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Aerodynamic Performance of Box Girder with Side Openings

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Abstract

Butterfly web girder has been recently introduced, which is a kind of box girder with openings on the side wall. The effects of these side wall openings on the aerodynamic performance of box girder have been investigated by using two butterfly web girder section models with side ratio 3.24. The research consists of two parts. In part one, the aerostatic force tests and vertical free vibration tests have been carried out for the single girder. In part two, the vertical free vibration tests have been carried out for the parallel girders situation. For the parallel girders situation, the displacement of the spring supported girder has been measured with another stationary girder at the upstream or downstream. In summary, the side openings has been confirmed to make the box girder with side openings a better aerodynamic performance than the same shape box girder without side openings for both single girder situation and parallel girders situation.

Introduction

The flexible structures like cable-stayed bridge and suspension bridge have been designed and constructed due to the requirement to expand the span to overcome complex terrain. Consequently, aerodynamic performance of such flexible structures has become an object of considerable attention.

The aerodynamic phenomenon that concerns the engineers and researchers consists of vortex induced vibration, galloping and etc. Galloping is a divergent vibration that has close relationship with Karman vortex shedding. Meanwhile based on the formation position of the vortices, the vortex induced vibration is divided into two types: motion-induced vortex vibration and Karman vortex vibration. The former one is caused by the coagulation of the vortices forming from leading and trailing edge, while the latter one is caused by Karman vortex.1)

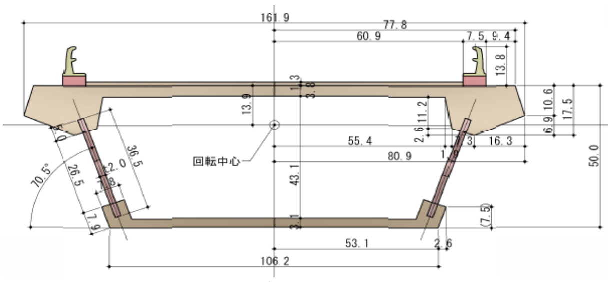
As an important part of the bridge, the bridge decks for those flexible bridges generally fall into two classification: open latticed truss work and a closed box-like girder. Recently, the butterfly web girder, a type of box girder with side openings, has been introduced to replace the traditional box girder, due to its advantage to increase the stiffness of main girder without the growth of its weight. According to Kasuga2), a girder of this type with side ratio 5 has been confirmed to have a better wind-resistance performance, i.e., heaving and torsional vortex induced vibrations are suppressed and torsional flutter under attack angle -3 deg., 0 deg. and +3 deg. are limited to a higher wind velocity range. However, more researches related to the aerodynamic performance of box girder with side openings with different side ratio is under requirement.

Besides, parallel girders are sometime constructed due to several reasons. When the girders are in parallel, the aerodynamic performance of the girders would be more complicated due to the interference effects between two girders. Okajima3) has investigated the aerodynamic performance of two rectangular cylinders with a different ratio of side length to height from 1 to 6 separated by a gap-to-diameter ratio from 1 to 5, along a common center-line in a direction of flow. By elastically supporting a cylinder and fixing the other one, the aerodynamic performance of an upstream and a downstream girder is separately examined. Takeuchi4) and etc. further includes the investigation on the aerodynamic performance of two rectangular cylinders both elastically supported by coil-springs with different ratio of side length to height. The effects of the gap-to-diameter ratio is also discussed. However, the investigation on the aerodynamic performance of box girder with side openings in parallel girders situation has never been carried out.

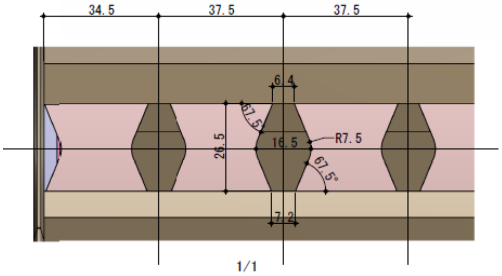
This research mainly focuses on the openings' effects on aerodynamic performance of box girder in single girder and parallel girders situation by using two same butterfly web girders with side ratio 3.24 in wind tunnel tests.

