

Effects of handrail details on vortex-induced vibration for a box-girder bridge

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Abstract

Evaluating the aerodynamic instability of a bridge girder fitted with bridge attachments such as handrails is critical for the wind-resistance design of a long-span bridge. However, the effects of the detailed configuration of handrails on the aerodynamic performance of a bridge girder have not been sufficiently studied. In this study, the heaving vortex-induced vibration (VIV) of a box-girder bridge was evaluated for non-grid and grid-like handrail cases by free vibration wind tunnel tests. The VIV amplitude decreased with the increase in the porosity ratio of handrails. However, the aerodynamic behaviors of the grid-like handrails are different from the non-grid ones. For the non-grid handrails, VIV amplitude was reduced with the increase of the number and the side ratio of middle horizontal bars. For the grid-like handrails, increasing the number of vertical bars have adverse effects on VIV whereas the number of horizontal bars had no influence on VIV. This study also provides new ideas on the optimization of handrail configuration with good aerodynamic properties and the simplification of handrail models for evaluating the aerodynamic properties of a bridge girder in the design process.

Keywords: vortex-induced vibration, handrail details, wind tunnel tests

Introduction

Long-span bridge structures tend to be light, slender, and low damping, which raises the risk of excitation into considerable motions by aerodynamic forces. Vortex-induced vibration (VIV) does not cause structural destruction like flutter, but it may influence traffic safety or cause fatigue stress cycles because it usually occurs under a specific vibration frequency and low wind velocity. VIV is sensitive to the aerodynamic configuration of a bridge girder as well as its attachments such as handrails. Therefore, it is meaningful to conduct a study to evaluate the effect of handrail details on VIV performance, and based on the discussion, determine the handrail components or parameters that may have significant effects on VIV. Moreover, it can also provide an experimental reference for optimizing the computational model to evaluate the aerodynamic properties of a bridge girder with handrails.

VIV is a common form of bridge aerodynamic instability, and a nonlinear dynamical response caused by “an in-phase exciting force produced by the vortices and maintained steadily” (Komatsu and Kobayashi, 1980). It is influenced by structural damping, wind velocity, wind attack angle, and the configuration of the bridge deck and attachments. Because bridge attachments such as windbreaks and handrails have a significant influence on VIV, a number of studies have been conducted on bridge deck details. Bruno and Mancini (2002) proved that the aerodynamic performance of a bridge girder section is sensitive to the details of the bridge deck, such as the handrails of the Normandy and Great Belt Bridges, which dramatically affected the pressure distribution on the bridge surfaces. Mannini et al. (2016) proved that the details of a bridge segment, such as the degree of the deck’s lower edges played a key role in the aerodynamic performance of the profile through unsteady RANS simulations. Based on the particle image velocimetry (PIV) technique, Avila-Sanchez et al. (2016) clarified that a windbreak caused an increase in the mean wind velocity and turbulence intensity near the leading edge of a bridge girder, but an additionally installed windbreak on the trailing edge restrained the separation bubble to the bridge deck. Laima et al. (2018) proposed that other than handrails, the maintenance rails under a bridge girder also generated a large flow separation at the leading edges, which resulted in large-scale vortices.

The aerodynamic performance of a bridge deck is sensitive to the bridge details. Therefore, aerodynamic

countermeasures were proposed by adjusting the bridge attachments or optimizing the aerodynamic configuration of a bridge deck. Larsen and Wall (2012) proposed an approach of diminishing vortex shedding by adjusting the angle between the horizontal bottom plate and inclined side web. To mitigate the VIV response of the Vila-Real Bridge in the north of Portugal, Vaz et al. (2016) adopted an elliptical contour to the border beams and a rounding corner at the base of the box girder to guide the flow towards the handrails and reduce the size of the recirculation zones. Ge et al. (2011) studied the VIV response of the Xihoumen Bridge and adopted adjustable wind barriers and guide vanes to decrease the VIV response. Li et al. (2018) pointed out that bridge attachments, such as wind fairings, guide vanes, and handrails influence the VIV performance of a bridge girder, and then verified the suppression effects of the proposed optimal countermeasures. Hu et al. (2019) studied the mechanism of using spoilers and guide vanes on inclined webs and corners to suppress VIV.

Because the handrails and wind barriers are the main bridge attachments that have a considerable influence on the VIV response, numerous studies related to the effect of the handrail shape and porosity ratio have been conducted. Nagao et al. (1997) proved that the VIV amplitude was remarkably influenced by the size and position of the top horizontal bar of the handrail. Matsumoto et al. (1993) verified that the maximum VIV amplitude changed with the change in the porosity ratio of the handrail. Liu et al. (2017) explained that an increase in the handrail porosity ratio decreased the wind-blockage area, which shrank the wake zone and decreased the value of drag coefficients. Based on flow visualization tests, Wu et al. (2017) proved that increasing the porosity ratio of handrails is effective for suppressing vertical and torsional VIVs. Kozmar et al. (2012, 2014) proved that wind barriers can reduce the wind velocity on a bridge girder, and increasing the barrier porosity decreases vorticity. Buljac (2017, 2020) verified that the wind barriers strongly influence the aerodynamic force and decrease the torsional flutter stability of bridge-deck sections. However, previous studies mainly paid attention to the effects of the porosity ratio and top bar on VIV and the influence of wind barriers on aerodynamic force and flutter. A deep understanding and discussion on the effects of handrail details such as the form and shape of handrail middle bars on VIV are still lacking. Therefore, further studies should be conducted to evaluate the effect of handrail details on the aerodynamic properties of a bridge girder, especially the role of handrail middle bars on vortex-induced instability.

Numerical simulation is often used to evaluate the effect of small attachments on the aerodynamic performance of a bridge-deck section. Noguchi et al. (2020) successfully calculated the VIV of a single-box girder with protuberances using CFD based on the forced-oscillation method. Sarwar et al. (2008) evaluated the aerodynamic characteristics of a box girder bridge section with bridge attachments by 3D CFD using the LES turbulence model. In their simulation, they reproduced some details of the handrails and omitted the vertical bars; however, it still requires a fine-mesh generation and a high-cost calculation. Sarwar and Ishihara (2010) then simplified the handrail shape using a top bar and footstone when studying the effect of aerodynamic countermeasures on VIV. In this sense, investigating the effect of handrail details on VIV can also provide some new thoughts on modeling handrails in experiments and numerical simulation.

In this study, spring-supported free-vibration wind tunnel tests under the heaving one-degree-of-freedom (1DOF) condition were conducted to evaluate the effect of the handrail configuration on the VIV response of two groups of handrails according to their classification in grid size and aerodynamic behaviors. On the one hand, various types of non-grid handrails with different detailed configurations were prepared to study their effects on VIV. The influence of the handrail details, especially that of the handrail middle bars, was evaluated. On the other hand, grid-like handrails which are more similar to a wind barrier structure were employed to further study the mechanism of handrail middle bars on VIV. Finally, based on the experimental results, the optimization of handrail configuration with good aerodynamic performance and the simplified method to evaluate the VIV response of a bridge girder equipped with handrails were discussed.

Experimental setup and models

Experimental setting

Wind tunnel tests were conducted using the room-circuit Eiffel-type wind tunnel located at Kyoto University. The measurement section of the wind tunnel has a height of 1.8 m and a width of 1.0 m. The section model was suspended by eight coil springs, and the motions in the torsional and swaying directions were fixed to obtain the vertical 1DOF condition. All tests were conducted under smooth flow conditions, where the turbulence intensity was lower than 0.3% at a wind velocity of 10 m/s. The vertical displacement was detected using four laser

displacement meters (Keyence, IL-300) and the VIV amplitude was read by a thermal strip chart recorder (Graphtec, WR5020-8).

