Fig. 3 Detail of side-surface openings

148 Table 1 Case lists of wind tunnel tests

Case name	Opening-area Ratio (OR)	Repeating Element-size Ratio (RER)	Configuration
Case 1	0	1.07	
Case 2	0.25		
Case 3	0.50		
Case 4	0.75		
Case 5	0.875		
Case 6	0.25	2.14	
Case 7	0.50		
Case 8	0.75		
Case 9	0.875		
Case 10	1		

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2.2. Aerodynamic force test

The aerodynamic forces working on the stationary model were measured by the load cell rigidly connected to the model in the smooth flow. As the model section is symmetrical to its centerline, the aerodynamic forces were measured at $\alpha = -2^\circ - 10^\circ$, where α is the angle of attack, and positive in the nose-up direction (Fig. 4). This research used the aerodynamic forces on the structural axes. These include the transverse force (F_y), which is the lift force defined on the transverse structural axis (y-direction), and the longitudinal force (F_x), which is the drag force defined on the longitudinal structural axis (x-direction) (see Fig. 4). The transverse (C_{Fy}) and longitudinal (C_{Fx}) force coefficients, fluctuating transverse force coefficient (C_{Fy}'), and Strouhal number (St) are defined 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 ρ is the air density (kg/m^3), U is the approaching wind velocity (m/s), f_{st} is the dominant frequency (Hz) of the Kármán-vortex shedding, $F_y(t)$ is the fluctuating transverse force time-series, $F_y'(t)$ is the transverse force component fluctuating in the frequency of f_{st} , and $F_y'(t)_{std}$ is the standard deviation of $F_y'(t)$. f_{st} was identified from $F_y(t)$, and $F_y'(t)$ was calculated by applying a bandpass filter with a center frequency of f_{st} to $F_y(t)$.

For the rectangular cylinder with openings, the actual area of the front/rear surface does not include the area of the opening. Thus, the ‘actual’ longitudinal force coefficient C_{Fxr} was calculated based on the ‘actual’ area of the front/rear surface as follows:

$$C_{Fxr} = \frac{F_x}{\frac{1}{2}\rho U^2 Dl} \times \frac{2}{2 - OR} \quad (7)$$

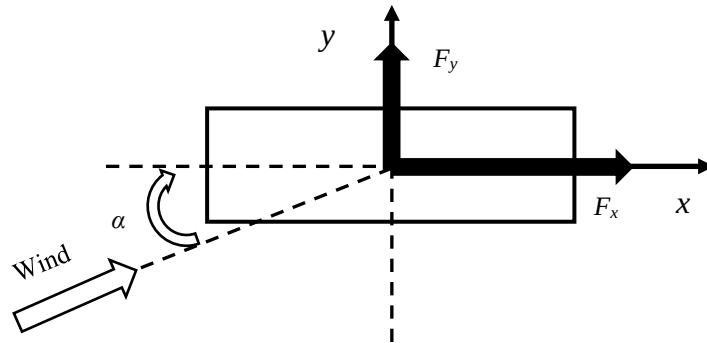


Fig. 4 Definitions of aerodynamic forces on the structural axis.

Table 2 Characteristic parameters for free vibration tests of different cases (vertical one-degree-of-freedom (1DOF), smooth flow)

Case name	OR	RER	m (kg/m)	f (Hz)	δ_η ($2A_\eta = 5\text{mm}$)	Sc_η
Case 1	0		3.26	4.52	0.0030	3.4
Case 2	0.25	1.07	3.25	4.53	0.0027	3.0
Case 6		2.14	3.25	4.53	0.0031	3.5
Case 4	0.75	1.07	3.31	4.49	0.0026	3.0
Case 8		2.14	3.31	4.49	0.0021	2.4
Case 10	1		3.27	4.51	0.0025	2.8

2.3. Free vibration test

To investigate the effects of the different-sized openings on the vortex-induced vibration and galloping, the vertical one-degree-of-freedom (1DOF) free vibration tests were conducted. The model was supported by eight springs and the displacement was measured by four laser gages at $\alpha = 0^\circ$ in the smooth flow. The current research mainly focuses on the aerodynamic response for the low mass-damping system. The galloping for the low mass-damping system is referred to the ‘full interaction between the vortex-induced vibration and galloping’ (Gao and Zhu, 2016; Mannini et al., 2014), which starts from the resonance wind velocity characterized by the reciprocal of the Strouhal number. Therefore, the mass and damping were minimized for the convenience of the discussion on the effects of the different-sized openings on the relationship between the critical wind velocity of galloping and Strouhal number. Furthermore, the mass and damping of the system were also as minimized as possible to facilitate observation of the aerodynamic response and were kept constant for all cases for the convenience of comparison (Table 2). The mass-damping parameter, namely Scruton number (Sc_η) for the vertical direction, is defined as follows:

$$Sc_\eta = \frac{2m\delta_\eta}{\rho D^2} \quad (8)$$

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

The reduced wind velocity, U_r , is defined as follows:

$$U_r = \frac{U}{fD} \quad (9)$$

where f is the natural frequency of the system.

2.4. Forced vibration test

The self-excited transverse force on a vertically oscillating bluff body are formulated by the aerodynamic derivatives H_i^* ($i = 1, 4$) as follows, according to Scanlan and Tomko (1971):

$$L_{se} = \frac{1}{2}\rho(2b)U^2 \left\{ kH_1^* \frac{\dot{\eta}}{U} + k^2 H_4^* \frac{\eta}{b} \right\} \quad (10)$$

where L_{se} is the self-excited transverse force per unit span (N/m) (downward direction is positive), η is the vertical one-degree-of-freedom (1DOF) sinusoidal displacement (m) (downward direction is positive), $(\cdot)$ indicates the time differentiation, b is half of the body width (m), k is the reduced frequency ($b\omega/U$), and ω is the angular frequency (rad/s).

To investigate the relationship between the size of the opening and the linear unsteady aerodynamic damping, the vertical 1DOF forced vibration tests were carried out on the models. The self-excited transverse force was measured by the load cells rigidly connected to the model under the vertical 1DOF sinusoidal oscillation at $\alpha = 0^\circ$ in the smooth flow; the displacement of the model was simultaneously recorded using laser gages. The aerodynamic derivatives were then calculated based on the self-excited transverse force and displacement. The linear unsteady aerodynamic damping in the vertical direction is characterized by the aerodynamic derivative H_1^* , the positive value of which indicates the instability in the vertical direction (Scanlan and Tomko, 1971; Matsumoto, 1996). Thus, in this research, the H_1^* is referred to aerodynamic damping. The effects of the openings on the galloping instability were discussed by comparing the aerodynamic damping H_1^* of the rectangular cylinder with different-sized openings. To obtain sufficiently large self-excited force, the vertical amplitude and frequency were set to 5 mm and 2.6 Hz, respectively. Furthermore, the inertial forces were set to a small value by minimizing the mass, and the inertial forces were isolated to obtain the accurate aerodynamic self-excited force.

3 Opening size and galloping instability

The relationship between the aerodynamic instability and the opening size, which is characterized by Opening-area Ratio (OR , Eq. (1)) and Repeating Element-size Ratio (RER , Eq. (2)), is investigated in this section. First, based on the vertical one-degree-of-freedom (1DOF) aerodynamic response, the effects of OR and RER on the vortex-induced vibration and galloping vibration are evaluated, with respect to the vibration amplitude and onset wind velocity. Thereafter, the role of OR and RER on aerodynamic damping are evaluated. Meanwhile, the asymptotic behavior of the linear unsteady aerodynamic damping to the aerodynamic damping predicted by the linear quasi-steady theory is investigated to validate the quasi-steady theory for the rectangular cylinder with side-surface openings. Furthermore, the effects of the openings on the relationship between the critical wind velocity for galloping and Strouhal number are discussed.

3.1. Vertical 1DOF aerodynamic response

The vertical one-degree-of-freedom (1DOF) aerodynamic responses of the rectangular cylinder with different-sized openings are summarized in Fig. 5. $2A\eta/D$ is the non-dimensional double amplitude of the displacement, where $A\eta$ is the amplitude of displacement. The vortex-induced vibration and galloping phenomena, were observed for all the cases except $OR = 1$, which did not display vibration at reduced wind velocity $U_r < 44$. The relationship between the size of the openings (OR and RER) and the two phenomena are discussed separately.

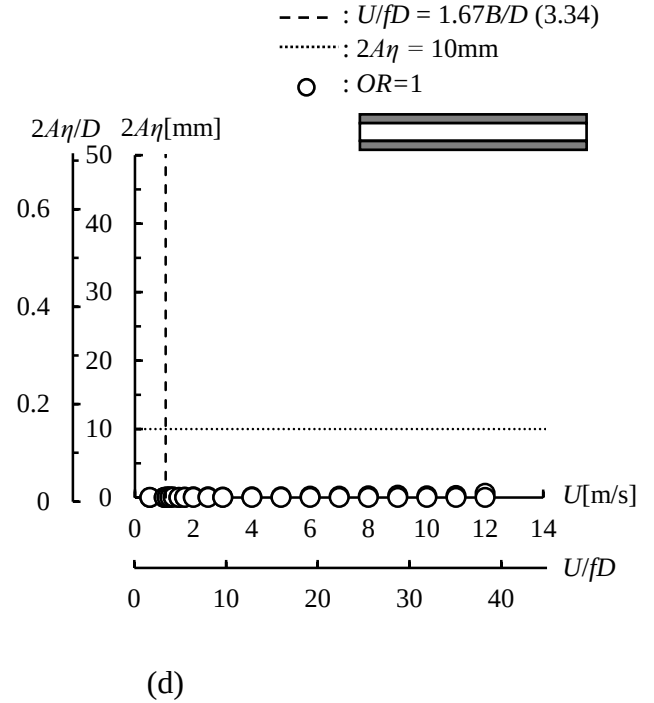
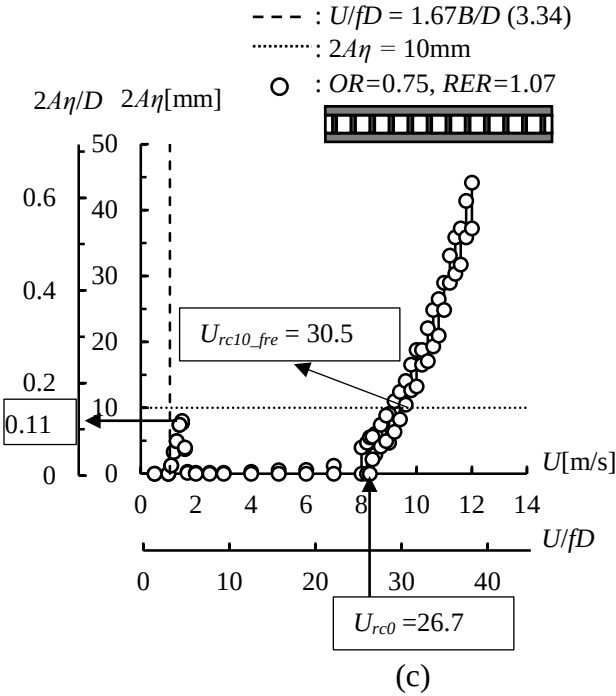
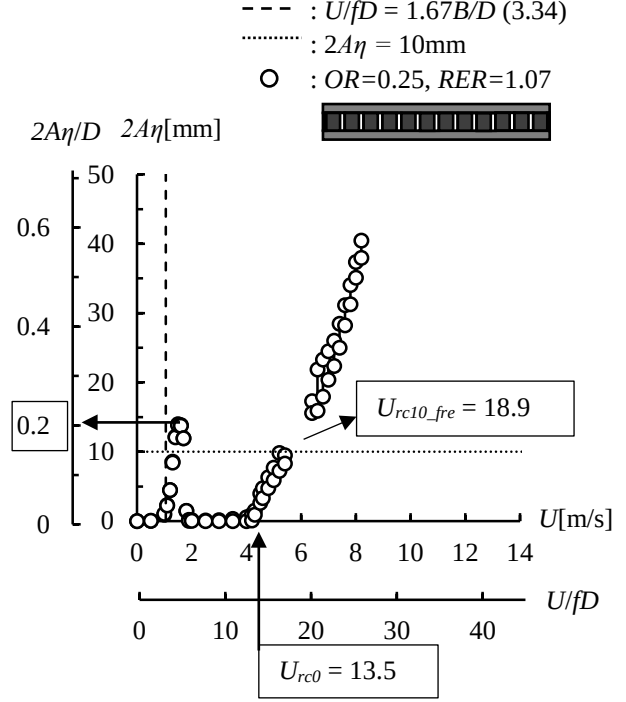
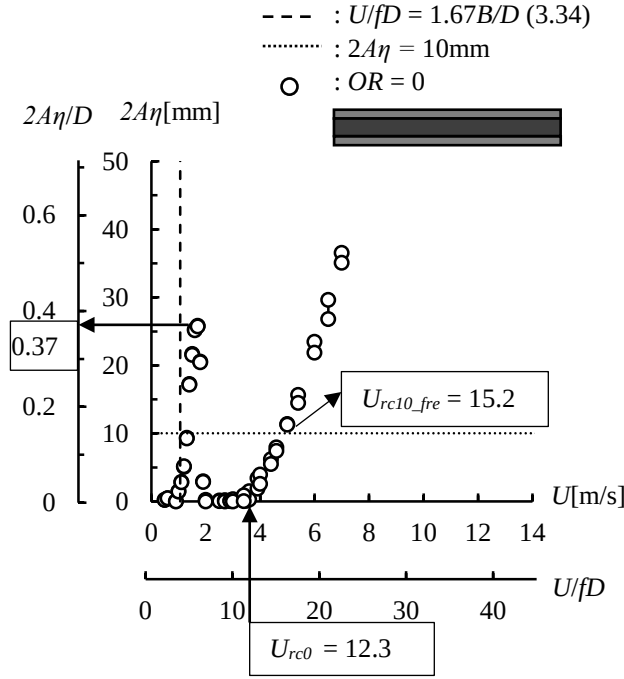


Fig. 5 Aerodynamic response of (a) Case 1 ($OR=0$); (b) Case 2 ($OR=0.25, RER=1.07$); (c) Case 4 ($OR=0.75, RER=1.07$); (d) Case 10 ($OR=1$); (e) Case 6 ($OR=0.25, RER=2.14$); (f) Case 8 ($OR=0.75, RER=2.14$). U_{rc0} is the critical wind velocity of galloping corresponding to $2A\eta$ of 0 mm. U_{rc10_fre} represents the wind velocity corresponding to $2A\eta$ of 10 mm. The symbol of two circles connected by the vertical line indicates limit cycle oscillation.