Experimental Set-up

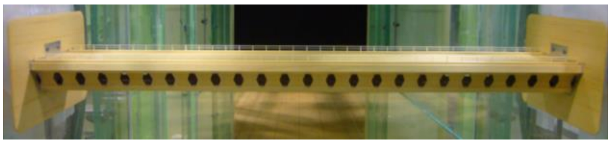
The experiments were carried out in the room-circuit Eiffel type wind tunnel located in Kyoto University with the working section of 1.8 m height by 1.0 m width. All the experiments were carried out in uniform flow.



(a) Section of the girder (unit: mm)



(b) Detail of the side openings (unit: mm)
Fig 1. Model for the experiment



(a) Open case (box girder with side openings)

(b) Close case (box girder without side openings)

Fig 2. Model cases for the experiment

Two butterfly web girder sectional models with a geometrical scale 1:80 were applied. The width and height of the model are 161.9 mm and 50 mm respectively. (Fig 1 (a)) The details of the openings' size on the side wall of the girder is shown in Fig 1 (b). For the convenience of discussion, the open case is defined as box girder with side openings shown as Fig. 2 (a), while the close case is defined as box girder without side openings shown as Fig 2 (b).

For the static experiment, the model was rigidly connected to the load cell and then three aerostatic forces were measured through the load cell.

For the free vibration tests, in order to simplify the problem, only one vertical degree freedom experiments were carried out for both single girder tests and parallel girders tests. As a fundamental research, the mass and damping of the system were set small and almost same for the single girder and parallel girders tests. Furthermore, the cases of the parallel girders tests were designed as that the upstream girder was elastically supported and the downstream girder was rigidly connected to the wall of the wind tunnel and vice versa. This is different from both two girders elastically supporting arrangement in the past research[4)] for the convenience of discussion. The distance between the two girders was defined as 2*B* (*B*=width of the girder), which distance is confirmed to have obvious interference effects for parallel girders in the past research[3)]. The vibration model was elastically supported by 8 coil springs. By using piano wire and torsion constraining equipment, the model could be guaranteed to vibrate only in vertical direction. The stationary model was rigidly connected to the wall of the wind tunnel. The displacement of the girder was measured through the laser displacement sensor.

For the convenience of discussion, the reduced wind velocity and reduced amplitude are defined as following:

$$\bar{U} = \frac{U}{fD} \tag{1}$$

$$\bar{A} = \frac{2\eta}{D} \tag{2}$$

Where, $\bar{U}$ is the reduced wind velocity, U is the mean wind velocity, f is the vibration frequency, D is the height of the girder, $\bar{A}$ is reduced amplitude, η is the vibration amplitude.

Aerostatic Force Coefficient

The three aerostatic force coefficients (lift, drag and moment), Strouhal number and fluctuating lift force coefficient could be defined as following:

$$C_L = \frac{F_L}{\frac{1}{2}\rho U^2 BL} \tag{3}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 DL} \tag{4}$$

$$C_M = \frac{M}{\frac{1}{2}\rho U^2 B^2 L} \tag{5}$$

$$S_{tr} = \frac{f_{st} D}{U} \tag{6}$$

$$C_L' = \frac{F_L(t)_{std}}{\frac{1}{2}\rho U^2 BL} \tag{7}$$

Where, C_L: lift force coefficient; C_D: drag force coefficient; C_M: moment coefficient; F_L: mean value of lift force; F_D: mean value of drag force; F_M: mean value of pitching moment; *Str*: Strouhal number; C_L': variation of lift coefficient; $F_L(t)$: lift force time series; $F_L(t)_{std}$: standard deviation of lift force time series; *B*: width of the girder; *D*: height of the girder; *L*: length of the girder along the span; ρ: air density; *U*: wind velocity; f_{st}: the frequency of the Karman vortex shedding.