Fig. 1 shows the section model used for the wind tunnel tests. The aerodynamic performance of this section without handrails was evaluated in previous studies (Šarkić et al., 2012; Nieto et al., 2015; Ito and Graham, 2016, 2017). Noguchi et al. (2020) mounted protuberances on this hexagonal section to excite VIV in wind tunnel tests and then simulated the VIV performance of the section by CFD. A large amplitude VIV was also observed for the section model with handrails shown in Fig. 1; therefore, this section was employed in this study. The height (D), width (B), and length (L) of the section model were 50, 275 ($B/D = 5.5$), and 890 mm, respectively, and the height of the handrail model was 10.8 mm. The scale ratio of the model was 1/100.

Schewe and Larsen (1998) studied the Reynolds number effect of a bluff bridge deck on the topological structure of the wake flow, Strouhal number and drag coefficient. The natural frequency of this system was set to 6.39 Hz to obtain a Reynolds number that was as large as possible ($Re = UD/\nu \approx 11,000$ at the peak amplitude, where U is the wind speed and ν is the kinematic viscosity). The Subcommittee on Similarity of Wind Tunnel Experiments (1994) indicated that when $Re > 1.0 \times 10^4$, the aerodynamic properties of such a bridge section with a side ratio $B/D=5.5$ (fitted with handrails) were less sensitive to the Reynolds number, and the maximum VIV amplitude of the bridge girder fluctuated within a 20% range as the Reynolds number increased. The errors of the VIV amplitude are considered to be within acceptable limits in the experiments.

The equivalent mass of the system was 3.54 kg/m. The logarithmic decrement in structural damping was $\delta = 0.0173$ at $\eta = 2.0$ mm ($\eta/D = 0.04$, η is the half-amplitude of the response), and the Scruton number ($S_c = 2m\delta/(\rho B^2)$) was 1.4, which is close to the conditions of an actual bridge. In each case, the mass-damping parameter S_c was kept nearly constant. Under this condition, the VIV amplitude is quite large, which makes it much easier to observe and compare between experiments. All cases were conducted under a wind attack angle of 0° . The experimental setup and details of the model are shown in Fig. 2.

Handrail cases and groups

Nagao et al. (1997) studied the effects of the height and thickness of the top horizontal bar on the VIV of bridge girders. Using flow visualizations tests, they proved that the top horizontal bar amplified the VIV

responses because it led to a secondary separation and enhanced the flow separation induced by the base of the handrails (the curbstone). However, the effects of handrail details such as the middle bars (the horizontal and vertical bars between the top bar and base) on the aerodynamic performance of bridge girders and their mechanisms have not been sufficiently studied. Therefore, to discuss the effect of handrail details on the VIV response in this study, the top horizontal bar was kept unchanged, whereas the shape and position of the middle bars were changed.

In this study, two groups of handrail models were designed and named Groups A and B. The standard for classifying the two groups is whether the handrail is a uniform grid-like structure because the aerodynamic properties for these two groups of handrails are different. Group A is a non-grid handrail group in which the handrails have relatively coarse members with different detailed configurations that may cause obvious flow separations and influence VIV response; Group B is a grid-like handrail group in which the handrails have relatively dense members with different porosity ratios or grid numbers, and they are similar to a porous wind-barrier structure. The variation in wind pressure is the dominant factor that may influence VIV.

Fig. 3 shows the standard cases of the two groups, Cases A-0 and B-0. Case B-0 has the same porosity ratio as Case A-0, but the number of vertical bars in Case B-0 is five times that of Case A-0, and the number of middle horizontal bars is four times. Therefore, to keep the same porosity ratio, the thicknesses of the vertical and horizontal bars in Case B-0 are $1/5$ and $1/4$ of those in Case A-0, respectively, and the grid number of Case B-0 is 5×5 in a 20 mm-long handrail segment. Additionally, two other cases were designed and named as Cases H and S, respectively. Case H is the hollow one without the handrail middle bars, and Case S is a completely solid handrail. The Reynolds numbers of the handrail components (Re calculated using the dimensions of the handrail bars) are mainly in a range of 30 to 240. The range of Reynolds number is quite small, which indicates that the flow characteristics of vortex shedding and reattachment induced by the handrail component are not significantly changed in this experimental study. Limited by the wind tunnel equipment and dimensions of the section model, the handrail is such a small attachment of the bridge section that a larger Reynolds number for the handrail component was unable to be achieved in the experiments. The experiment results of the scale model can exhibit the aerodynamic properties of a real bridge section to some extent and provide references for the design of

handrails in engineering practice. However, to improve the applicability and reliability of the experimental conclusions for a full-scale bridge, the effect of Reynolds number of handrail components on VIV may need to be further evaluated and studied in future research.

A total of 18 handrail models were designed. Each handrail is explained in detail in the following sections. The handrails in Group A were designed based on Case A-0, which includes ten cases. The change in VIV response induced by the various types of horizontal and vertical middle bars was discussed. Additionally, a method for optimizing the handrail model in the experiments and numerical simulation to obtain results with a controllable error was also discussed. The handrails in Group B were designed based on Case B-0, which includes six cases. Case B-0 is the boundary between the non-grid handrails and the grid-like handrails, and the grid size of each case in Group B is equal to or smaller than Case B-0. The aerodynamic performance of a grid-like handrail, which varies with the change of porosity ratios and the grid numbers in vertical and horizontal directions, is similar to a windbreak structure. All the handrail models were made by a 3D printer with a resolution of 0.04 mm × 0.0635 mm × 0.015 mm, which meets our accuracy requirements for handrails.

Experiment results of the non-grid handrail group

To evaluate the effect of the handrail configuration on VIV response, nine other handrails were designed based on Case A-0 (the standard handrail) and numbered from A-1 to A-9. The discussions were conducted on the following aspects: the porosity ratio of the handrails, the position of the middle horizontal bar, and the number and side ratio of the middle bars. Other than the porosity ratio of the handrails, the other three factors related to the middle bars of the handrails have not been discussed in detail in previous studies. By conducting free vibration tests to evaluate VIV responses induced by different handrail configurations, the optimization and modeling of handrails with consideration of the aerodynamic performance were discussed.

Influence of porosity ratios

The influence of the porosity ratio on VIV performance has been discussed in previous studies (Matsumoto et

al., 1993; Liu et al., 2017; Wu et al., 2017; Li et al., 2018). The porosity ratio is a significant parameter for describing the block effect of the handrail middle bars; therefore, it is necessary to discuss and compare its effects on the VIV response. As illustrated in Fig. 4, the porosity ratio was calculated based on the area covered by the top bar, base, and center lines of the neighboring vertical bars.

Fig. 5 shows four handrails with different porosity ratios. Case H does not have middle horizontal bars, and Case S is a completely solid handrail. The height of the horizontal middle bar and width of the vertical bars are doubled for Case A-1 and tripled for Case A-2. The porosity ratios of each handrail are listed in Table 1.

Fig. 6 (a) shows the steady-state response of VIV obtained from the wind tunnel tests, and Fig. 6 (b) clearly shows that the maximum amplitude and corresponding reduced wind velocity varied with the porosity ratio. The VIV amplitude increased with the decrease in the porosity ratio, and the VIV lock-in range extended, whereas the onset points did not change. The maximum amplitude and reduced wind velocity at the peak had a relatively linear relationship with the porosity ratio of the handrails ($R^2 > 0.95$). Because the decrease in the porosity ratios of the handrails increased the block region of the handrails, which enlarged the negative pressure region behind the windward handrails and influenced the reattachment points of airflow, the VIV amplitude increased.