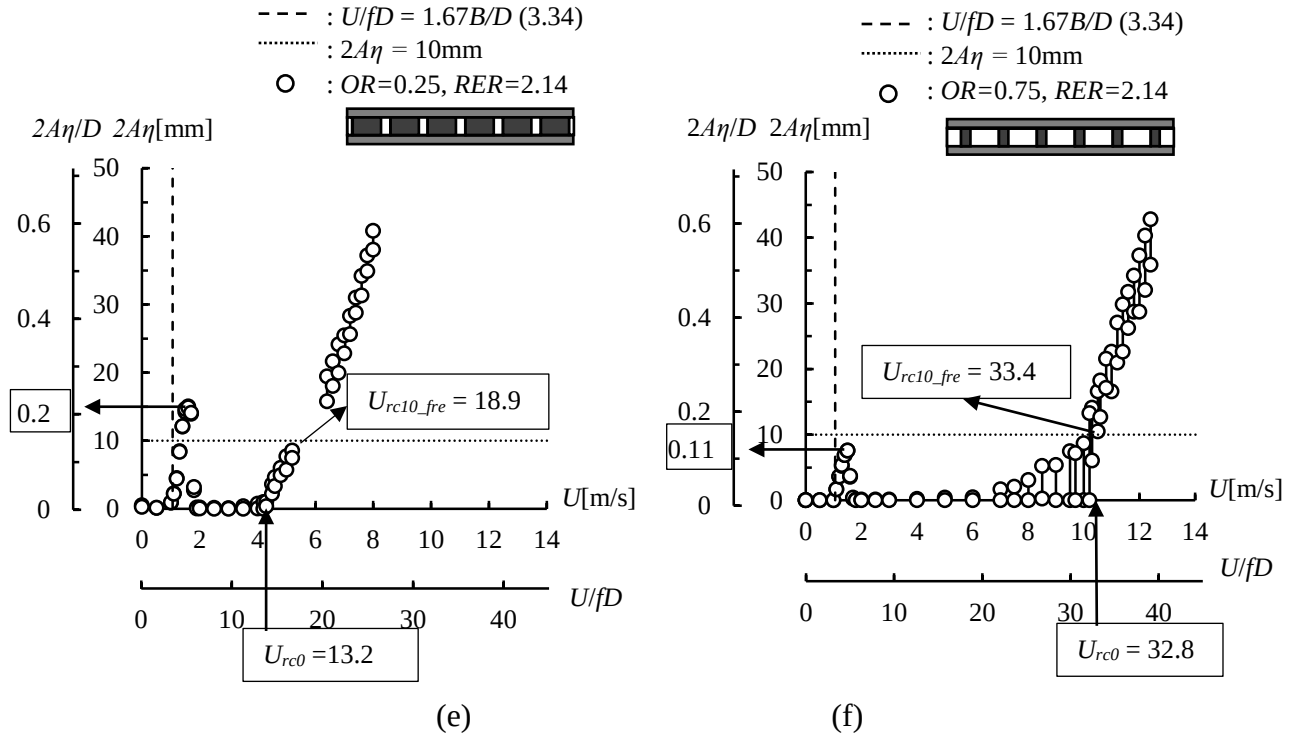


Fig. 5 Continued

3.1.1. Vortex-induced vibration

According to Fig. 5, a noticeable result is that for Case 1 ($OR = 0$), Case 2 ($OR = 0.25, RER = 1.07$), Case 4 ($OR = 0.75, RER = 1.07$), Case 6 ($OR = 0.25, RER = 2.14$), and Case 8 ($OR = 0.75, RER = 2.14$), the reduced critical wind velocity of vortex-induced vibration was constant at $Ur = 3.2$, which is close to the value of $1.67 \times B/D (=3.34)$. According to Matsumoto et al. 2008, the vortex-induced vibration is divided into two types: Kármán-vortex and motion-induced. As the motion-induced vortex vibration occurs at reduced wind velocity $Ur = 1.67B/D$ (Matsumoto et al. 2008), the vortex-induced vibration for the current models is of the motion-induced type. It is caused by the resonance between the system and the vortex convection along the surface. The velocity of the vortex convection along the surface is approximately 60% of the approaching wind velocity U (Kiya and Nozawa 1987). As B is constant for all the cases, the critical wind velocity of vortex-induced vibration for all cases indicates that the openings did not affect the velocity of vortex convection along the surface. Therefore, the critical wind velocity of the motion-induced vortex vibration was not affected by the openings.

Another noticeable result is that the largest reduced double amplitude of motion-induced vortex vibration ($2A\eta(\max)/D$) gradually decreased from 0.37 to 0 with an increase of OR from 0 to 1 for $RER = 1.07$. Meanwhile, by comparing Fig. 5 (b) and (e), for $OR = 0.25$, $2A\eta(\max)/D$ was 0.2 for both $RER = 1.07$ and 2.14. By comparing Fig. 5 (c) and (f), for $OR = 0.75$, $2A\eta(\max)/D$ was 0.11 for both $RER = 1.07$ and 2.14. Therefore, the amplitude of motion-induced vortex vibration was gradually minimized by increasing OR , while RER has no significant effects on the amplitude.

3.1.2. Galloping instability

By comparing Fig. 5 (a)-(d), the effect of increasing the Opening-area Ratio (OR , Eq. (1)) was a progressive decrease of vibration amplitude at a certain wind velocity. Meanwhile, the reduced critical wind velocity (U_{rc0}) of galloping increased with OR and galloping did not occur for $OR = 1$. Additionally, for $OR = 0.25$, U_{rc0} was similar for $RER = 1.07$ and 2.14 ; whereas, for $OR = 0.75$, U_{rc0} was slightly different for different Repeating Element-size Ratios (RER , Eq. (2)). The reduced wind velocity (U_{rc10_fre}) corresponding to $2A\eta = 10$ mm is marked in the figure. By comparing Fig. 5 (b) and (e), for $OR = 0.25$, $2A\eta$ approached 10 mm at around $U_{rc10_fre} = 18.9$ for both $RER = 1.07$ and 2.14 . By comparing Fig. 5 (c) and (f), for $OR = 0.75$, $2A\eta$ approached 10 mm at $U_{rc10_fre} = 30.5$ for $RER = 1.07$, and at $U_{rc10_fre} = 33.4$ for $RER = 2.14$. Therefore, RER slightly affected the onset of galloping for the case of large OR (i.e., 0.75), whereas it had no significant effects for small OR (i.e., 0.25). Once the galloping occurred, RER barely had effects on the aerodynamic response. The OR played an important role in stabilizing the galloping, because of which the amplitude of galloping response decreased and the critical wind velocity increased with an increase of OR .

3.2. Aerodynamic force characteristics

The relationship between the openings' size (Opening-area Ratio (OR , Eq. (1))) and Repeating Element-size Ratio (RER , Eq. (2))) and the galloping was further discussed. At high wind velocities, the linear unsteady aerodynamic damping approaches the aerodynamic damping predicted by the linear quasi-steady theory (Nakamura and Mizota, 1975; Obasaju, 1983; Washizu et al., 1978; Yagi et al., 2013). According to the quasi-steady theory, the instantaneous aerodynamic forces acting on the oscillating cylinder are equal to those of the stationary cylinder subject to relative velocity $U_{rel} = (U^2 + \dot{\eta}^2)^{1/2}$, resulting from the relative angle of attack α_0 ($\alpha_0 = \tan^{-1}(\dot{\eta}/U)$), where $\dot{\eta}$ is the cylinder vertical velocity, and positive in the downward direction, while α_0 is positive in the nose-up direction. Based on the linear quasi-steady theory, the transverse force L_{qs} (downward direction is positive) working on the oscillating body was

$$L_{qs} = -\frac{1}{2}\rho U^2 B \frac{dC_{Fy}}{d\alpha} \frac{\dot{\eta}}{U} \quad (11)$$

When slope of the transverse force coefficient against angle of attack $dC_{Fy}/d\alpha$ is negative, the galloping would occur at a certain wind velocity. To compare with the H_1^* identified from the forced vibration tests (Eq. (10)), the H_1^* based on linear quasi-steady theory is calculated as

$$H_1^* = -\frac{1}{k} \frac{dC_{Fy}}{d\alpha} \quad (12)$$

3.2.1. Opening-area Ratio (OR) and galloping instability

The distribution of the transverse force coefficients (C_{Fy}) against the angle of attack (α) for different OR s are depicted in Figs. 6 and 7. As the models were symmetrical to the central lines, the distribution of C_{Fy} against α was zero-point antisymmetric. Therefore, C_{Fy} was shown only at $-2^\circ \leq \alpha \leq 10^\circ$. According to Fig. 6, with the increase of OR from 0 to 0.875, the α range, where the slope of the transverse force coefficient against the angle of attack $dC_{Fy}/d\alpha$ indicated negative

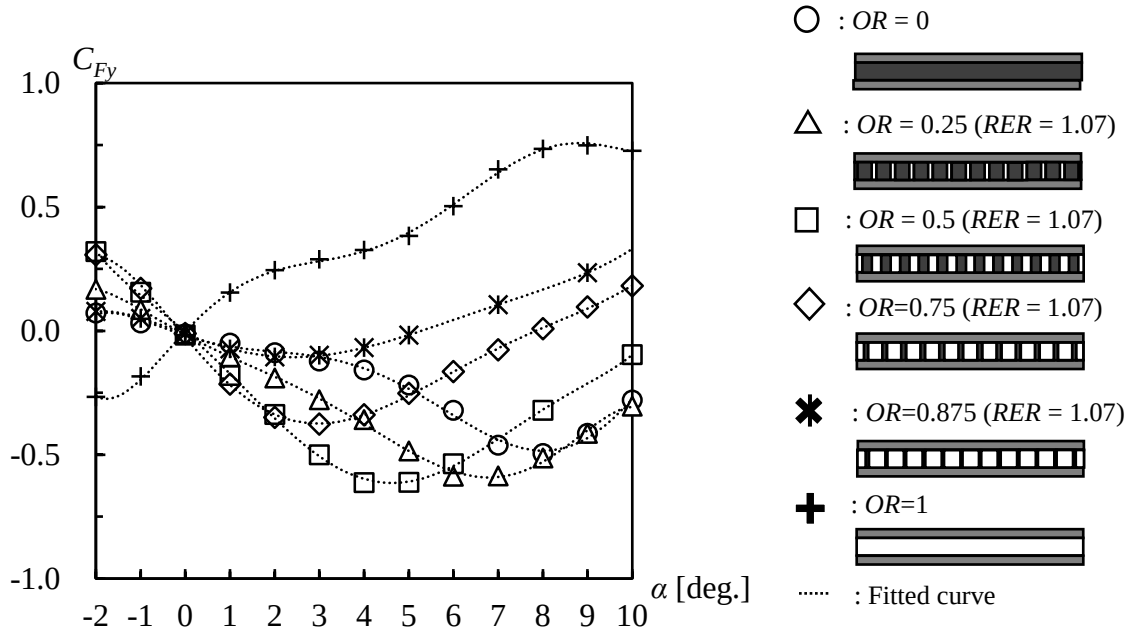


Fig. 6 Change of transverse force coefficients with OR ($OR = 0, 0.25, 0.5, 0.75, 0.875$ and 1) for $RER = 1.07$ ($U = 6$ m/s, smooth flow).

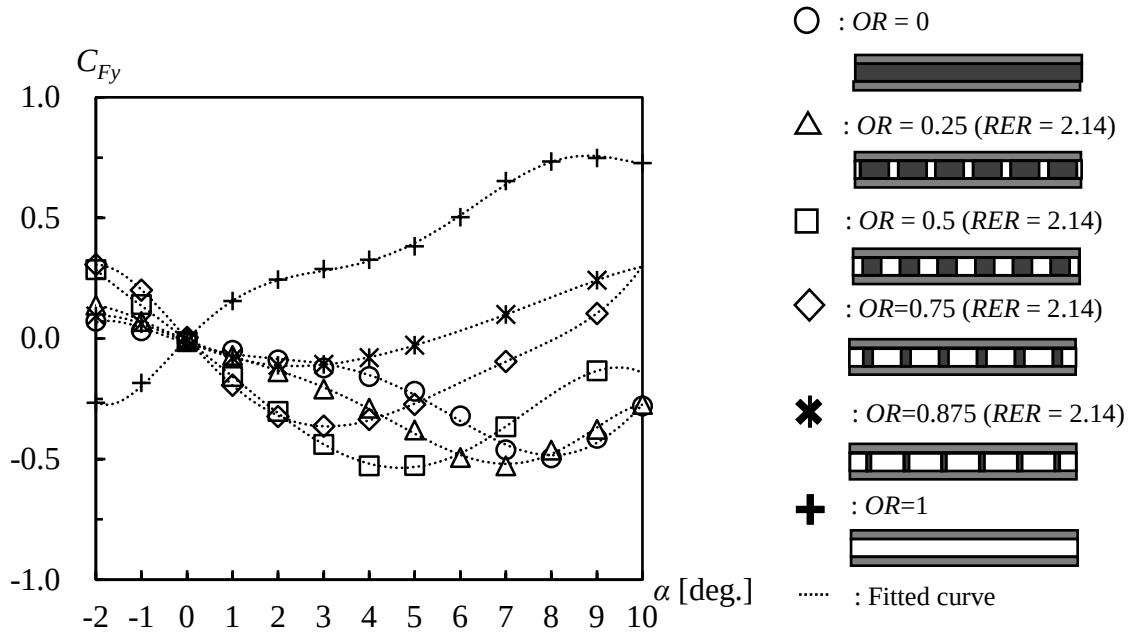


Fig. 7 Change of transverse force coefficients with OR ($OR = 0, 0.25, 0.5, 0.75, 0.875$ and 1) for $RER = 2.14$ ($U = 6$ m/s, smooth flow).

value, decreased. Meanwhile, $dC_{Fy}/d\alpha$ for ($OR = 1$) was positive at $-10^\circ \leq \alpha \leq 10^\circ$. As depicted in Fig. 7, the α range, where $dC_{Fy}/d\alpha$ was negative, also decreased with the increase of OR for $RER = 2.14$. As the $dC_{Fy}/d\alpha < 0$ indicates the galloping instability, with the increase of OR , the galloping would occur at a relatively smaller α -range. Furthermore, $-dC_{Fy}/d\alpha$ at $\alpha = 0^\circ$ are summarized in Fig. 8. According to Fig. 8, $-dC_{Fy}/d\alpha$ increased from 2.4 to 13.9 with the increase of OR from 0 to

0.75 and decreased from 13.9 to 5.8 with the increase of OR from 0.75 to 0.875. The relationship between $-dC_{Fy}/d\alpha$ and OR is qualitatively discussed in section 4.3.2 based on the time-averaged flow field. Furthermore, $-dC_{Fy}/d\alpha$ for the same OR was similar for $RER = 1.07$ and 2.14. Therefore, the OR played an important role in determining the aerodynamic damping characterized by $-dC_{Fy}/d\alpha$, whereas the RER had no significant effects on the aerodynamic damping.