Experiment Results for Single Girder

Aerostatic Performance and Karman Vortex Shedding

The lift, drag and moment coefficient are presented in structural axis in Fig. 3, Fig. 4 and Fig. 5 respectively. Based on the Fig. 3, Fig.4 and Fig. 5, the lift, drag and moment coefficients' absolute magnitudes of the open case are smaller than those of the close case at each attack angle. This indicates that the side openings of the box girder would lead to smaller aerostatic lift, drag and moment.

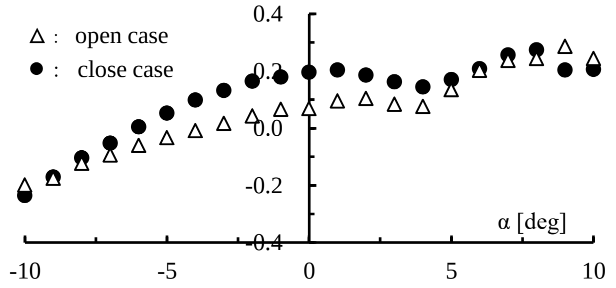


Fig 3. Lift force coefficient (Wind velocity: 6 m/s)

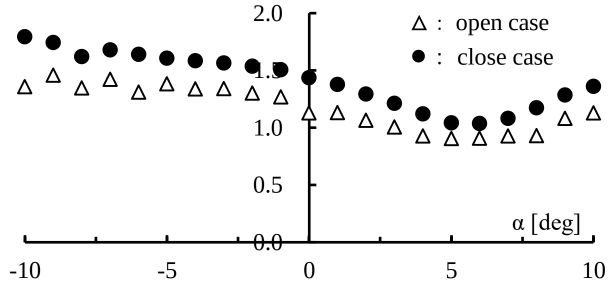


Fig 4. Drag force coefficient (Wind velocity: 6 m/s)

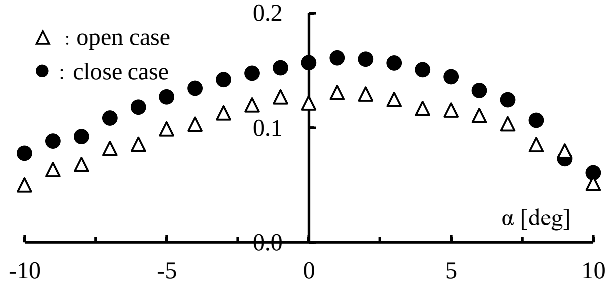


Fig 5. Moment coefficient (Wind velocity: 6 m/s)

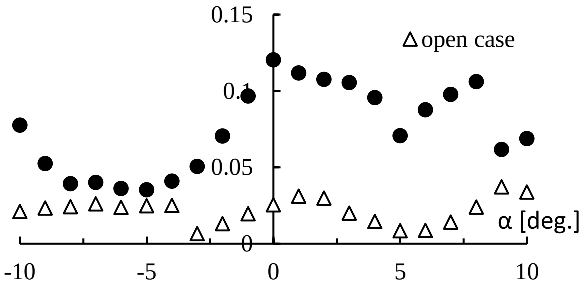


Fig 6. Variation of lift coefficient (Wind velocity: 6 m/s)

Opening condition	Attack angle	Strouhal Number
Close case	0 deg.	0.164
Open case	0 deg.	0.166