Influence of the middle horizontal bar position

In previous studies, the top bar position has been proved to have a significant influence on the VIV performance (Nagao et al., 1997); however, further evaluation on the effect of the position of the middle horizontal bar is still lacking. To clarify this, two handrails were designed as shown in Fig. 7. Compared to Case A-0, the position of the middle horizontal bar was moved downward and upward from the original position to the 1/3 and 5/6 heights of the vertical bar in Cases A-3 and A-4, respectively.

Fig. 8 shows that the VIV onset wind speed and maximum amplitude of Cases A-3 and A-4 were consistent with those of Case A-0, which means that changing the position of the middle bar has no effect on its VIV performance. This indicates that the position of the middle horizontal bar is unlikely to influence the characteristics of the flow separation and reattachment it induces.

Influence of horizontal and vertical middle bar number

The number of separation points increases as the number of middle horizontal bars increases, which may lead to a change in their VIV response. Cases A-5 and A-6 (Fig. 9) were designed to analyze the effects of the number of middle horizontal bars. To maintain the same porosity ratio with Case A-0, the heights of the middle horizontal bars in Cases A-5 and A-6 were decreased to half and a quarter, and this also changed the side ratios of the middle bars from 1 to 2.2 and 4.4, respectively.

Fig. 10 shows that the VIV maximum amplitude decreased as the number of middle horizontal bars increased. The onset wind velocity and the peak position shifted slightly to the low wind speed region. Two factors may contribute to this variation. One possibility is that increasing the number of middle horizontal bars caused an increase in the separation points, and the interference of airflow between multiple horizontal bars weakened the vortex shedding process induced by each middle horizontal bar, which may affect the formation of separation bubbles as well as the flow field behind the handrails. Moreover, the generation of vortices at the lower surface of the top bar may be disturbed by the multiple middle horizontal bars, so the integrated flow separation induced by multiple middle horizontal bars may be weaker than that induced by one middle horizontal bar. Another possibility is that the increase in the side ratio of the middle horizontal bars changed the pattern of flow detachment and reattachment on the surfaces of the horizontal bars. However, the middle horizontal bar is such a small part that it is questionable whether its side ratio influenced the VIV amplitude. Further discussion regarding the side ratio effect of the middle bar would be presented in the next section.

To evaluate the influence of the number of vertical bars on the VIV performance of a bridge girder, Case A-9 (as shown in Fig. 11 (a)) was designed using double the number of vertical bars compared to Case A-0. As shown in Fig. 11 (b), the VIV amplitudes of Cases A-0 and A-9 were almost the same. Therefore, the number of vertical bars had no influence on the VIV response. One reason for this is that the vortex shedding induced by the vertical bars was perpendicular to the flow separation layer caused by the top bar of the handrail and the wind fairing of the bridge girder. Consequently, it did not influence the intensity of the vortex that excited the heaving VIV oscillation. Furthermore, for modeling handrail shapes in numerical simulation, the vertical bars can be simplified to reduce the computation load.

Side ratio effects of the middle horizontal bar

As inferred in the previous section, the side ratios of the middle horizontal bars have a significant impact on the VIV amplitude. To eliminate the influence of multiple separation points and address this problem, Cases A-7 and A-8 (Fig. 12) were designed with one middle horizontal bar. By adjusting the width of the middle horizontal bar, the side ratios of Cases A-7 and A-8 are the same as those of Cases A-5 and A-6, respectively. The configuration parameters of all the cases (including Cases A-5 and A-6) are listed in Table 2.

Fig. 13 shows that the VIV maximum amplitude decreased as the side ratio of the middle horizontal bar increased. Additionally, the wind speed range of VIV shifted to the lower wind speed region. The change of VIV response of Cases A-7 and A-8 was similar to that of Cases A-5 and A-6 (as shown in Fig. 11).

To analyze the mechanism, the modes of vortex formation classified by the side ratios of a bluff body (Naudascher and Wang, 1993) were considered. The characteristics of flow separation and reattachment of a rectangular prism are determined by its side ratio, and the turbulent shear stress and turbulent kinetic energy decrease with the increase of the side ratio (Sohankar, 2008). Similarly, the increase in the side ratio of middle horizontal bars possibly changed the characteristics of the secondary flow separation and reattachment induced by the middle horizontal bars, and therefore the vortex shedding process induced by the middle horizontal bar became weaker, which mitigated the VIV response induced by the entire handrail.

Moreover, considering the movement of the VIV lock-in region, the VIV onset wind speed is determined by the side ratio of the girder section. According to Shiraishi and Matsumoto (1983), over a B/D (side ratio of a bluff body) range from approximately 2 to 7.5, the onset wind speed of the heaving motion-induced VIV can be approximated as shown below:

$$(V_r)_{cr} = \frac{B/D}{0.6} \frac{1}{n} \quad (1)$$

where B = deck width, D = deck height, and n = natural number.

The installation of handrails on the bridge deck increases the effective height of the section. Therefore, considering this bridge section with handrails, the effective B/D is lower than 5.5. The onset wind speeds of Cases A-7 and A-8 were lower than that of Case A-0, which indicates that the effective B/D of this section

decreased as the side ratio of the middle bar increased. A similar conclusion can be obtained from the variation in the onset wind speeds between Cases A-6 and A-0. Calculated by the onset wind speed, the effective B/D of the bridge section was reduced from 4.7 to 4.3 while the side ratio of the middle horizontal bars increased from 1 to 4. Although the variation in the effective B/D of the bridge section was quite small, this indicates that the middle horizontal bar with a large side ratio acts as a guide flow structure to some extent. This not only reduced the VIV amplitude and the VIV lock-in range but also affected and improved the aerodynamic configuration of the section with handrails. It provides a new approach for improving VIV performance by optimizing the configuration of the handrail middle horizontal bars because increasing the side ratio of the handrail middle bar is helpful in controlling VIV.

Experiment results of the grid-like handrail group

Based on Case B-0, five handrails were designed as uniform grid-like structures with different porosity ratios and grid sizes and numbered from B-1 to B-5. Group B can imitate the condition of flow passing through a uniform grid-like structure like a wind barrier. This kind of porous structure is more efficient in generating a longer wind-velocity reduction region to protect the effect of wind on vehicles (Cornelis and Gabriels, 2005). By evaluating the effect of grid density and distribution on VIV performance, it can provide an experimental reference for the design of grid-like handrails or wind barriers with good aerodynamic properties. Moreover, the grid-like handrail is easily defined and modeled by a simple mathematical physical model in numerical simulation, such as the porous media model that adopts the pressure loss coefficient to describe and simulate the airflow passing through a grid-like structure (Giannouslis et al., 2010; Hong et al., 2015). By comparing the VIV response of grid-like handrails, the use of a porous media model to replace an actual handrail configuration was evaluated, and the parameters that may influence the pressure loss coefficient when modeling the handrail by this model were also discussed.

Influence of porosity ratios

The porosity ratio is the most relevant parameter to describe the characteristics of a grid-like structure. Therefore, it is necessary to compare the VIV response induced by different porosity ratios of grid-like handrails. In the previous section, it was clarified that increasing the porosity ratio of the handrail led to a decrease in the maximum VIV amplitude for the non-grid handrail cases (Group A). To analyze and discuss the effect of the porosity ratio for grid-like handrails, Cases B-1 and B-2 were designed with different porosity ratios compared to Case B-0 (Fig. 14). For convenient comparison, the porosity ratio of the cases in Group B is the same as that of the corresponding cases in Group A. Because this type of handrail can be regarded as a porous screen specified by diameter d and wire spacing l , it is worth noting that the porosity ratios can also be calculated by $\beta = (1 - d/l)^2$ (Laws and Livesey, 1978). Calculated by this equation, the β value of each case is the same as that computed using our previous definition for non-grid handrails.