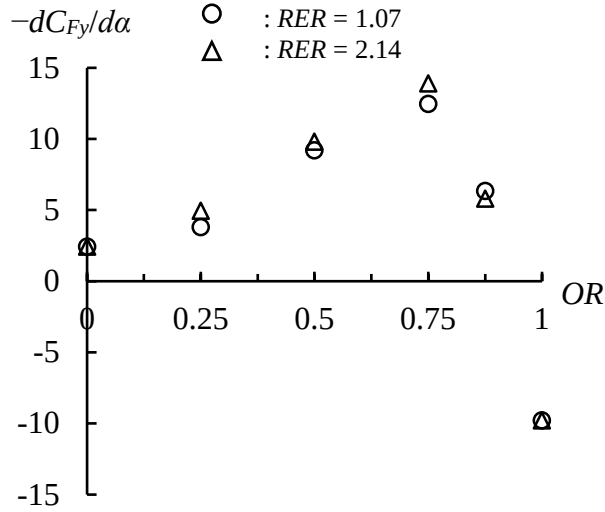


Fig. 8 Slope of the transverse force coefficient against angle of attack at angle of attack $\alpha = 0^\circ$. ($U = 6$ m/s, smooth flow)

To further discuss the effects of the openings on aerodynamic damping, Figs.9 and 10 depict H_1^* for different OR s both identified from the forced vibration tests and calculated based on the linear quasi-steady theory. For both $RER = 1.07$ and 2.14, the reduced critical wind velocity of galloping, which is characterized by the change of H_1^* from negative to positive, gradually increased with the increase of OR from 0 to 0.875, and $OR = 1$ did not display galloping. Furthermore, even though there are some discrepancies between H_1^* identified from the forced vibration tests and H_1^* calculated based on the linear quasi-steady theory at low wind velocities, the former gradually approaches the latter at high wind velocities. Therefore, at high wind velocity range, the linear quasi-steady theory can predict the linear unsteady aerodynamic damping. Meanwhile, at high wind velocities (about reduced wind velocity $Ur > 40$), H_1^* gradually increased with the increase of OR from 0, achieving a maximum at $OR = 0.75$, and then decreased with OR from 0.75 to 1.

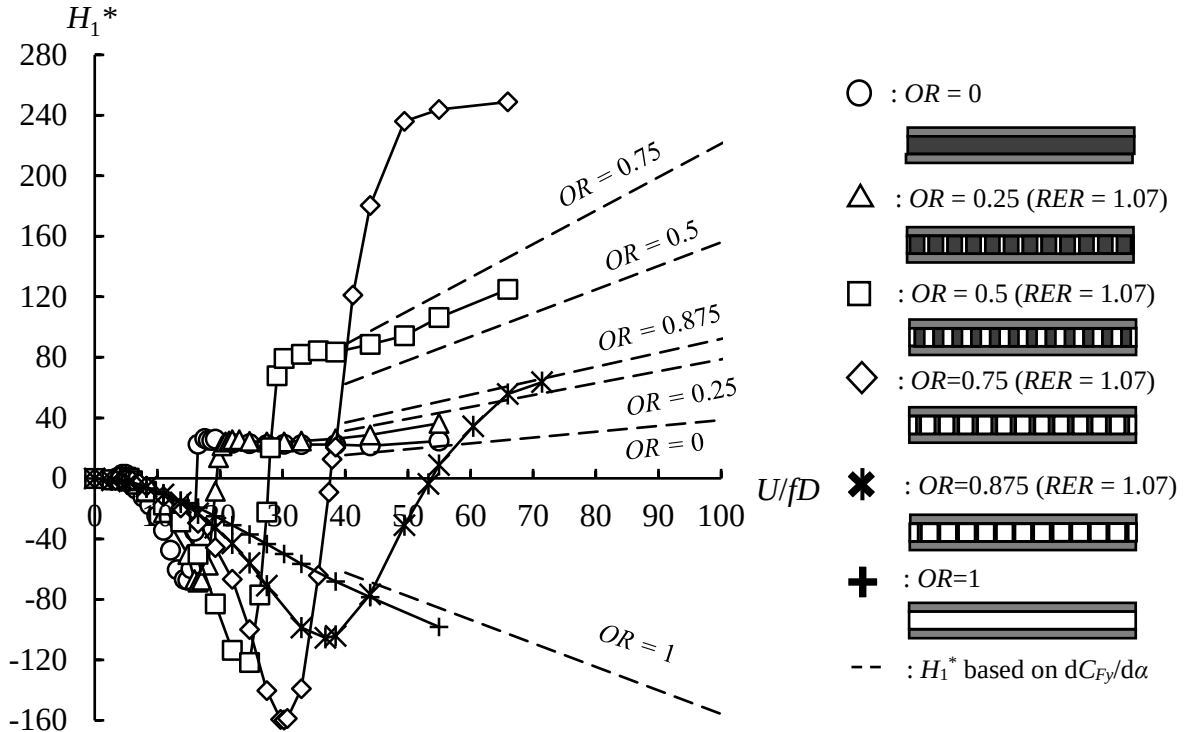


Fig. 9 Change of H_1^* with OR (OR = 0, 0.25, 0.5, 0.75, 0.875 and 1) for $RER = 1.07$ (smooth flow, $\alpha = 0^\circ$, $f = 2.6$ Hz, $2A_\eta = 10$ mm).

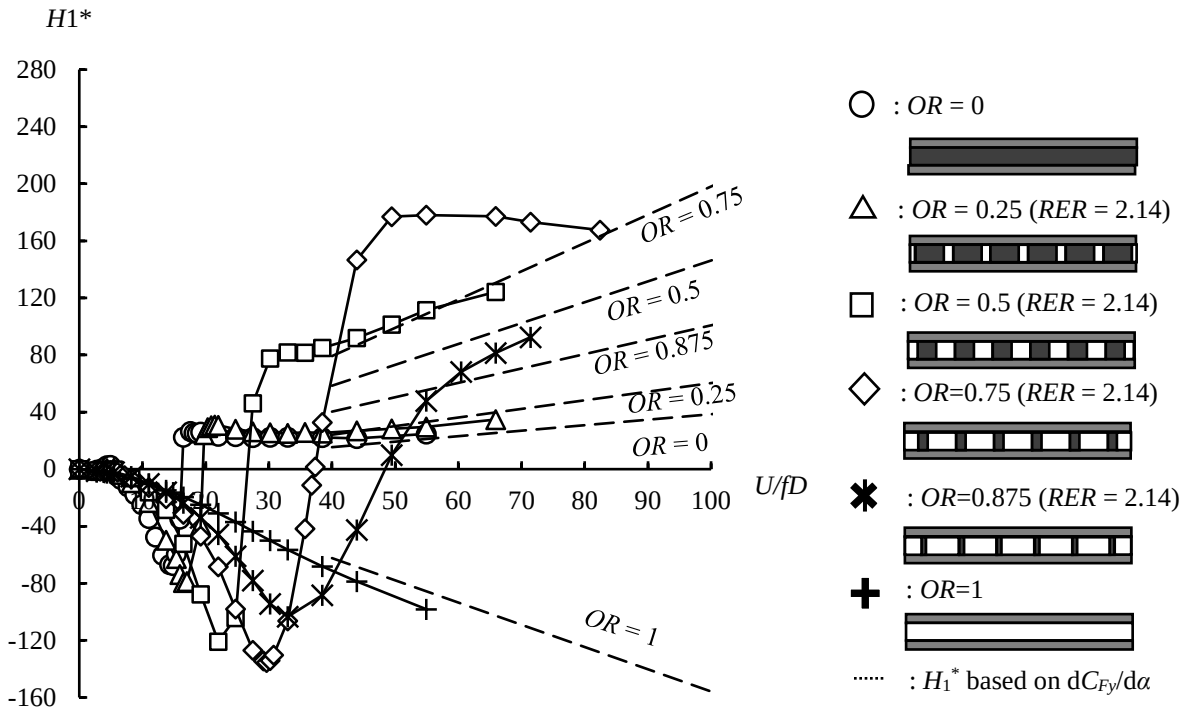


Fig. 10 Change of H_1^* with OR (OR = 0, 0.25, 0.5, 0.75, 0.875 and 1) for $RER = 2.14$ (smooth flow, $\alpha = 0^\circ$, $f = 2.6$ Hz, $2A_\eta = 10$ mm).

3.2.2. Repeating Element-size Ratio (RER) and galloping instability

For each OR , H_1^* for different RER s ($RER = 1.07$ and 2.14) is compared in Fig. 11. For $OR = 0.25$ and 0.5 , H_1^* displayed similar values at each wind velocity for $RER = 1.07$ and 2.14 . For $OR = 0.75$ and 0.875 , H_1^* displayed slightly different values for different RER s at high reduced wind velocities. Thus, the effects of RER on aerodynamic damping are insignificant. Because OR played an important role in the galloping instability of the rectangular cylinders with side-surface openings, only the effects of OR on the galloping instability (critical wind velocity and aerodynamic damping) were discussed further.

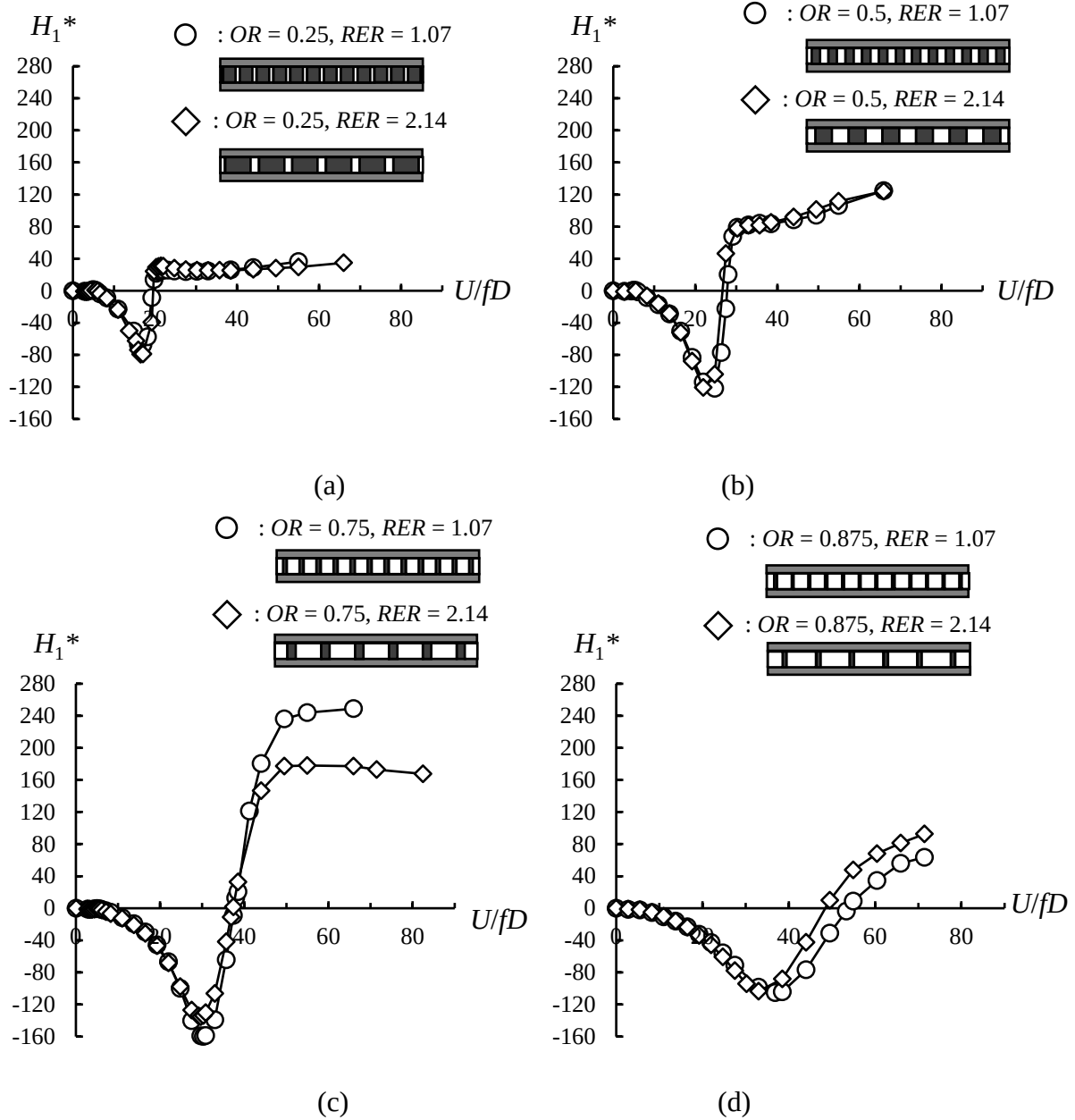


Fig. 11 Comparison between H_1^* of cases of $RER = 1.07$ and 2.14 for (a) $OR = 0.25$; (b) $OR = 0.5$; (c) $OR = 0.75$; (d) $OR = 0.875$ (smooth flow, $\alpha = 0^\circ$, $f = 2.6$ Hz, $2A_{\eta} = 10$ mm).

3.3. Critical wind velocity of galloping and Strouhal number

The mechanism related to the increase of critical wind velocity of galloping with Opening-area ratio (OR , Eq. (1)) is further discussed in this subsection. The relationship between St and OR is shown in Fig. 12 (a). St was almost the same for $OR = 0$ and 0.25 , and it then decreased with the increase of OR from 0.25 to 0.875 (Fig. 12 (a)). According to Fig. 12 (b), the reduced critical wind velocity (U_{rc0}) of galloping from the free vibration tests was almost the same as $1/St$. This result coincides with the findings of a previous study (Parkinson and Wawzonek, 1981), in which U_{rc0} is found to be almost the same as $1/St$ for rectangular cylinders with different side ratios (from 0.7 to 2.8). Therefore, U_{rc0} is controlled by $1/St$. Furthermore, according to Fig. 12 (b), U_{rc0} and $1/St$ increased simultaneously with the increase of OR , indicating that the increase of $1/St$ with OR resulted in the increase of U_{rc0} .