Table 1. Strouhal number of each case

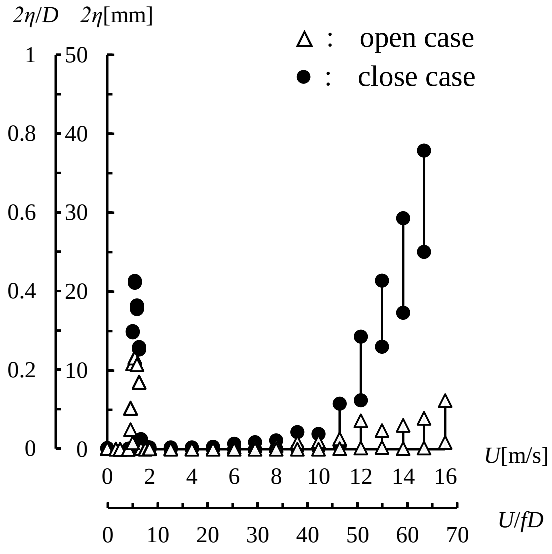


Fig 7. Vertical aerodynamic response of the girder

According to Fig. 6, the variation of lift coefficient for the open case is obviously smaller than that for the close case at each attack angle. However, based on the Table 1, the Strouhal numbers of close case and open case are generally same at 0 deg. attack angle. This could be explained as that the Karman vortex shedding of the girder is suppressed by the openings on the side wall, but the frequency of the vortex shedding is not affected by the openings. Besides, due to that the drag force of the open case is smaller than that of the close case, the time average flow around and in the wake of the open case girder shows smaller curvature than that of the close case. Thus, it also could prove that the Karman vortex shedding of the open case girder is reduced to a low intensity.

Aerodynamic Performance

The one degree vertical free vibration tests were carried out for both close and open case under attack angle -3 deg., 0 deg. and +3 deg. As galloping occurred for the close case at +3 deg., the one degree vertical responses of close case and open case under attack angle +3 deg. summarized in Fig. 7 are discussed. For the close case, the motion-induced vortex vibration with a largest reduced amplitude 0.42 occurs at about reduced wind velocity range 4~5 and galloping occurs at about reduced wind velocity 50. While for the open case, the motion-induced vortex vibration's largest reduced amplitude turns to be 0.24 at the same reduced wind velocity range 4~5 and the galloping does not occur. This indicates that the openings on the side wall could diminish the motion-induced vortex vibration and lead to galloping stability.

Besides, according to Fig. 3, lift coefficient for the close case shows negative gradient at a relatively larger attack angle range (1 deg. to 4 deg.) than that for the open case (2 deg. to 4 deg.). This also could prove that the side opening of the girder would lead to galloping stability at larger attack angle range.

Experiment Results for Parallel Girders

Aerodynamic Performance of the Upstream Girder with a Stationary Downstream Girder

The upstream girder free vibration tests were carried out under attack angle 0 deg. and +3 deg. with a stationary girder at the downstream side. As the galloping only occurred for the upstream open case and close case girder under attack angle +3 deg., the vertical aerodynamic performance of upstream girder with a stationary downstream girder under attack angle +3 deg. summarized in Fig. 8 are discussed.

According to Fig. 8, by comparing the 'close-close' case and 'open-close' case, the motion-induced vortex vibration with a largest reduced amplitude about 0.44 at reduced wind velocity range 4~5 and the galloping with a critical reduced wind velocity about 25 occur for the upstream close case, while the largest reduced amplitude of the motion-induced vortex vibration turns to be 0.28 and the galloping critical reduced wind velocity turns to be about 40 for the upstream open case. Furthermore, by comparing the 'open-open' case and 'close-open' case, the motion-induced vortex vibration with a largest reduced amplitude about 0.44 at reduced wind velocity range 4~5 and the galloping with a critical reduced wind velocity about 25 occur for the upstream close case, while the largest reduced amplitude of the motion-induced vortex vibration turns to be 0.28 and the galloping critical reduced wind velocity turns to be about 50 for the upstream open case. This indicates that the openings on the side wall of the upstream girder could limit the motion-induced vortex vibration of upstream girder to a smaller amplitude and lead to better galloping stability of the upstream girder regardless of the downstream girder's type.