In this section, to focus on the effect of the porosity ratio, the vertical and horizontal grid numbers of Cases B-1 and B-2 are the same as those of Case B-0. We employed the vertical and horizontal grid numbers in a 20 mm-long handrail segment for discussion. The grid number of each case in a 20 mm-long segment is 5×5 (horizontal $\times$ vertical).

Fig. 15 (a) shows the steady-state response of VIV obtained from the wind tunnel tests. As the porosity ratio decreased, the VIV amplitude increased, whereas the onset wind velocity did not change. Additionally, the VIV lock-in range extended, and the position of the VIV peak shifted slightly to the high wind speed region.

Fig. 15 (b) shows that the maximum VIV amplitude had a relatively linear relationship with the porosity ratio for two groups of handrails. The grid-like handrails have well-distributed grids between the top bar and the base, and therefore the effect of the porosity ratio plays a dominant role in VIV amplitude than that of the non-grid handrails. However, when the porosity ratio β of the handrail is smaller than 50% (Case B-2), the effects of a small porosity ratio occurred because the flow through each element of the grid-like structure could either coalesce or diverge with its neighbor in a fairly random manner (Baines and Peterson, 1951, Bradshaw 1964, 1965), which will generate a pattern of trailing vortices of various sizes and may influence the vortex intensity induced by the top bar. This is an additional effect induced by the decrease of porosity ratio especially for the

grid-like structure, which may have effects on the VIV amplitude of the bridge girder.

Influence of the vertical and horizontal grid numbers

In this section, the study laid stress on the grid size of the handrails with the same porosity ratio. As the number of bars increases, the grid size decreases, and the grid number in a segment of the handrail increases. The effects of the vertical and horizontal grid numbers on VIV response are discussed in this section.

Laws and Livesey (1978) and Groth and Johansson (1988) utilized the local Reynolds number ($Re_L = Ud/\beta v$), which is a parameter calculated using the wire diameter d and wire-gauze porosity ratio β , to evaluate the flow status across a porous screen. In this section, all the cases can be regarded as porous screens and have similar porosity ratios ($\beta \approx 78\%$), and the local Reynolds number of each case was calculated by the dimensions of the middle bar of the handrail. By calculation, the Re_L values for these grid-like handrails are in the range of 34 to 80. Previous research (Laws and Livesey, 1978) indicated that when Re_L is lower than 80, the grid-like handrails can be regarded as sufficiently fine screens, which give control of the scale size and the intensity of the turbulence behind the structure. Therefore, the flow structures across these handrails are similar and can be easily modeled using the porous media model.

To analyze the effect of vertical grid number (number of the middle horizontal bar), three handrail models were designed (Fig. 16). To maintain the same porosity ratio with Case B-0, the thickness of the middle bars was changed when changing the bar numbers in each case. The middle horizontal bar numbers of Cases B-3 and B-5 are double those of Cases B-0 and B-4, respectively. The grid numbers for each case are presented in Table 3.

For non-grid handrails (Group A), it was proved that the number of middle horizontal bars had a significant effect on the VIV performance. On the contrary, Fig. 17 shows that for grid-like handrail (Group B) with different numbers of the middle horizontal bar (vertical grid number), the VIV responses of each case were similar. Therefore, the roles of the middle horizontal bars against VIV were different in Groups A and B. For the cases in Group B that can be regarded as fine-mesh screens, the turbulence induced by the horizontal bar is of small scale and tends to decay (Laws and Livesey, 1978). As the number of middle horizontal bars was increased, the interference of the airflow between the multiple horizontal bars exhibited no obvious change; therefore, the VIV

responses were similar. For the grid-like handrails, changing the vertical grid number (middle horizontal bar number) does not affect the VIV response.

To analyze the effect of the horizontal grid number (vertical bar number), we compared the VIV amplitudes of Cases A-6, B-0, and B-4 (as shown in Fig.18 (a)) that have the same vertical grid number but different horizontal grid numbers (vertical bar numbers). Table 4 presents the grid numbers for each case. Fig. 18 (b) shows that the maximum VIV amplitude increased as the vertical bar number was increased, which is different from the tendency of Group A. One reason may be that increasing the number of vertical bars decreased the size of the grids along the horizontal direction, and the structure tended to act as a porous windbreak structure with square elements. Groth and Johansson (1988) indicated that the grid size influences the pressure loss coefficient of uniform porous screens. Therefore, the number of vertical bars may influence the pressure drop across the handrail and the VIV amplitude. Moreover, though the vortex shedding induced by the vertical bars was perpendicular to the flow separation caused by either the corner of the bridge girder or the horizontal bars of the handrail, it may interact with the vortex bubbles induced by the middle horizontal bars because each element of the porous structure is very small.

Mitigation of VIV by optimizing handrail shape and simplification of handrail models

The effect of handrail details on VIV was investigated by wind tunnel tests and further discussion was conducted about the suppression of VIV by optimizing the configuration of handrails. Considering two groups of handrails, a large porosity ratio of the handrails is advantageous for decreasing the VIV amplitude. Therefore, we should increase the porosity ratio of handrails to reduce the VIV amplitude. For the non-grid handrails, VIV amplitude decreased with the increase of the number and side ratio of middle horizontal bars, whereas the position of the middle bar and the number of vertical bars did not influence VIV. Without changing the porosity ratio of handrails, non-grid handrails should be designed with multiple middle horizontal bars to achieve good aerodynamic properties. Moreover, the middle horizontal bar with a large side ratio, which acts as a guide flow structure, helps to reduce the VIV amplitude because the form of the vortex shedding induced by the middle bar and the turbulence intensity are determined by its side ratio. For the grid-like handrails that are similar to porous

screens, the VIV amplitude increased with the increase of the number of vertical bars, whereas the number of horizontal bars had no influence on VIV. Therefore, it is feasible to improve the VIV stability of a grid-like handrail by decreasing the vertical bar number.

The same factors of the handrail details, such as the horizontal and vertical bar numbers, exhibited opposite changes in VIV response for Groups A and B. It indicates that the flow fields or patterns across the non-grid and grid-like handrails are not similar, and the dominant factors that influence the VIV are different. Nevertheless, the flow structures behind the different types of handrails have not been discussed in detail, and the boundary between the non-grid and grid-like handrails is unclear. In future research, these aspects will be further studied and analyzed by comparing the flow fields via CFD simulations. Moreover, because the optimizing scheme for reducing the VIV by adjusting the middle bar of the handrail was only proven under the condition of a wind attack angle of 0° , the feasibility of this scheme for reducing the VIV under other wind attack angles needs to be investigated in further studies.

For the design of handrail models in wind tunnel tests, the effects of the porosity ratio and middle horizontal bars should be considered, whereas extraneous components and factors of the handrail can be simplified when it is difficult to fabricate a model that is exactly like the prototype. This study also provides some optimal methods and engineering references in establishing a simplified CFD model to predict the aerodynamic properties of a bridge girder with handrails. In simulations, the effect of the number and the side ratio of middle horizontal bars cannot be ignored; but extraneous factors, such as the vertical bars and the position of the middle horizontal bar can be simplified.

In addition, the flow pattern and pressure loss across the grid-like handrail are easily modeled by the porous media model. Therefore, in the engineering design process, it is feasible to use the porous media model to estimate the VIV response induced by a non-grid handrail with the same porosity ratio because the maximum VIV amplitude was linear to the porosity ratio in both groups A and B with $R > 0.95$ and the VIV response of the grid-like handrail agreed well with that of the non-grid handrail with the same porosity. Based on the experimental results of Group B, the pressure drop across the grid-like handrails is affected by not only the porosity ratio but also the horizontal grid number (number of vertical bars). Fig. 18 (b) shows that the maximum VIV amplitude of

Case B-4 was similar to that of Case A-0. This may be a coincidence, but the feasibility of using the porous media model to replace the actual handrail model and excite a similar VIV response was demonstrated. Because the porosity ratio is not the only parameter that may influence the aerodynamic characteristic of the grid-like handrail, further study should be conducted to discuss how to modify the pressure drop across handrails to get a more accurate simulation result when using the porous media model. Moreover, because the vortex shedding induced by the important handrail components (such as the top bar and base of the handrail) cannot be ignored, it would be better to develop a partial porous media model based on the basic handrail framework that includes the essential handrail components.