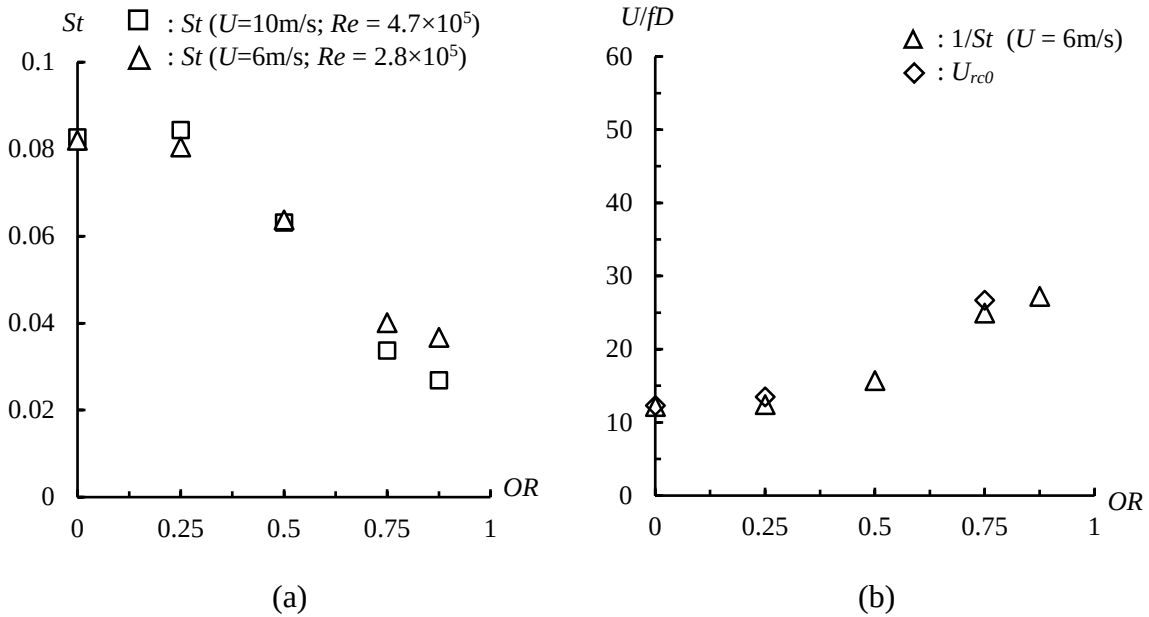


Fig. 12 (a) Change of Strouhal number (St) with OR ($RER = 1.07$, smooth flow). (b) Change of reduced critical wind velocity of galloping with OR ($RER = 1.07$, smooth flow).

St of the rectangular cylinder with different side-ratios as obtained in previous studies is shown in Fig. 13. The St of different OR s is also included as a comparison in Fig. 13. The St at $OR = 0$ was the same as that for $B/D = 2$ in previous studies. Furthermore, St decreased with the increase of side ratio from 2 to 2.8 . The decrease of St with B/D from 2 to 2.8 is similar to the decrease of St with OR from 0 to 0.875 . Subsequently, the side ratio of the model effectively increased from 2 to about 2.8 owing to the increase of OR from 0 to 0.875 . Here, the effective side ratio B'/D' is introduced, where B' is the effective body width and D' is the effective body depth. The effective side ratio is the side ratio of the rectangular cylinder that shows a similar value of aerodynamic force coefficients as those of the $B/D = 2$ rectangular cylinder with different-sized openings. Therefore, increasing the OR had effects on increasing the B'/D' .

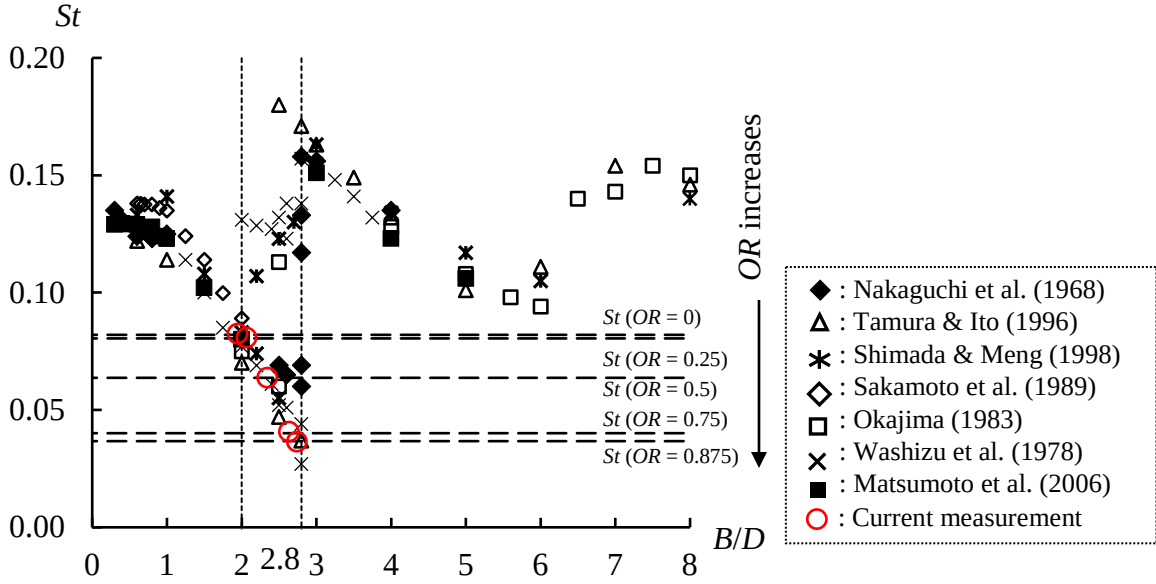


Fig. 13 Change of Strouhal number with side ratio B/D .

To further verify the assumption of the effective side ratio, the relationship between the aerodynamic force coefficients (fluctuating transverse force coefficient $C_{Fy'}$, longitudinal force coefficient C_{Fx} and C_{Fxr}) and OR , and the relationship between $(C_{Fy'}$ and $C_{Fx})$ and B/D are comparatively investigated. The change of fluctuating transverse force coefficient $C_{Fy'}$ with OR is depicted in Fig. 14 (a), and is compared with the change of $C_{Fy'}$ with side ratio from previous studies in Fig. 14 (b). The $C_{Fy'}$ value for $OR = 0$ agrees with that of the $B/D = 2$ rectangular cylinder in previous studies. The $C_{Fy'}$ value decreased with OR similar to the decrease in $C_{Fy'}$ with B/D . Additionally, Fig. 15 depicts the longitudinal force coefficient C_{Fx} that was calculated based on the total front/rear surface (Eq. (4)), and the value of longitudinal force coefficient C_{Fxr} that was calculated based on the actual front/rear surface (Eq. (7)). C_{Fx} or C_{Fxr} for $OR = 0$ was similar to C_{Fx} of the $B/D = 2$ rectangular cylinder in the previous studies (Fig. 15 (c)). Meanwhile, C_{Fxr} decreased with OR similar to the decrease in C_{Fx} with B/D (Fig. 15 (c)). Therefore, the B'/D' of the model with the openings increased from 2 to approximately 2.8 with the increase of OR from 0 to 0.875. As the C_{Fxr} value for $OR = 1$ was nearly the same as the C_{Fx} of the rectangular cylinder with a side ratio of approximately 4, the model of $OR = 1$ had an effective side ratio greater than 2.8 (approximately 4).

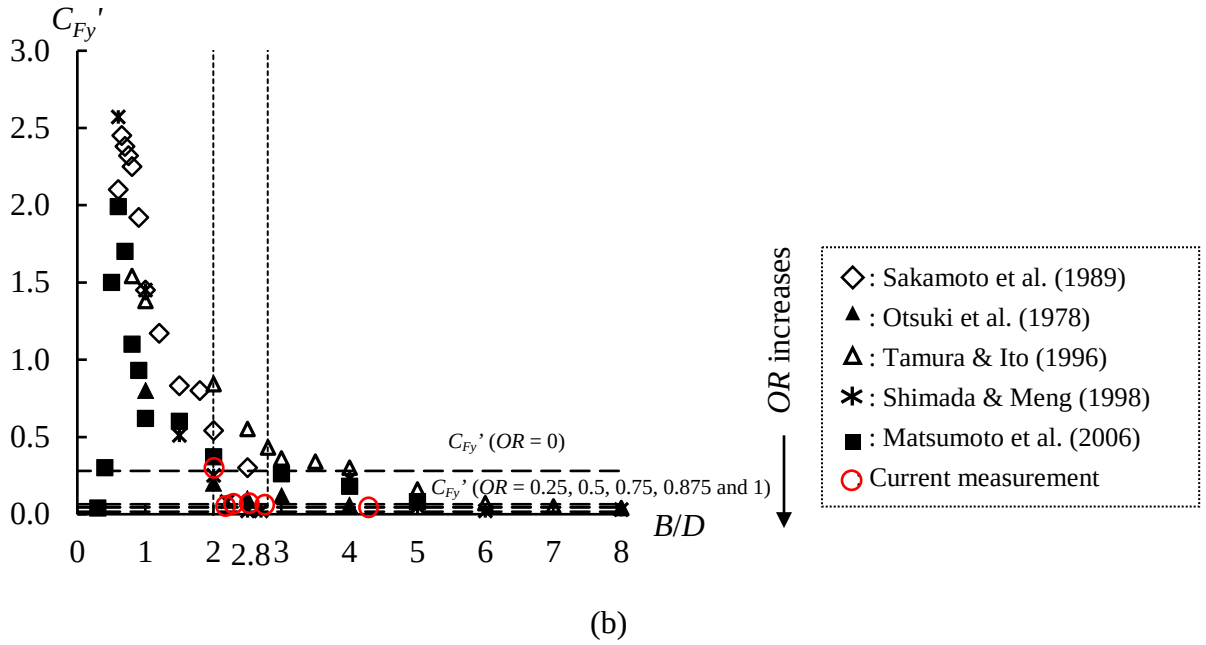
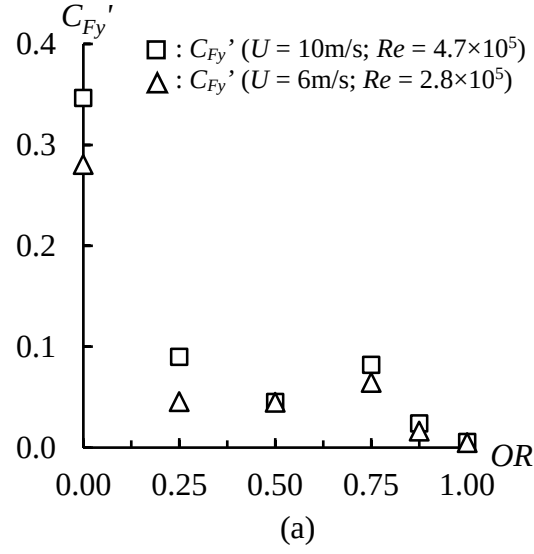
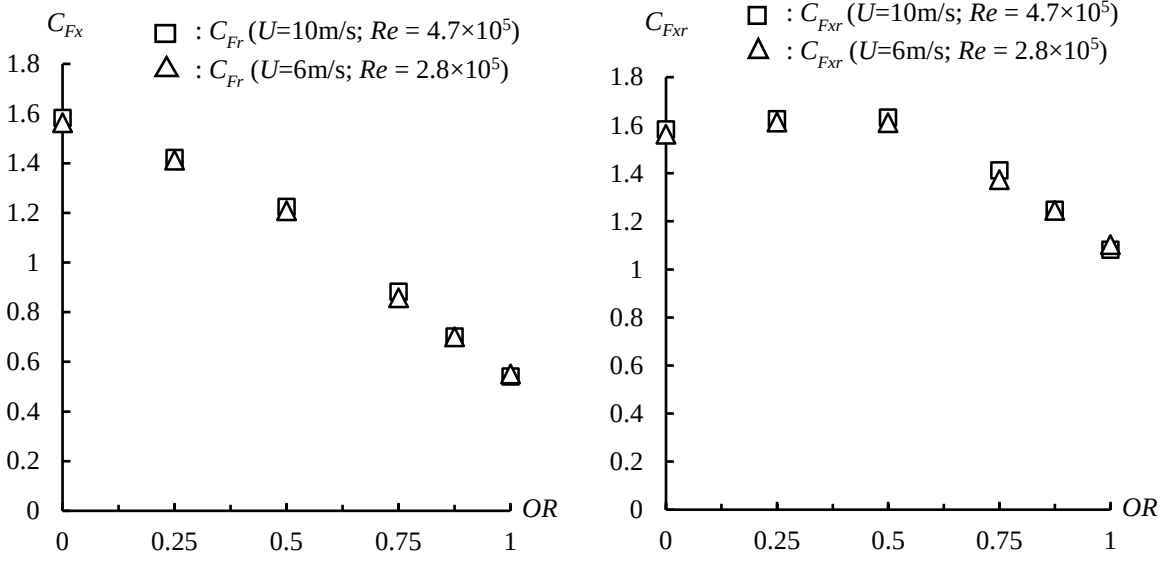
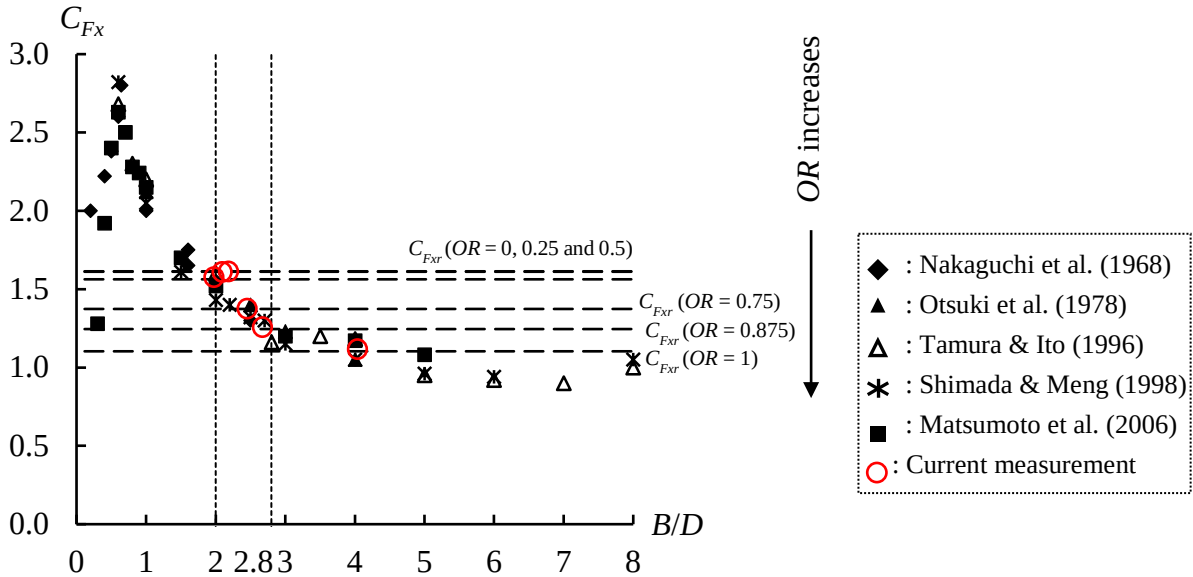


Fig. 14 Change of fluctuating transverse force coefficients (a) with OR ($RER = 1.07$, smooth flow); (b) with side ratio B/D .