Aerodynamic Performance of the Downstream Girder with a Stationary Upstream Girder

The downstream girder free vibration tests were carried out under attack angle 0 deg. and +3 deg. with a stationary girder at the upstream side. The vertical aerodynamic performance of downstream girder with a stationary upstream girder under attack angle +3 deg. summarized in Fig. 9 are discussed.

As shown in Fig. 9, the motion-induced vortex vibration and galloping are diminished and another wind velocity restricted vibration occurs at reduced wind velocity range 7-10 for the downstream girder. By comparing the 'close-close' case and 'close-open' case, the largest reduced amplitude for this vibration of close case downstream girder is about 0.7 while for the open case downstream girder, the largest reduced amplitude for this vibration is about 0.54. The same result could be concluded by comparing the 'open-close' case and 'open-open' case. Thus, this wind velocity restricted vibration is diminished by the openings on the side wall of the downstream girder irrespective of upstream girder's type.

Besides, this wind velocity restricted vibration may be triggered by the vortex shedding from stationary upstream girder. As the amplitude of this vibration is decided by the downstream girder's type, this vibration may turn into motion-induced vortex vibration from 'force vibration' due to the vortex shedding from the upstream girder.

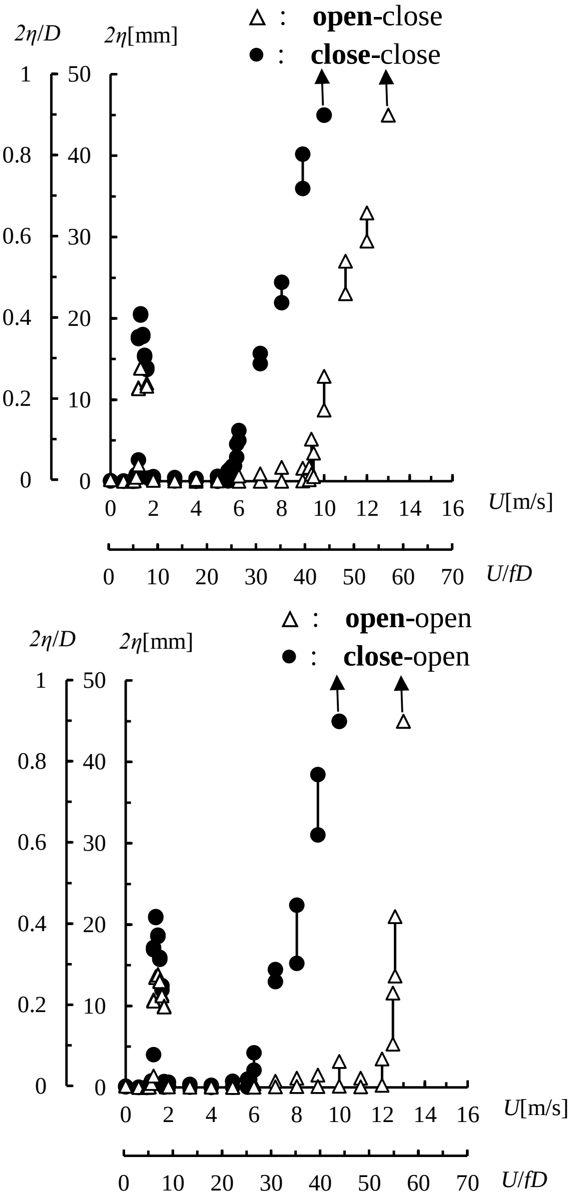


Fig 8. Vertical aerodynamic responses of the upstream girder

(**close**-close, **open**-close, **close**-open, **open**-open: the left bold word indicates the spring supported upstream girder type, and the right word indicates the stationary downstream girder type.)