Concluding remarks

The purpose of this study was to evaluate the effect of handrail details on VIV performance and provide some basic ideas on optimizing the handrail configuration with good aerodynamic performance. Eighteen handrail models were designed and divided into the non-grid and the grid-like handrail group, and heaving 1DOF spring-supported wind tunnel tests were conducted. The effect of two types of handrails on VIV performance and their different aerodynamic properties were compared and analyzed. It also provides an experimental reference for simplifying the handrail model in wind tunnel tests or numerical simulation to obtain results with acceptable errors. The conclusions are as follows:

- 1) For both non-grid and grid-like handrails, keeping the top bar of the handrails unchanged, the VIV amplitude approximately exhibited a linear relationship with the porosity ratio. As the porosity ratio of the handrails decreased, the VIV amplitude increased and the VIV lock-in range extended, whereas the onset wind velocity did not change.
- 2) For the non-grid handrail cases, the position of the middle horizontal bar and the number of vertical bars had no influence on the VIV response. However, with the increase of the number and side ratio of the middle horizontal bars, the maximum VIV amplitude decreased and the onset wind speed was lowered. For the grid-like handrails, increasing the horizontal grid number increased the VIV maximum amplitude, whereas the

vertical grid number did not affect the VIV performance. This indicated that the aerodynamic properties and the effect of the vertical and horizontal bars on VIV are different for two types of handrails.

3) To optimize the handrail configuration with good aerodynamic properties, non-grid handrails should be designed with a large porosity ratio and multiple middle horizontal bars. Moreover, the middle horizontal bar with a large side ratio is also efficient in mitigating the VIV. For grid-like handrails or wind barriers, increasing the porosity ratio can reduce the VIV response. Because the vertical bars exhibited adverse effects on VIV, decreasing the vertical bar number can help to decrease VIV amplitude.

4) When modeling the handrail configuration in wind tunnel tests or CFD simulations, the effects of the porosity ratio and middle horizontal bars should be considered. However, some components of the handrail can be simplified in fabricating the handrail model, and extraneous components can be ignored during simulation to reduce calculation costs. Porous media models can be used to estimate the VIV response induced by a non-grid handrail with the same porosity ratio. In future studies, additional factors need to be investigated to correct the pressure loss model, and a partial porous media model should be developed based on the basic handrail framework including the top bar and the base.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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References

- Avila-Sanchez, S., Lopez-Garcia, O., Cuerva, A., Meseguer, J. 2016. "Characterisation of cross-flow above a railway bridge equipped with solid windbreaks." *J. Eng. Struct.*, 126, 133–146.
<http://dx.doi.org/10.1016/j.engstruct.2016.07.035>.
- Baines, W.D., Peterson, E. G. 1951. "An investigation of flow through screens." *Trans. ASME.*, 73, 467-480.
- Bradshaw, P. 1964. "Wind tunnel screens: flow instability and its effect on aerofoil boundary layers." *J. R. Aeronaut. Soc.*, 68, 198. <https://doi.org/10.1017/S0001924000061157>.
- Bradshaw, P. 1965. "The effect of wind tunnel screens on normally two-dimensional boundary layers." *J. Fluid Mech.*, 22, 679-687. <https://doi.org/10.1017/S0022112065001064>.
- Bruno, L., Mancini, G. 2002. "Importance of deck details in bridge aerodynamics." *Struc. Eng., Int. IABSE*. 12(4), 289–294. <https://doi.org/10.2749/101686602777965234>.
- Buljac, A., Kozmar, H., Pospíšil, S., Macháček, M. 2017. "Flutter and galloping of cable-supported bridges with porous wind barriers." *J. Wind Eng. Ind. Aerodyn.*, 171, 304-318.
<https://doi.org/10.1016/j.jweia.2017.10.012>.
- Buljac, A., Kozmar, H., Pospíšil, S., Macháček, M., Kuznetsov, S. 2020. "Effects of Wind-Barrier Layout and Wind Turbulence on Aerodynamic Stability of Cable-Supported Bridges." *J. Bridge Eng.*, 25 (12): 04020102.
- Cornelis, W. M., Gabriels, D. 2005. "Optimal windbreak design for wind-erosion control." *J. Arid Environ.*, 61(2): 315-332. <https://doi.org/10.1016/j.jaridenv.2004.10.005>.
- Ge, Y., Yang, Y., Cao, F. 2011. "VIV sectional model testing and field measurement of Xihoumen Suspension Bridge with twin box girder". *Proc., 13th Int. Conf. Wind Eng.*, Amsterdam, Netherlands: TNO.
- Giannoulis, A., Mistriotis, A., Briassoulis, D. 2010. "Experimental and numerical investigation of the airflow around a raised permeable panel". *J. Wind Eng. Ind. Aerodyn.*, 98, 808-817.
<https://doi.org/10.1016/j.jweia.2010.07.005>.
- Groth, J., Johansson, A. 1988. "Turbulence reduction by screens." *J. Fluid Mech.*, 197, 139-155.
<https://doi.org/10.1017/S0022112088003209>.

465 Hong, S., Lee, I., Seo, I. 2015. Modeling and predicting wind velocity patterns for windbreak fence design. *J.*
 466 *Wind Eng. Ind. Aerodyn.*, 142, 53-64. <https://doi.org/10.1016/j.jweia.2015.03.007>.
 467 Hu, C., Zhao, L., Ge, Y. 2019. "Mechanism of suppression of vortex-induced vibrations of a streamlined closed-
 468 box girder using additional small-scale components." *J. Wind Eng. Ind. Aerodyn.*, 189, 314-331.
 469 <https://doi.org/10.1016/j.jweia.2019.04.015>.
 470 Ito, Y., Graham, J.M.R. 2016. LES for investigation of span-wise domain size effect and evaluation of flutter
 471 derivatives of a box bridge. *Proc. 8th Int. Colloq. Bluff Body Aerodyn.*, Appl. 184.
 472 Ito, Y., Graham, J.M.R. 2017. "Large eddy simulation for static and unsteady wind forces of a box girder and the
 473 effect of span-wise domain size." *J. Jpn. Soc. Civ. Eng. Ser.*, A1. 73 (1), 195-205. [In Japanese.]
 474 <https://doi.org/10.2208/jscejseee.73.218>.
 475 Komatsu, S., Kobayashi, H. 1980. "Vortex-induced oscillation of bluff cylinders." *J. Wind Eng. Ind. Aerodyn.*,
 476 6, 335–362. [https://doi.org/10.1016/0167-6105\(80\)90010-0](https://doi.org/10.1016/0167-6105(80)90010-0).
 477 Kozmar, H., Procino, L., Borsani, A., Bartoli, G. 2014. "Optimizing height and porosity of roadway wind barriers
 478 for viaducts and bridges." *Eng. Struc.*, 81, 49-61. <https://doi.org/10.1016/j.engstruct.2014.09.029>.
 479 Kozmar, H., Procino, L., Borsani, A., Bartoli, G. 2012. "Sheltering efficiency of wind barriers on bridges." *J.*
 480 *Wind Eng. Ind. Aerodyn.*, 107-108, 274-284. <https://doi.org/10.1016/j.jweia.2012.04.027>.
 481 Laima, S., Li, H., Chen, W., and Ou, J. 2018. "Effects of attachments on aerodynamic characteristics and vortex-
 482 induced vibration of twin-box girder." *J. Fluids Struc.*, 77, 115–133.
 483 <https://doi.org/10.1016/j.jfluidstructs.2017.12.005>.
 484 Larsen, A., Wall, A. 2012. "Shaping of bridge box girders to avoid vortex shedding response." *J. Wind Eng. Ind.*
 485 *Aerodyn.*, 104-106, 159–165. <https://doi.org/10.1016/j.jweia.2012.04.018>.
 486 Laws, E. M., Livesey, J. L. 1978. "Flow through screens." *Ann. Rev. Fluid Mech.*, 10, 247-266.
 487 <https://doi.org/10.1146/annurev.fl.10.010178.001335>.
 488 Li, M., Sun, Y., Jing, H., Li, M. 2018. "Vortex-induced vibration optimization of a wide stream box girder by
 489 wind tunnel test." *J. Civ. Eng.*, Published Online November 12.
 490 <http://dx.doi.org/10.1007/s12205-018-0548-y>.