(a)

(b)



(c)

Fig. 15 (a) Change of longitudinal force coefficient C_{Fx} with OR ($RER = 1.07$, smooth flow); (b) change of longitudinal force coefficient C_{Fxr} with OR ($RER = 1.07$, smooth flow); (c) change of C_{Fx} with side ratio B/D . (C_{Fx} was calculated based on the total front/rear surface, while C_{Fxr} was calculated based on the actual area of the front/rear surface).

According to past studies (Parkinson and Wawzonek, 1981; Smith, 1962; Parkinson and Brooks, 1961; Hirata, 1993; Nakamura and Hirata, 1994), with the increase of B/D from 0.67 to 2.8, the amplitude of galloping vibration at a certain wind velocity gradually decreased, while the critical wind velocity increased. The rectangular cylinder with $B/D > 2.8$ did not display galloping.

Meanwhile, as mentioned earlier, the effective side ratio B'/D' of the rectangular cylinder with side-surface openings increased owing to the increase of OR . Therefore, the critical wind velocity of galloping and $1/St$ increased with the increase of OR from 0 to 0.875, because B'/D' increased from 2 to about 2.8 with the increase of OR from 0 to 0.875. The $OR = 1$ model had an effective side ratio larger than 2.8, as it did not display galloping. To validate the assumption of the effective side ratio owing to the OR , the time-averaged flow around the model with different OR s in the vertical plane will be further investigated. Meanwhile, as the aerodynamic damping based on the quasi-steady theory is related to the time-averaged flow field around the model in the vertical plane, the change in aerodynamic damping with OR will be further explained based on the change in the time-averaged flow field with OR .

4 Time-averaged flow field around rectangular cylinder with side-surface openings

In this section, the time-averaged flow field around the rectangular cylinder with side-surface openings is investigated. First, the setup for the Particle-Image Velocimetry (PIV) measurement is outlined in section 4.1. Section 4.2 investigates the time-averaged flow field in the inner space and wake of the model, focusing on the time-averaged flow rate of the through-body flow. Furthermore, the relationship between the time-averaged flow around the model in the vertical plane and the Opening-area Ratio (OR , Eq. (1)) is illustrated in Section 4.3. This relationship is qualitatively explained by the time-average flow rate of the through-body flow. Finally, the relationship between the time-averaged flow in the vertical plane and OR is utilized to interpret the effects of the openings on the aerodynamic damping and the critical wind velocity of galloping, thereby explaining the mechanism related to the stabilization against the galloping owing to the side-surface openings.

4.1. PIV measurement

The PIV tests were carried out to monitor the flow field around the model in the vertical plane and flow through the inner space of the model into the wake at $\alpha = 0^\circ$. Through the PIV analysis, the instantaneous wind-velocity vectors were calculated.

4.1.1. Model for PIV measurement

A transparent acrylic model was utilized to monitor the flow field in and around the model, as depicted in Fig. 16. The section of the model was the same as that of the wooden model for the free-vibration tests (Fig. 2 (b)). For the flow visualization tests in the vertical plane, the upside surface of the model and the downside surface of the inner space of the girder were covered with black paper to avoid the reflection of the laser.

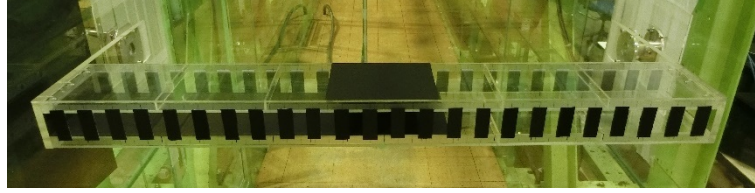


Fig. 16 Model for flow visualization tests

4.1.2. Setup for PIV measurement

The setup for the PIV measurement in the X - Z plane (horizontal plane) is depicted in Fig. 17, and that in the X - Y plane (vertical plane) is depicted in Fig. 18. The coordination was in the right-hand system: the approaching wind direction was defined as the positive X -direction, the upside vertical direction was defined as the positive Y -direction, and the span-wise direction as the Z -direction. The flow was seeded with $0.3\text{--}1\text{ }\mu\text{m}$ droplets of glycol provided by the smoke generator (KANOMAX, MOEL 8384), and illuminated by the thin laser sheet provided by the continuous laser (KATO KOKEN, PIV laser LB2000). The PIV high-speed camera (KATO KOKEN, k8-USB) with a maximum spatial resolution of 2592×2048 pixels was located perpendicular to the

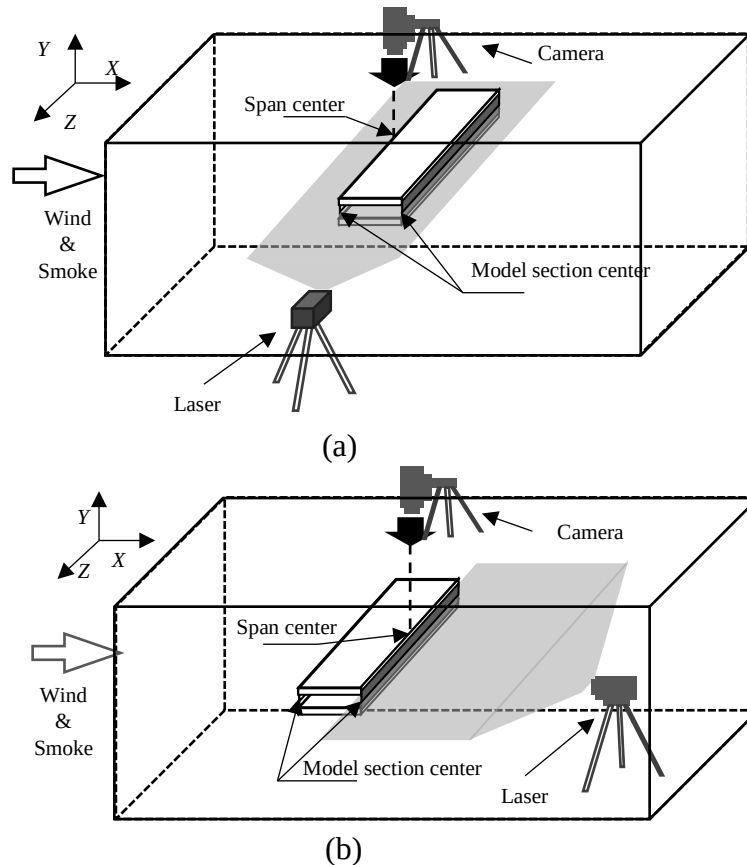


Fig. 17 Set-up for the flow visualization test in X - Z plane for (a) the inner space of model; (b) the wake of the model. The laser sheet is set in the X - Z plane through the center of the model section. The origin of coordinate is at the span center and upside leading edge.

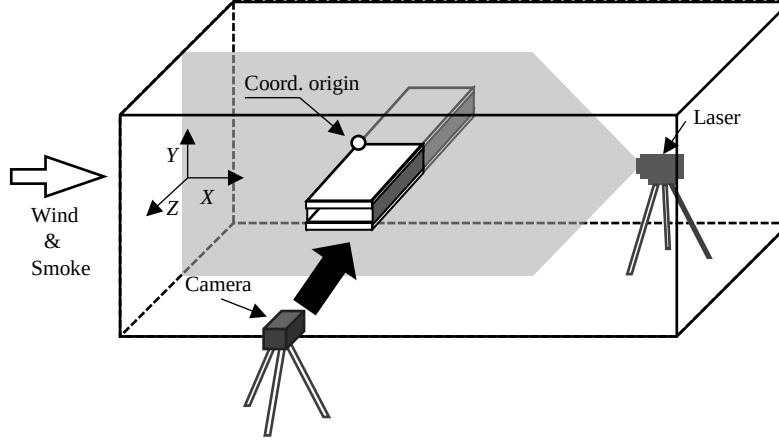


Fig. 18 Set-up for the flow visualization tests in X-Y plane.

laser sheet to acquire sequential images of the illuminated flow field. As the PIV equipment utilized in this research can provide better results at low wind velocities, we set $U = 1.5 \text{ m/s}$ ($Re = 0.7 \times 10^5$) for the PIV tests. Furthermore, St (see Fig. 12 (a)) and longitudinal force coefficient C_{Fx} that was calculated based on the total front/rear surface (Eq. (4)) (see Fig. 15 (a)) in each case demonstrated almost identical values for $Re = 2.8 \times 10^5$ ($U = 6 \text{ m/s}$) and $Re = 4.7 \times 10^5$ ($U = 10 \text{ m/s}$). Therefore, at $Re = 2.8 \times 10^5 \sim 4.7 \times 10^5$, the effects of the Reynolds number were negligible for the $B/D = 2$ rectangular cylinder with side-surface openings. Even though it is necessary to discuss the effects of the Reynolds number in greater detail, the PIV results at $U = 1.5 \text{ m/s}$ ($Re = 0.7 \times 10^5$) are capable of qualitatively describing the effects of the side-surface openings on the time-averaged flow field in the inner and outer space of the model. The images were captured at 300 fps for 14.88 s with a shutter speed of $1/300 \text{ s}$. A total of 4465 frames were used to calculate the time-averaged wind velocity. As the frequency of vortex shedding from the models varied from 0.7 Hz to 1.7 Hz, the time length of 14.88 s could cover 10 to 25 periods.

According to Fig. 17, for the tests in the X-Z plane, the laser sheet was set in the X-Z plane through the sections center and the camera was placed on the upside transparent wall of the wind tunnel perpendicular to the laser sheet. For the inner space, the laser was placed outside of the wind tunnel pointing at the Z direction, and the camera center was set at the span center of the leading edge. For the wake part, the laser was set on the downstream side of the model, and the camera center was at the span center of the trailing edge. As depicted in Fig. 18, for the tests in the X-Y plane, the laser was placed on the downstream side and the camera was set outside the wind tunnel pointing at the Z direction. The flow field around the closed and open sections were both monitored (Fig. 19). The closed section was at the center of the plate, while the open section was at the center of the opening. As the flow around the model in the X-Y plane is symmetrical to the horizontal centerline of the section, only the flow field above the upside surface and in the wake of the model was monitored. The flow field in the wake and above the model in the X-Y plane was measure separately (Fig. 19). The particle images were processed by using a 2-dimensional fluid analysis software (Flownizer 2D v1.12). Based on the sequential particle image, the cross-correlation method was utilized to extract instantaneous vector fields. The interrogation window was $15 \times 15 \text{ pixels}^2$ with a 75% overlap. The instantaneous vector fields were ensemble-averaged

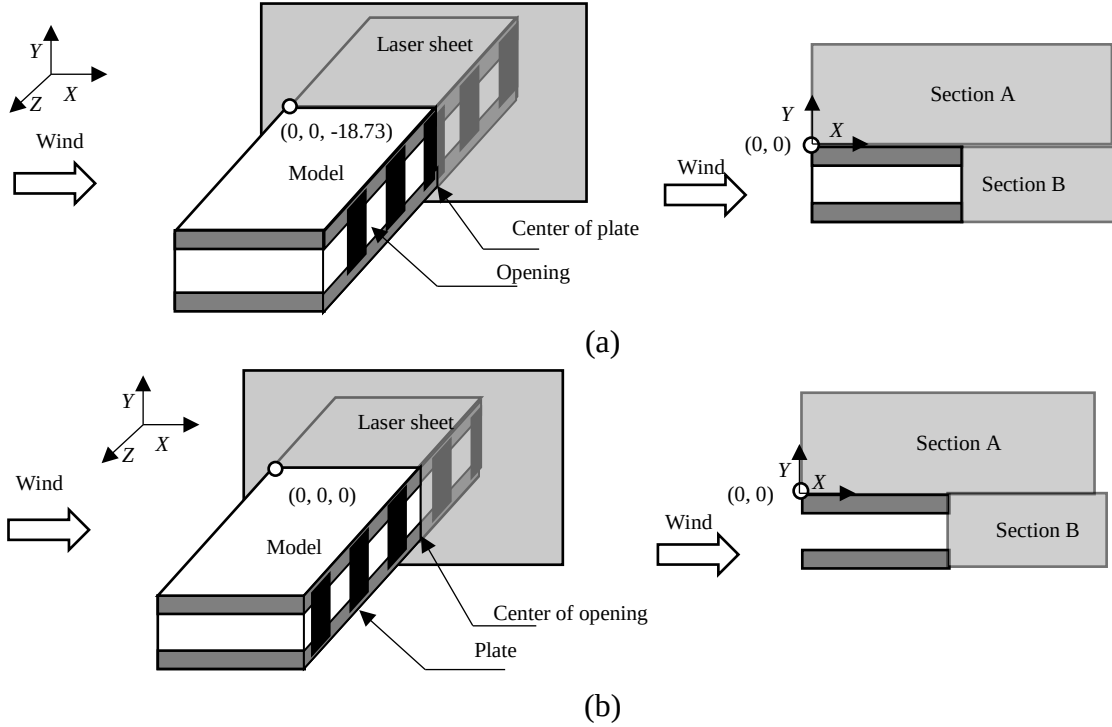


Fig. 19 Measurement position (X-Y plane) for (a) closed section ($z = 0$ mm); (b) open section ($z = 18.73$ mm). The left part for each figure shows the position of closed section and open section. The right part of each figure shows two measurement areas: Section A is for the flow above the upside surface and Section B is for the flow in the wake.