Conclusion

For the single girder, the side openings can reduce the motion-induced vortex vibration. Moreover, the Karman vortex shedding of box girder can also be suppressed by the side openings. Furthermore, the box girder with side openings shows better galloping stability than the box girder without side openings. For the parallel girders situation, regardless of the stationary downstream girder type, the side openings of the spring supported upstream box girder can diminish its vertical motion induced vortex vibration. Meanwhile, the spring supported upstream box girder with side openings shows better galloping stability than the girder without side openings irrespective of the downstream girder's type. In terms of the spring supported downstream girder, the wind velocity restricted vibration triggered by the wake flow of the upstream girder is limited to a relatively smaller amplitude of the box girder with side openings than that of the box girder without side openings.

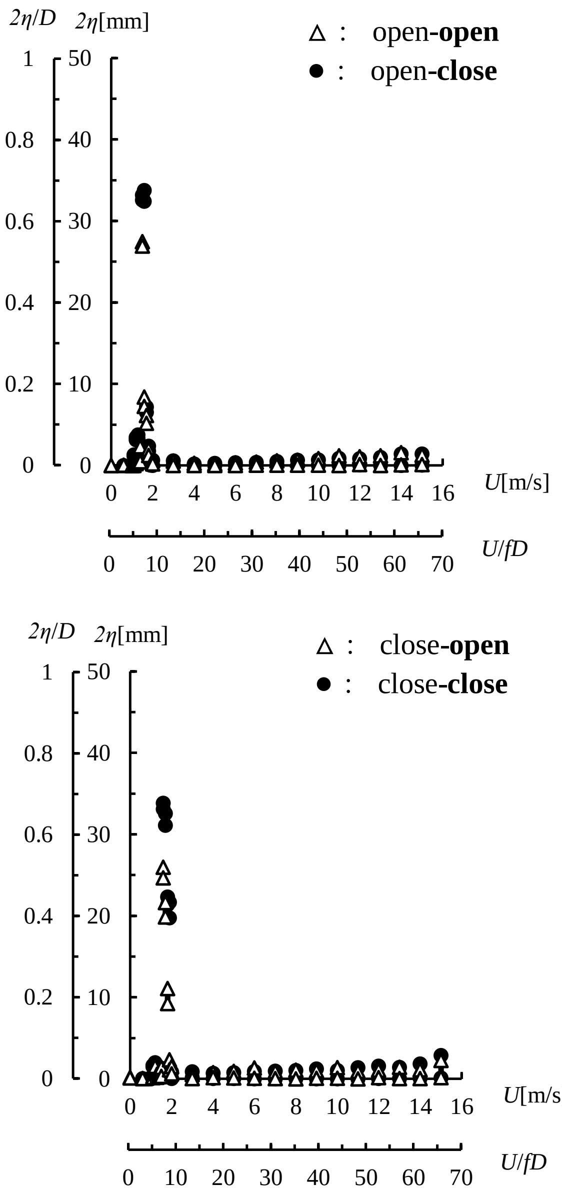


Fig 9. Vertical aerodynamic responses of the downstream girder

(close-**close**, open-**close**, close-**open**, open-**open**: the left word indicates the stationary upstream girder type, and the right bold word indicates the spring supported downstream girder type.)

Reference

[1] Shiraishi, N., & Matsumoto, M. (1983). On classification of vortex-induced oscillation and its application for bridge structures. Journal of Wind Engineering and Industrial Aerodynamics, 14(1-3), 419-430.

[2] Kasuga, A. (2015, June). Multi-span extradosed bridges. In Multi-Span Large Bridges: International Conference on Multi-Span Large Bridges, 1-3 July 2015, Porto, Portugal (p. 67). CRC Press.

[3] Atsushi OKAJIMA, Akihito ABE, Takahiro KIWATA (1990). Aeroelastic instability of two rectangular cylinders in a tandem arrangement. Journal of Structural Engineering, 36, 859-864. (in Japanese)

[4] Takeuchi, T., & Matsumoto, M. (1992). Aerodynamic response characteristics of rectangular cylinders in tandem arrangement. Journal of Wind Engineering and Industrial Aerodynamics, 41(1-3), 565-575.