491 Liu, L., Zhang, L., Wu, B., Chen, B. 2017. "Effect of accessory attachment on static coefficients in a steel box
 492 girder for long-span suspension bridges." *J. Eng. Sci. Tech. Rev.*, 10(1), 68-83.
 493 <https://doi.org/10.25103/jestr.101.11>.

494 Matsumoto, M., Shiraishi, N., Shirato, H., Yagi, T. 1993. "Mechanism of, and turbulence effect on vortex-
 495 induced oscillations for bridge box girders." *J. Wind Eng. Ind. Aerodyn.*, 49, 467-476.
 496 [https://doi.org/10.1016/0167-6105\(93\)90041-L](https://doi.org/10.1016/0167-6105(93)90041-L).

497 Mannini, C., Sbragi, G., Schewe, G. 2016. "Analysis of self-excited forces for a box-girder bridge deck through
 498 unsteady RANS simulations." *J. Fluids Struct.*, 63, 57-76.
 499 <https://doi.org/10.1016/j.jfluidstructs.2016.02.007>.

500 Nagao, F., Utsunomiya, H., Yoshioka, E., Ikeuchi, A., and Kobayashi, H. 1997. "Effects of handrails on separated
 501 shear flow and vortex-induced oscillation." *J. Wind Eng. Ind. Aerodyn.*, 69–71, 819–827.
 502 [http://dx.doi.org/10.1016/S0167-6105\(97\)00208-0](http://dx.doi.org/10.1016/S0167-6105(97)00208-0).

503 Naudascher, E., Wang, Y. 1993. "Flow-induced vibrations of prismatic bodies and grids of prisms." *J. Fluids
 504 Struct.*, 7(4), 341–373. <https://doi.org/10.1006/jfls.1993.1021>.

505 Nieto, F., Owen, J. S., Hargreaves, D. M., Hernández, S. 2015. "Bridge deck flutter derivatives: Efficient
 506 numerical evaluation exploiting their interdependence." *J. Wind. Eng. Ind. Aerodyn.*, 136, 138-150.
 507 <http://doi.org/10.1016/j.jweia.2014.11.006>.

508 Noguchi, K., Ito, Y., Yagi, T. 2020. "Numerical evaluation of vortex-induced vibration amplitude of a box girder
 509 bridge using forced oscillation method." *J. Wind Eng. Ind. Aerodyn.*, 196, 104029.
 510 <https://doi.org/10.1016/j.jweia.2019.104029>.

511 Šarkić, A., Fisch, R., Höffer, R., Bletzinger, K.-U. U. 2012. "Bridge flutter derivatives based on computed,
 512 validated pressure fields." *J. Wind Eng. Ind. Aerodyn.*, 104-106, 141-151.
 513 <https://doi.org/10.1016/j.jweia.2012.02.033>.

514 Sarwar, M. W., Ishihara, T., Shimada, K., Yamasaki, Y., Ikeda, T. 2008. "Prediction of aerodynamic
 515 characteristics of a box girder bridge section using the LES turbulence model." *J. Wind Eng. Ind. Aerodyn.*,
 516 96, 1895–1911. <https://doi.org/10.1016/j.jweia.2008.02.015>.

517 Sarwar, M. W., Ishihara, T. 2010. "Numerical study on suppression of vortex-induced vibrations of box girder
 518 bridge section by aerodynamic countermeasures." *J. Wind Eng. Ind. Aerodyn.*, 98(12), 701-711.
 519 <https://doi.org/10.1016/j.jweia.2010.06.001>.
 520 Schewe, G., Larsen, A. 1998. "Reynolds number effects in the flow around a bluff bridge deck cross section." *J.*
 521 *Wind Eng. Ind. Aerodyn.*, 74-76, 829-838. [https://doi.org/10.1016/S0167-6105\(98\)00075-0](https://doi.org/10.1016/S0167-6105(98)00075-0).
 522 Shiraishi, N., Matsumoto, M. 1983. "On classification of vortex-induced oscillation and its application for bridge
 523 structure." *J. Wind Eng. Ind. Aerodyn.*, 14, 419-430. [https://doi.org/10.1016/0167-6105\(83\)90043-0](https://doi.org/10.1016/0167-6105(83)90043-0).
 524 Sohankar, A. 2008. "Large eddy simulation of flow past rectangular-section cylinders: Side ratio effects." *J. Wind*
 525 *Eng. Ind. Aerodyn.*, 96(5), 640-655. <https://doi.org/10.1016/j.jweia.2008.02.009>.
 526 Subcommittee on Similarity of Wind Tunnel Experiments, 1994. "Study on similarity of wind tunnel experiments.
 527 Doboku Gakkai Ronbunshu." [In Japanese.] *J. Jpn. Soc. Civ. Eng. Ser.*, 1994 (489), 17-25.
 528 https://doi.org/10.2208/jscej.1994.489_17.
 529 Vaz, D. C., Almeida, R. A. B., Didier, E., Urgueira, A. P. V., Borges, A. R. J. 2016. "Improving the aerodynamic
 530 performance of Vila-real bridge deck-section." *J. Wind Eng. Ind. Aerodyn.*, 156, 72-83.
 531 <http://dx.doi.org/10.1016/j.jweia.2016.07.002>.
 532 Wu, Bo., Zhang, L., Yang, Y., Liu, Lianjie., Li, H. 2017. "Investigation and control of VIVs with multi-lock-in
 533 regions on wide flat box girders." *J. Control Sci. Eng.*, 2017: 7208241.
 534 <https://doi.org/10.1155/2017/7208241>.
 535

Tables

Table 1. Porosity ratios of non-grid handrails

Case name	H	A-0	A-1	A-2	S
Porosity ratio	94%	78%	58%	40%	0%

Table 2. Configuration parameters of Case A-0 and A-5–A-8

Case number	A-0	A-5	A-6	A-7	A-8
Number of middle horizontal bars	1	2	4	1	1
Height of middle bars (mm)	1	0.5	0.25	1	1
Width of middle bars (mm)	1.1	1.1	1.1	2.2	4
Side ratio of middle bars	1.1	2.2	4.4	2.2	4