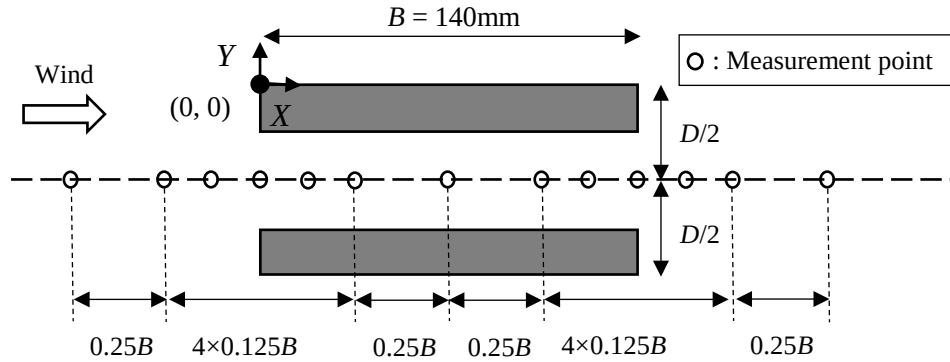


Fig. 20 Distribution of the measurement points for the wind velocity of the flow getting through the inner space of the rectangular cylinder.

to obtain the spatial distributions of the mean wind velocity vector and the time-averaged streamline.

As the PIV method is incapable of measuring the wind velocity at the edge of the transparent body, the wind velocity of the flow passing through the openings was also measured by the 'X'-type hotwire. Meanwhile, as the hotwire can measure the wind velocity more accurately than the PIV tests, the results of the PIV tests were validated by comparing them with those of hotwire

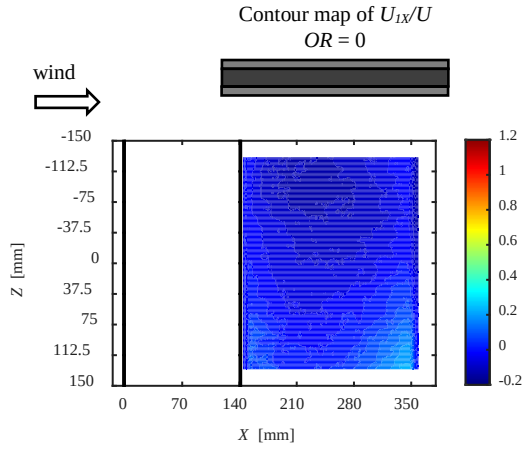
measurement in section 4.2. As depicted in Fig. 20, the measurement points are along the horizontal centerline of the model ($Y = -37.5$ mm).

4.2. Through-body flow

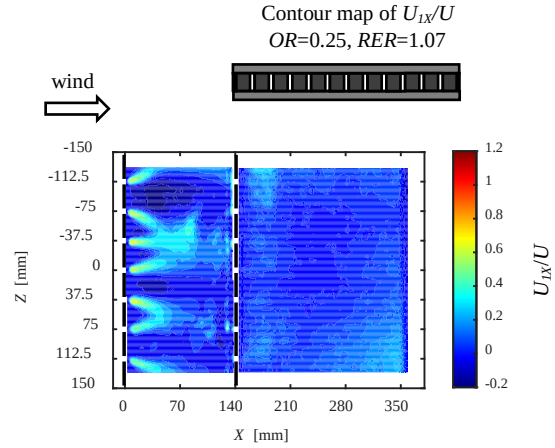
This subsection presents the investigation on the effects of the side-surface openings on the time-averaged non-dimensional X -direction wind velocity U_{1X}/U (U_{1X} is the measured time-averaged X -direction wind velocity, U is the approaching wind velocity) in the inner space and wake. First, U_{1X}/U measured by the hotwire is compared with PIV measurements to validate the results of PIV tests. Thereafter, the change in the time-averaged flow rate through the inner space of the model into the wake with Opening-area Ratio (OR , Eq. (1)) is investigated. Finally, the variation of the time-averaged flow field in the inner space and wake of the model along the Z -direction is discussed.

The contour map of the time-averaged non-dimensional X -direction wind velocity U_{1X}/U in the X - Z plane is depicted in Fig. 21. For $OR = 0$, only the wake part was measured. According to Fig. 21, the flow got through the upstream openings into the inner space of the model and then got out from downstream openings into the wake. Fig. 22 depicts the U_{1X}/U measured by the hotwire and the PIV tests in the X - Y and X - Z plane along the X direction ($Z = 0$ mm and $Y = -D/2$ (-35 mm)). According to Fig. 22, for the complicated three-dimensional flow in the near wake, the U_{1X}/U measured by the PIV method did not agree well with that measured by the hotwire for the $OR = 0.25, 0.5$, and 0.75 . However, these discrepancies did not change the trend wherein U_{1X}/U decreased as X increased from 140 mm to 210 mm, in each case. These discrepancies also did not alter the trend of the increase of U_{1X}/U with OR at each position at 140 mm $< X < 210$ mm. Furthermore, the discrepancies between the U_{1X}/U of the two-dimensional flow in the inner space measured by the two methods were generally less than 20% . As the PIV tests in this study mainly focused on the two-dimensional flow around the model and in its inner space, the PIV results are capable of describing the qualitative change of these flow fields in the inner space of the model (X - Z plane) and around the model (X - Y plane).

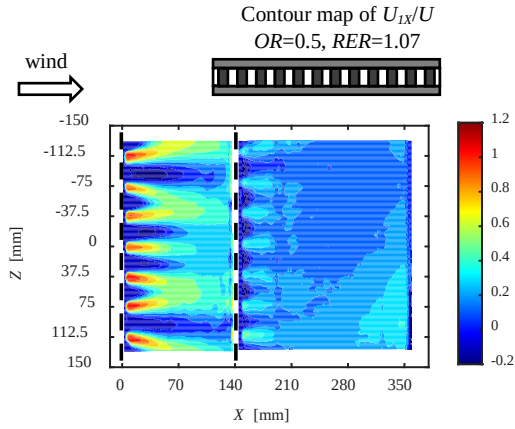
According to the results of the hotwire measurement in Fig. 22, U_{1X}/U almost equals to 1 at $X = 0$ mm and 140 mm for $OR = 0.25-1$, indicating that the U_{1X} at the upstream ($X = 0$ mm) and downstream openings ($X = 140$ mm) was not affected by the OR . Here, U_{1X} denotes the measured time-averaged X -direction wind velocity, and U denotes the approaching wind velocity. Therefore, it is assumed that the time-averaged wind velocity of the through-body flow at the upstream and downstream openings was U . Meanwhile, the time-averaged flow rate Q through the total front-surface area S_{fro} of the model separated into two parts: the time-averaged flow rate Q_1 through the total-openings area S_{op} and the time-averaged flow rate Q_2 into the separated flow (Fig. 23). Owing to the increase of S_{op} , the Q_1 through the total openings increased with OR (Table 3). According to Figs. 21 and 22, even though U_{1X}/U was quite small at 140 mm $< X < 210$ mm for $OR = 0.25, 0.5$ and 0.75 , the overall U_{1X}/U at 0 mm $< X < 350$ mm apparently increased with OR , confirming that the Q_1 increased with OR . Because the time-averaged flow rate Q through the total front surface of the model was constant (approximately 0.378 m³/s), the Q_2 decreased with OR .



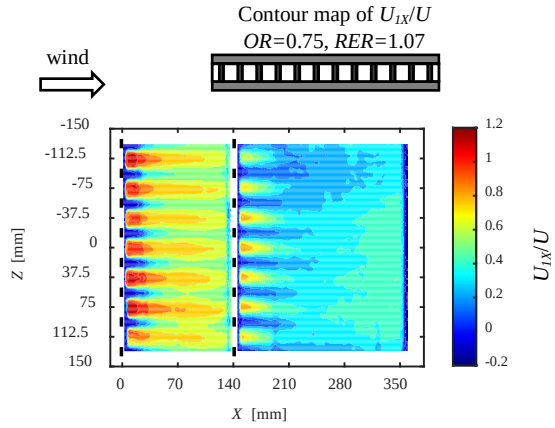
(a)



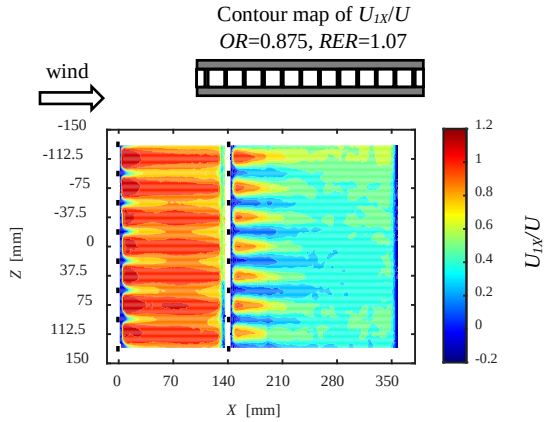
(b)



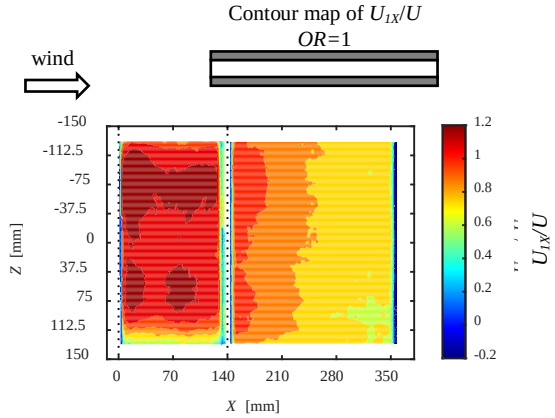
(c)



(d)

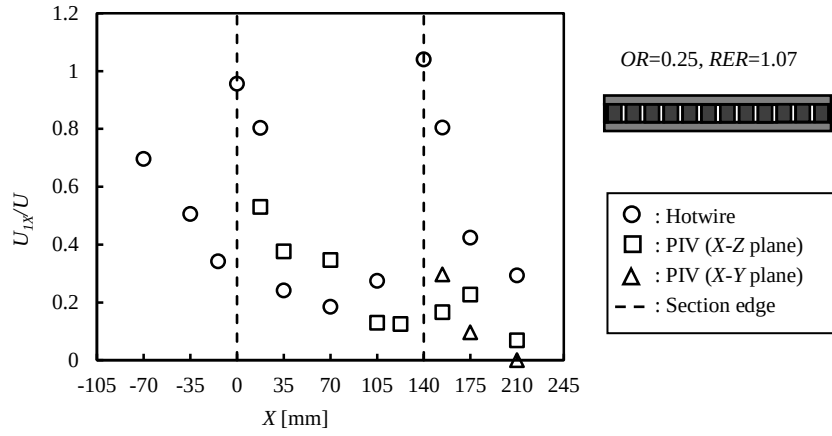


(e)

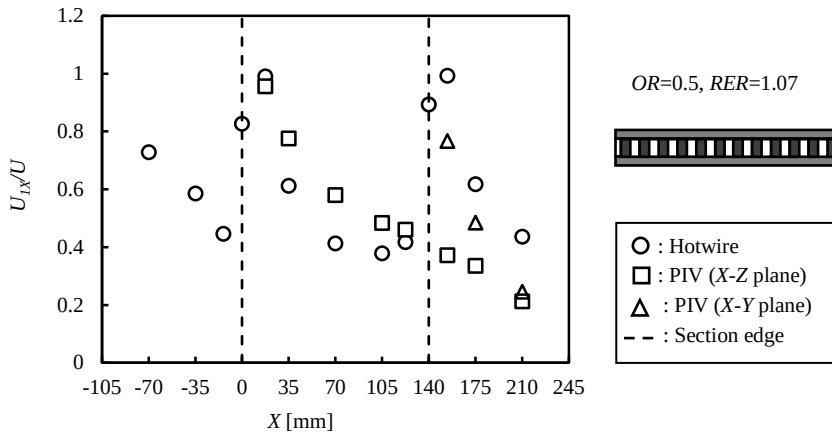


(f)

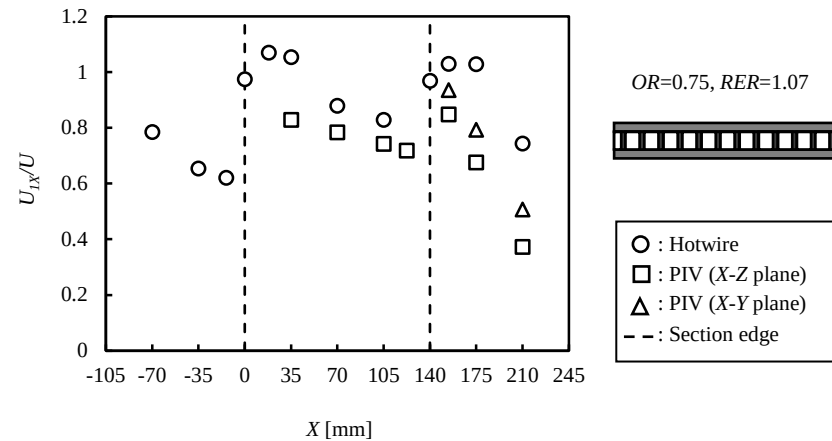
Fig. 21 Contour map of time-averaged non-dimensional X -direction wind velocity (U_{1X}/U) in X - Z plane of (a) Case 1 ($OR = 0$); (b) Case 2 ($OR = 0.25$, $RER = 1.07$); (c) Case 3 ($OR = 0.50$, $RER = 1.07$); (d) Case 4 ($OR = 0.75$, $RER = 1.07$); (e) Case 5 ($OR = 0.875$, $RER = 1.07$), (f) Case 10 ($OR = 1$) ($U = 1.5$ m/s, smooth flow).



(a)



(b)



(c)

Fig. 22 Time-averaged non-dimensional X -direction wind velocity (U_{1X}/U) of the flow through the model of (a) Case 2 ($OR = 0.25, RER = 1.07$); (b) Case 3 ($OR = 0.50, RER = 1.07$); (c) Case 4 ($OR = 0.75, RER = 1.07$); (d) Case 5 ($OR = 0.875, RER = 1.07$); (e) Case 10 ($OR = 1$) (PIV tests: $U = 1.5$ m/s, smooth flow; wind velocity measurement: $U = 6$ m/s, smooth flow).

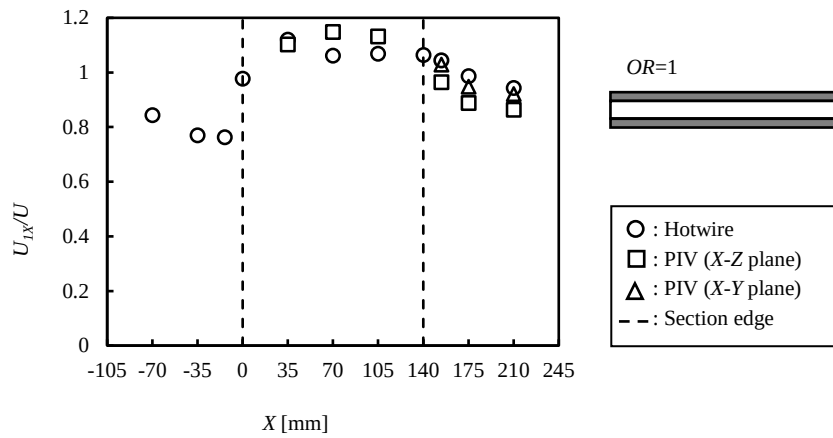
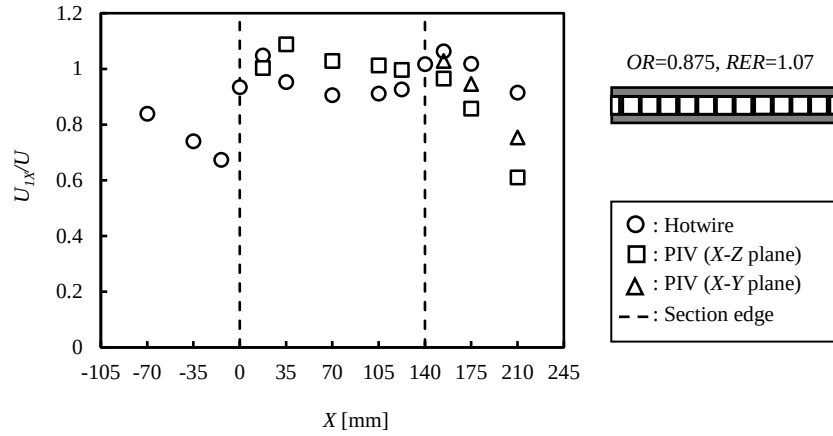


Fig. 22 (Continued)

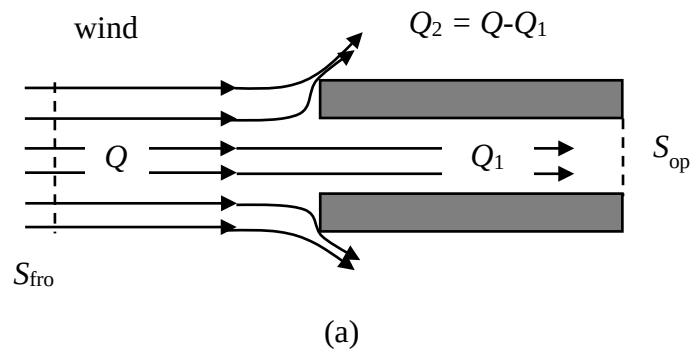


Fig. 23 (a) Side view (in span-wise direction) of the time-averaged flow rate Q through the total front-surface area S_{fro} of the model, the time-averaged flow rate Q_1 through the total-openings area S_{op} and the time-averaged flow rate Q_2 into the separated flow ($Q = Q_1 + Q_2$). (b) Sketch for S_{fro} and S_{op} (n is 24 for $RER = 1.07$; $S_1 = D_0^2 \times OR \times RER$).

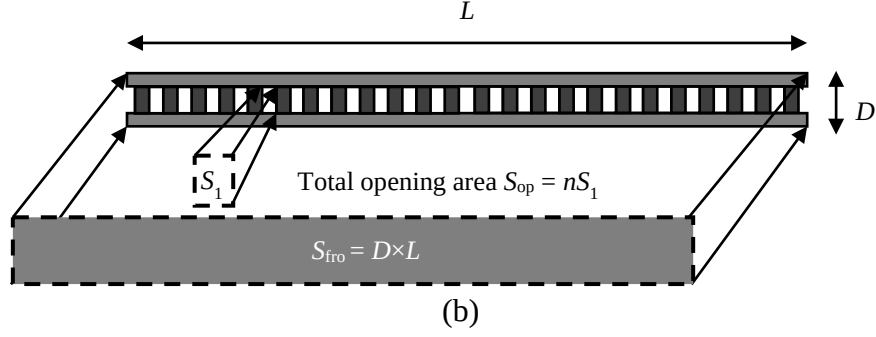


Fig. 23 Continued

Table 3 Time-averaged flow rate Q_1 through the total-openings area ($RER = 1.07$, $n = 24$, $U = 6$ m/s; $Q = 0.378$ m³/s)

OR	Total-openings area S_{op} (unit: m ²)	Flow rate Q_1 (unit: m ³ /s) ($Q_1 = S_{op} \times U$)	Flow rate Q_2 (unit: m ³ /s) ($Q_2 = Q - Q_1$)
0	0	0.000	0.378
0.25	3.277×10^{-4}	0.047	0.331
0.5	6.554×10^{-4}	0.094	0.284
0.75	9.831×10^{-4}	0.142	0.236
0.875	1.147×10^{-4}	0.165	0.213
1	1.311×10^{-4}	0.189	0.189

According to Fig. 21, owing to the discretely distributed openings, the time-averaged non-dimensional X -direction wind velocity U_{1X}/U varied along both the X - and Z - directions in the inner space and the wake. However, the flow field in the inner space was limited to a narrow space of a constant height of D_0 in Y direction, and the model was symmetrical to the horizontal centerline of the section. Therefore, it is assumed this flow field did not obviously contribute to the aerodynamic performance. However, according to past studies (Laneville and Yong, 1983; Koutmos et al., 2004; Huang et al., 2017), the outflow from the downstream openings disturbs the flow entrainment in the wake, affecting the flow field around the bluff body in the X - Y plane. As shown in Fig. 24, the contour map of the time-averaged non-dimensional X -direction wind velocity U_{1X}/U in the near wake in the X - Y plane of the closed section was different from that of the open section for $OR = 0.5$ and 0.75 . However, as shown in Fig. 24, the contour map of U_{1X}/U at $Y > 0$ mm was identical for the closed section and open section for $OR = 0.5$ and 0.75 . Therefore, even though the time-averaged flow field in the X - Y plane in the near wake varied along the Z -direction owing to the discretely distributed openings, the time-averaged flow field around the model in the X - Y plane was identical along the Z -direction.

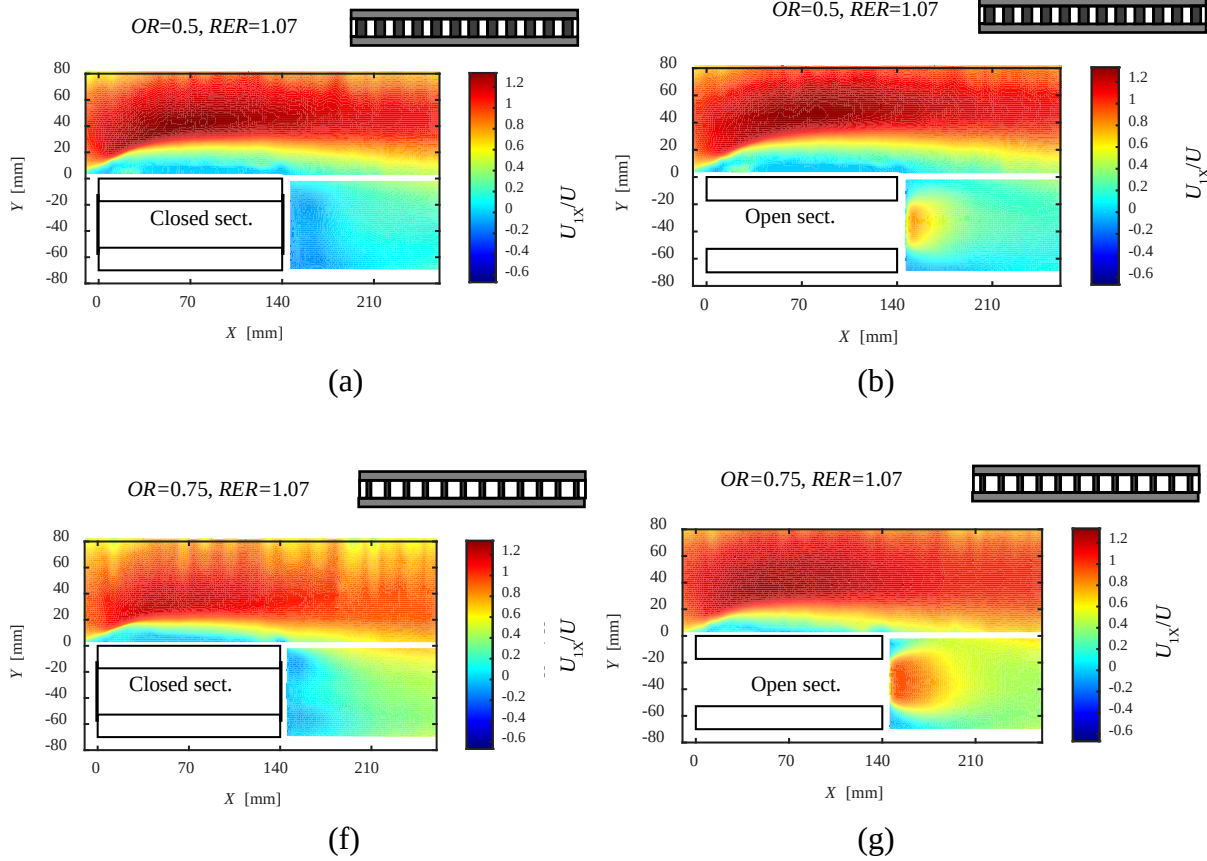


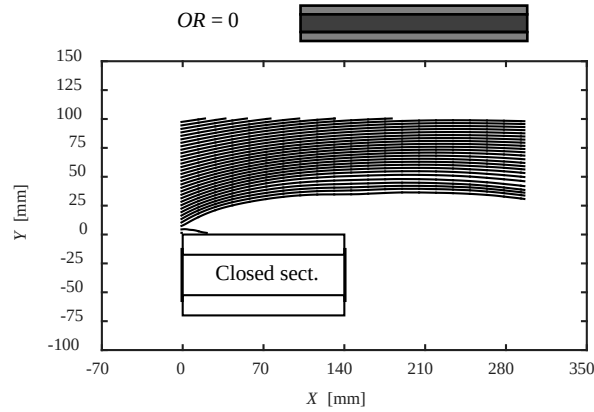
Fig. 24 Contour map of the time-averaged non-dimensional X -direction wind velocity (U_{1X}/U) of: (a) closed section of Case 3 ($OR = 0.5$, $RER = 1.07$); (b) open section of Case 3; (c) closed section of Case 4 ($OR = 0.75$, $RER = 1.07$); (d) open section of Case 4 ($U = 1.5\text{m/s}$, smooth flow).

4.3. Time-averaged flow field in X - Y plane

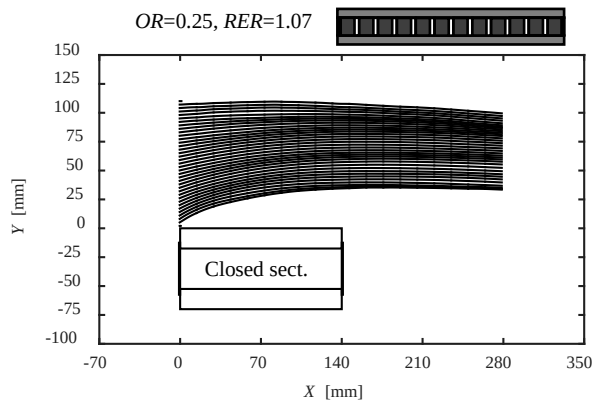
This subsection explains the stabilization against galloping owing to the side-surface openings, based on the relationship between the time-averaged flow field in the X - Y plane and the Opening-area Ratio (OR , Eq. (1)). First, the relationship between the time-averaged flow field and OR is described. Additionally, their relationship is qualitatively compared with the time-averaged flow field and side ratio to verify the assumption that increasing the OR resulted in the increase of the effective side ratio. Further, the effects of side-surface openings on the critical wind velocity of galloping and aerodynamic damping are discussed based on the time-averaged flow field in the X - Y plane.

4.3.1. Time-averaged streamline and Opening-area Ratio

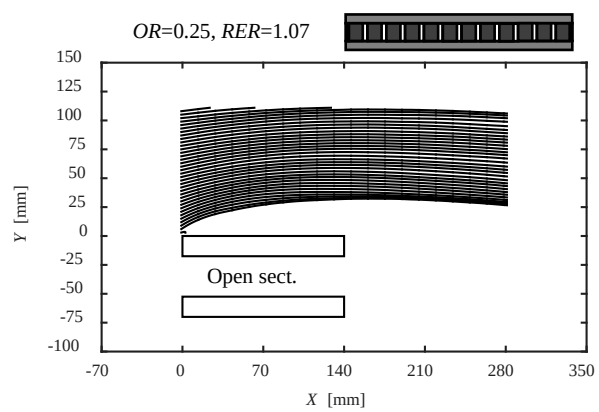
The time-averaged streamlines in the X - Y plane around the closed and open sections for different OR s are depicted in Fig. 25. The time-averaged streamline around the closed section and the open section were approximately the same except for a slight difference around the trailing edge for $OR = 0.75$ and 0.875 . This difference was probably caused by the interaction between the outflow



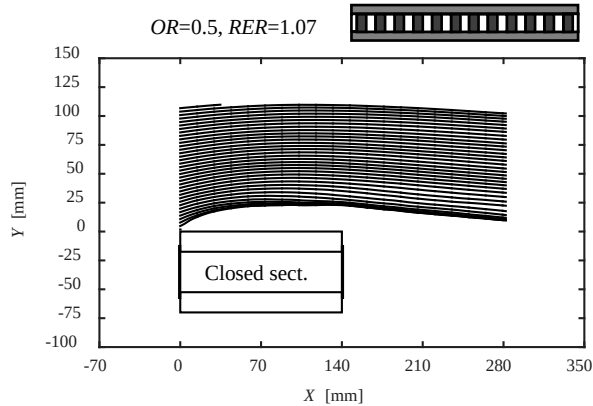
(a)



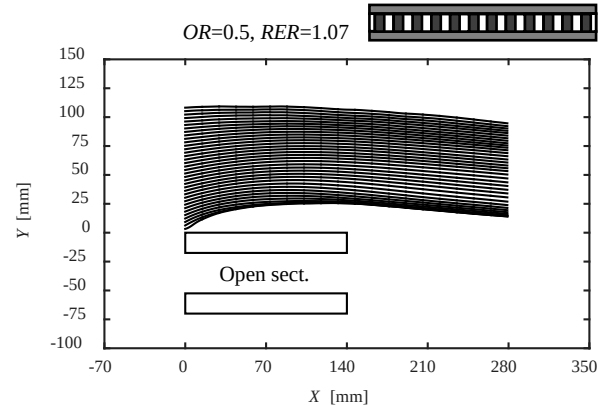
(b)