Table 3. Grid number of each case in horizontal and vertical directions

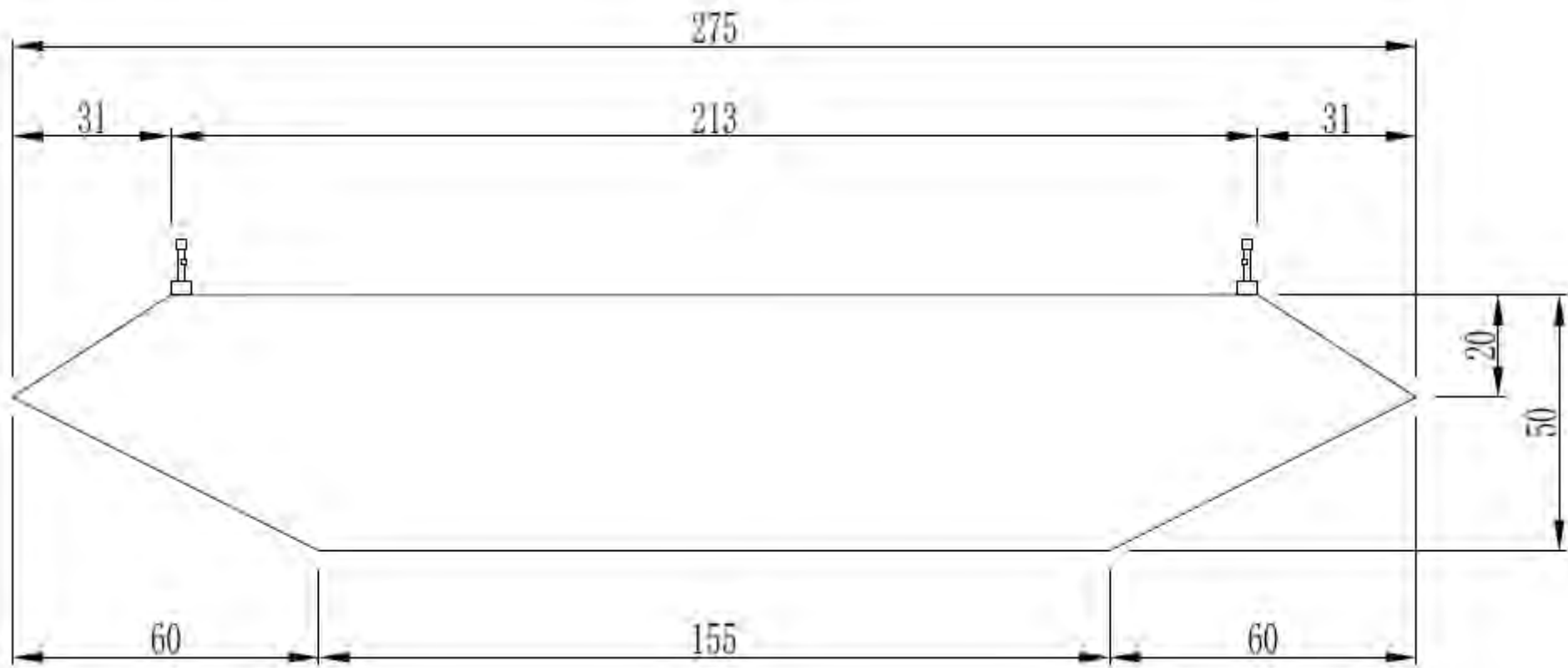
Case number	B-0	B-3	B-4	B-5
Grid number per 20mm (horizontal × vertical)	5×5	5×9	10×5	10×9

Table 4. Grid numbers of each case in horizontal and vertical directions

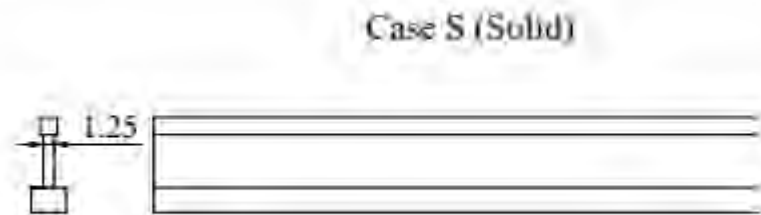
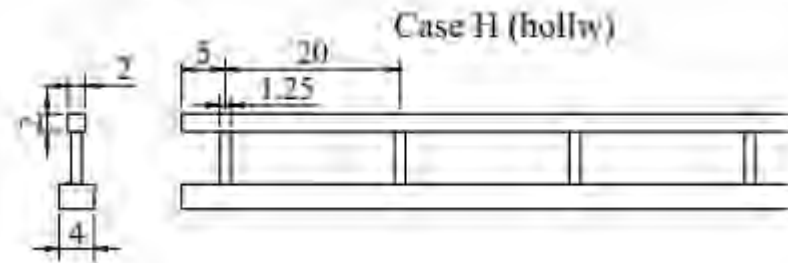
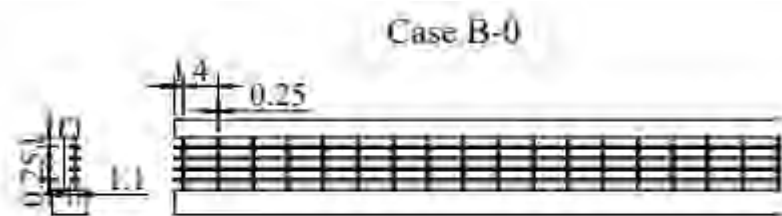
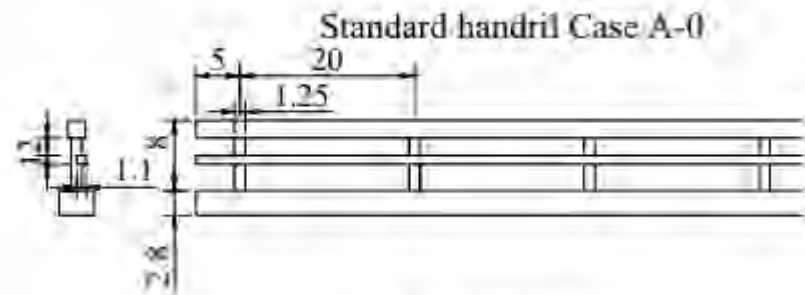
Case number	A-6	B-0	B-4
Grid number per 20mm (horizontal × vertical)	1×5	5×5	10×5

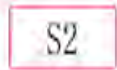
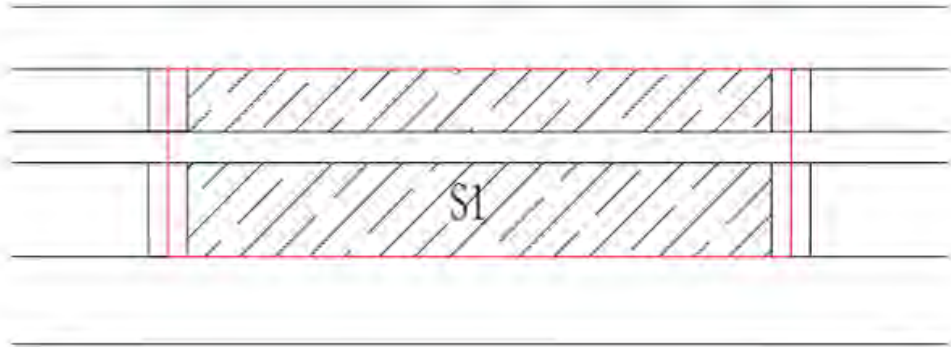
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- Fig. 5.** Non-grid handrail cases with different porosity ratios (unit: mm).
- Fig. 6.** Heaving VIV responses of cases with different porosity ratios. (a) VIV amplitude varied with reduced wind velocity, (b) η/D^* (maximum amplitude) and U/fD^* at the peak of cases with different porosity ratios.
- Fig. 7.** Non-grid handrail cases with different middle bar positions (unit: mm).
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- Fig. 13.** Heaving VIV responses of cases with different side ratios of handrail middle bar.
- Fig. 14.** Grid-like handrail cases with different porosity ratios (unit: mm).
- Fig. 15.** Effect of porosity ratios. (a) VIV amplitude varied with reduced wind velocity, (b) η/D^* (maximum amplitude) of cases with different porosity ratios.
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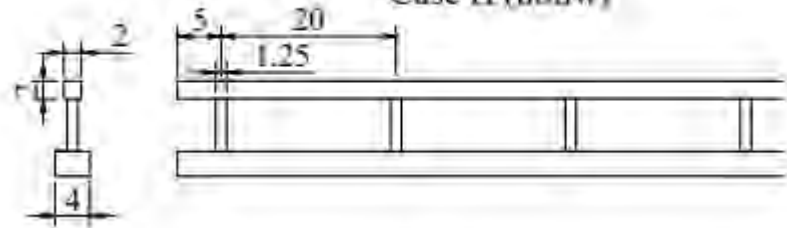