(c)

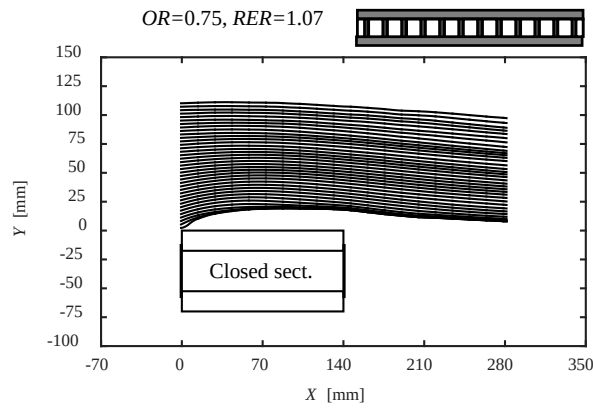


(d)

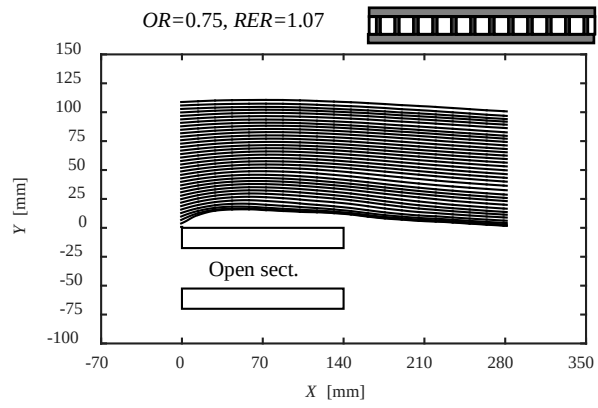


(e)

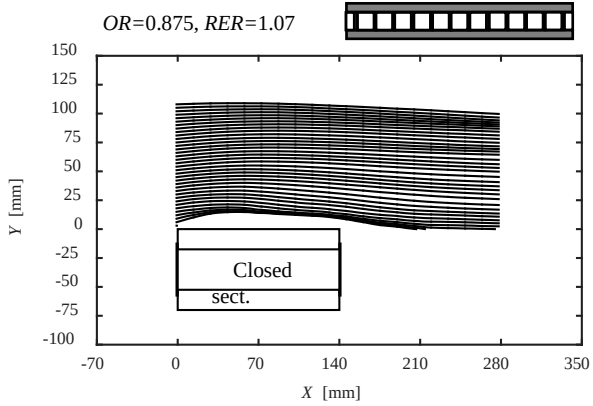
Fig. 25 Time-averaged streamline in X-Y plane around (a) section of Case 1 ($OR = 0$); (b) closed section of Case 2 ($OR = 0.25$, $RER = 1.07$); (c) open section of Case 2; (d) closed section of Case 3 ($OR = 0.50$, $RER = 1.07$); (e) open section of Case 3; (f) closed section of Case 4 ($OR = 0.75$, $RER = 1.07$); (g) open section of Case 4; (h) closed section of Case 5 ($OR = 0.875$, $RER = 1.07$); (i) open section of Case 5; (j) section of Case 10 ($OR = 1$) ($U = 1.5$ m/s, smooth flow).



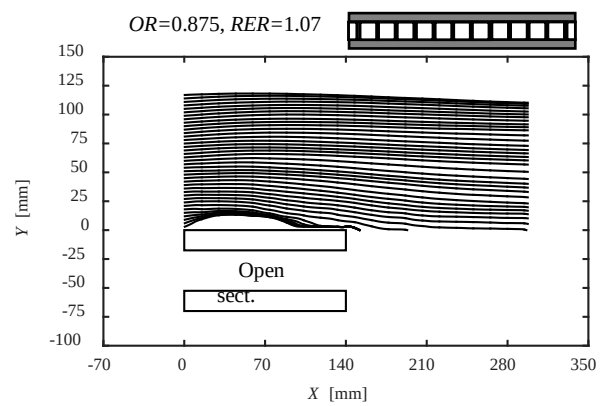
(f)



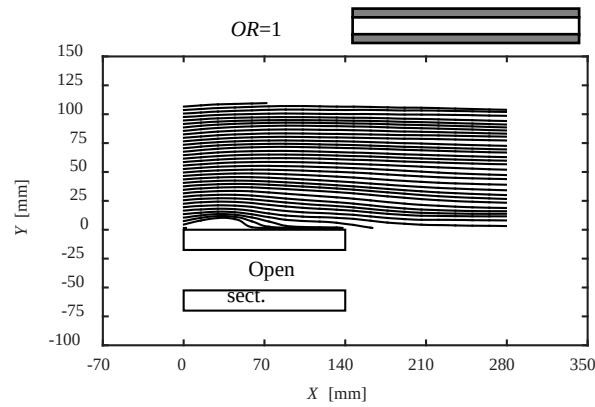
(g)



(h)



(i)



(j)

Fig. 25 Continued

from the downstream openings and the flow entrainment in the wake. Therefore, the time-averaged flow field in the X-Y plane was identical along the Z direction. Furthermore, the time-averaged shear layer gradually approached the side surface with the increase of OR , starting to reattach to the side surface for $OR = 0.875$. As the streamline is the contour line of the stream function, the

difference of which is the flow rate (White, 2011), the change in the location of the time-averaged separated shear layer must be caused by the change of the time-averaged flow rate. Specifically, owing to the increase of the time-averaged flow rate Q_1 through the total-openings area with OR , and the subsequent decrease of the time-averaged flow rate Q_2 from the front surface into the separated flow with OR (Table 3), the time-averaged separated shear layer gradually approached to the side surface. Additionally, Repeating Element-size Ratio (RER , Eq. (2)) in the current research is 1.07 and 2.14 to reflect the actual condition of the bridge (Wang et al., 2020). In this narrow range of RER , the change in the wake owing to the change in RER had limited effects on the flow field around the model in the X - Y plane. Thus, instead of RER , the flow field in the X - Y plane is dominated by the OR . Therefore, the OR played a dominant role in galloping.

According to past studies (Nakaguchi et al., 1968; Mizota and Okajima, 1981; Laneville and Yong, 1983; Nakagawa et al., 1999; Sohankar, 2008), the time-averaged separated shear layer around the rectangular cylinder gradually approached the side surface with the increase of B/D from 2 to 2.8, and with a further increase of B/D , the reattachment point gradually moved upstream. As that the time-averaged separated shear layer approached the side surface with the increase of OR from 0 to 0.875 and with the increase of B/D from 2 to 2.8, the effective side ratio of the rectangular cylinder with openings also increased. The flow pattern of the model for $OR = 1$ was the total reattachment type, confirming that the model of Case 10 had an effective side ratio larger than 2.8.

4.3.2. Effects of side-surface openings on galloping instability

The time-averaged separated shear layer gradually approached the side surface with the increase of Opening-area Ratio (OR , Eq. (1)), indicating an increasing interference between the separated shear layer and the model afterbody. According to past studies (Gerrard, 1966; Nakaguchi et al., 1968; Laneville and Yong, 1983; Bearman and Trueman, 1972), an increasing interference between the separated shear layer and the afterbody, which is caused by the increase of B/D from 2 to 2.8, induces the decrease in the longitudinal force coefficient (C_{Fx}), fluctuating transverse force coefficient (C_{Fy}'), and Strouhal number (St). Meanwhile, C_{Fxr} , C_{Fy}' , and St also decreased with the increase of OR . Furthermore, according to past studies (Parkinson and Wawzonek, 1981; Laneville and Parkinson, 1971; Laneville, 1973; Nakamura and Tomonari, 1977; Kwok and Melbourne, 1980; Nakamura et al., 1991 and 1994; Hirata, 1993), the promotion of the interference between the separated shear layer and the afterbody, which is accompanied by the time-averaged separated shear layer approaches to the side surface, can cause the increase in the critical wind velocity of galloping. Thus, the critical wind velocity of galloping increased with OR .

The transverse force coefficient (C_{Fy}) is associated with the time-averaged separated shear layer (Kwok and Melbourne, 1980; Hu et. al., 2016). By introducing the side-surface openings, the separated shear layer approached the model surface at $\alpha = 0^\circ$, resulting in the early reattachment of the downside shear layer to the side surface at the angle of attack α_{max} ($\alpha_{max} > 0$), where the absolute value of C_{Fy} ($C_{Fy} < 0$) reached the maximum. Thus, as that the separated shear layer gradually approached the side surface with the increase of OR from 0 to 0.875 at $\alpha = 0^\circ$, the angle of attack α_{max} decreased with OR as depicted in Fig. 6. Subsequently, the angle of attack α range, along the slope of the transverse force coefficient against angle of attack $dC_{Fy}/d\alpha < 0$ gradually

decreased with the increase of OR from 0 to 0.875. If the flow pattern is of reattachment type at $\alpha = 0^\circ$, at $\alpha > 0^\circ$ the reattachment point on the downside surface should move upstream, while on the upside surface it should move downstream, resulting in an upward transverse force. Therefore, for $OR = 1$, C_{Fy} continuously increased with α from 0° to 10° , and $dC_{Fy}/(d\alpha)$ kept positive at $-10^\circ < \alpha < 10^\circ$.

At high wind velocities, the linear unsteady aerodynamic damping was characterized by $dC_{Fy}/d\alpha$ (Fig. 9). According to Fig. 8 and Fig. 25, the increase of the $|-dC_{Fy}/d\alpha|_{\alpha=0^\circ}$ with the increase of OR from 0 to 0.75 was accompanied by the time-averaged separated shear layer approaching the side surface at $\alpha = 0^\circ$. Therefore, the pressure difference between the upside and downside surfaces at a small α ($\alpha > 0^\circ$) is directly proportional to the extent to which the time-averaged separated shear layer approaches the side surface at $\alpha = 0^\circ$. For $OR = 0.875$, when the time-averaged separated shear layer started to reattach to the side surface at $\alpha = 0^\circ$, it reattached further upstream to the downside surface at a small α ($\alpha > 0^\circ$), resulting in a decrease in the absolute value of C_{Fy} . Subsequently, $|-dC_{Fy}/d\alpha|_{\alpha=0^\circ}$ started to decrease as the OR increased from 0.75 to 0.875.

Conclusion

The objective of this research is to study the mechanism related to stabilization against galloping owing to the side-surface openings. A box girder was simplified as a rectangular cylinder with a side ratio B/D of 2, where B is the girder width and D is the girder depth. A series of wind tunnel tests, i.e., aerodynamic force tests, vertical one-degree-of-freedom (1DOF) free vibration tests, vertical 1DOF forced vibration tests, wind velocity measurement, and PIV tests were carried out for the rectangular cylinder with discretely distributed side-surface openings. The opening size was defined by two parameters: Opening-area Ratio (OR), the ratio between the total opening area and half the front surface area of the model; and Repeating Element-size Ratio (RER), the ratio between the length of a repeating element (defined as a group of a plate and an opening) and half the model depth. The following conclusions were summarized:

(1) The critical wind velocity of the motion-induced vortex vibration was not affected by the openings, indicating that the vortex-convection velocity from the leading edge along the side surface was not affected by the side-surface openings. RER had no effects on the amplitude of the motion-induced vortex vibration, while the amplitude decreased with the increase of OR .

(2) The galloping response was slightly affected by RER for $OR = 0.75$, but unaffected for $OR = 0.25$. However, with the increase of OR , the amplitude of galloping vibration significantly decreased. Furthermore, as the reduced critical wind velocity of galloping is controlled by the reciprocal of Strouhal number, the decrease in the Strouhal number owing to the increase of OR resulted in the increase of the critical wind velocity of galloping.

(3) The transverse force coefficients (C_{Fy}) and slope of the transverse force coefficient against angle of attack ($dC_{Fy}/d\alpha$) were not affected by RER , but significantly affected by OR . More specifically, the angle of attack α range, along $dC_{Fy}/d\alpha < 0$ gradually decreased with the increase of OR . Therefore, the side-surface openings reduced the angle of attack α range, where galloping may occur. At high reduced wind velocities, the aerodynamic damping (H_1^*) identified from the forced vibration tests was asymptotic to the curve of H_1^* predicted by the linear quasi-steady theory, which is characterized by $-dC_{Fy}/d\alpha$. This indicates the validation of the quasi-steady theory for the

rectangular cylinder with side-surface openings. Furthermore, the aerodynamic damping characterized by H_1^* and $-dC_{Fy}/d\alpha$ increased with the growth of OR from 0 to 0.75, achieving the maximum at $OR = 0.75$, as the separated shear layer gradually approached the trailing edge of the model with OR . With further increase of OR , the aerodynamic damping started to decrease at $OR = 0.875$, because the separated shear layer started to reattach on the side surface. For $OR = 1$, the aerodynamic damping indicated negative value owing to the total reattachment of the separated shear layer on the side surface.

(4) Even though the openings discretely distributed along the span-wise direction, the time-averaged flow field in the vertical plane around the rectangular cylinder was almost the same at the opening center and the plate center (gap between the plates is the opening). Furthermore, because the flow rate through the total openings increased significantly with the increase in the area of total openings, the time-averaged separated shear layer gradually approached the side surface with the increase of OR . Therefore, rather than RER , the OR played an important role in the aerodynamic performance of the rectangular cylinder with side-surface openings.

(5) With the increase of OR , the side-surface openings promoted the separated shear layer to approach the side surface and effectively increased the side ratio. The effective increase of side ratio owing to the increase of OR was also verified by Strouhal number, longitudinal force coefficient, and fluctuating transverse force coefficient. It changed with OR in a similar manner as the change of those coefficients with the side ratio. The approaching of the separated shear layer to the side surface indicated an increasing interference between the separated shear layer and side surface, resulting in the increase of the critical wind velocity of galloping with OR .

Even though at high wind velocities, the relationship between the aerodynamic damping and opening size was complicated, increasing the OR effectively increased the side ratio by promoting the separated shear layer to reattach on the side surface, resulting in better galloping stability. Therefore, introducing the openings to the side surface is a promising method to manipulate the flow field around the rectangular cylinder-like bluff bodies to benefit the aerodynamic performance. The effects of the Reynolds number on the aerodynamic performance of the rectangular cylinder with side-surface openings, and the effects of the outflow from downstream openings on the interaction between the unsteady flow and the afterbody remain to be explored.

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