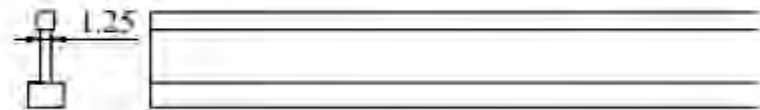


Porosity ratio
 $\phi = S1/S2$

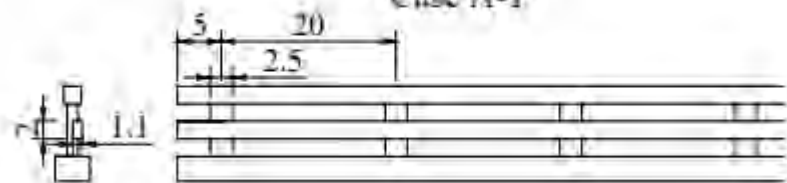
Case H (bulb)



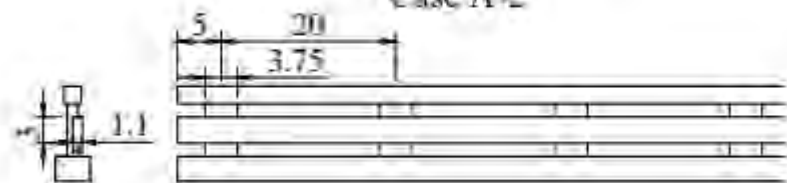
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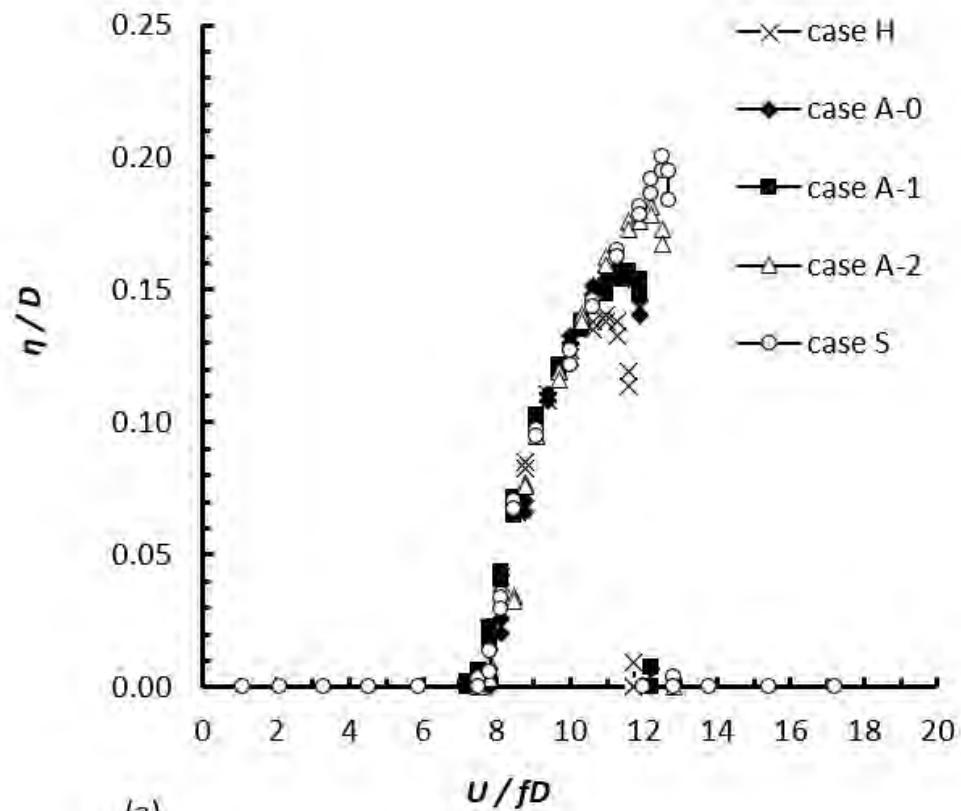


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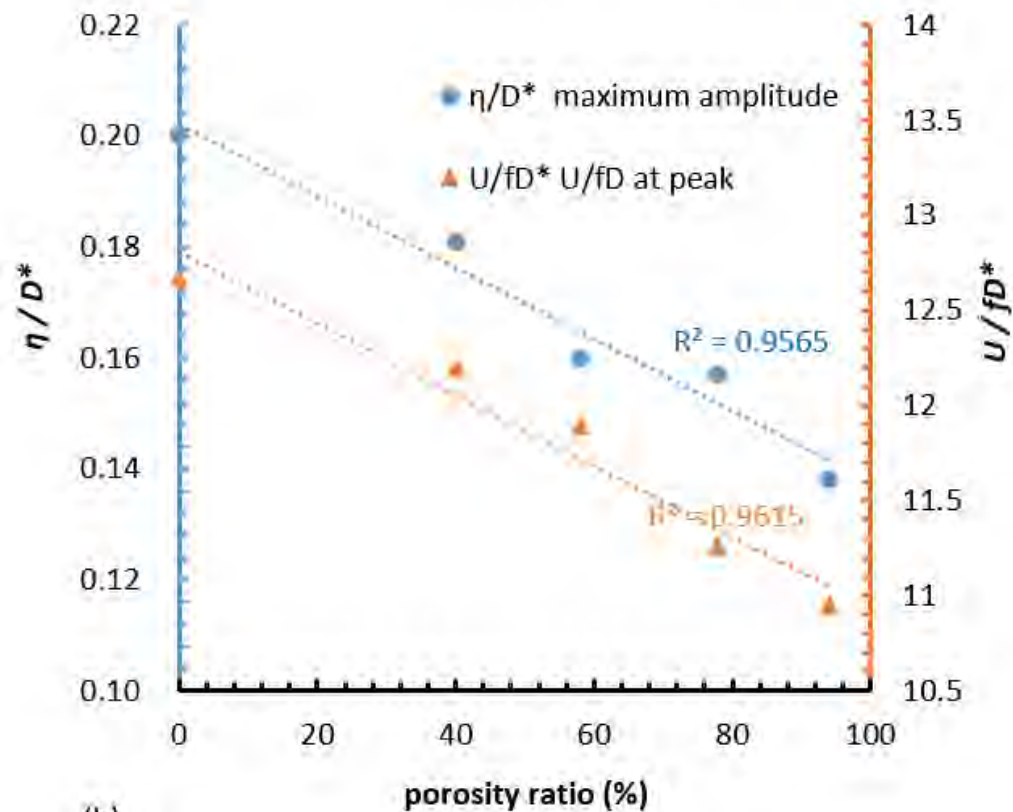


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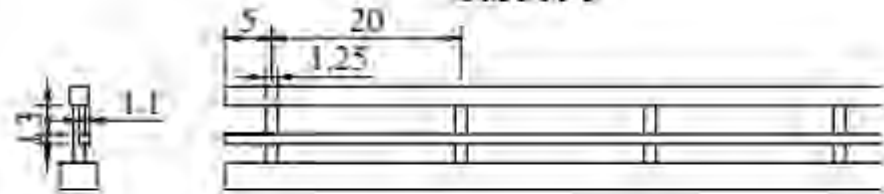


(a)

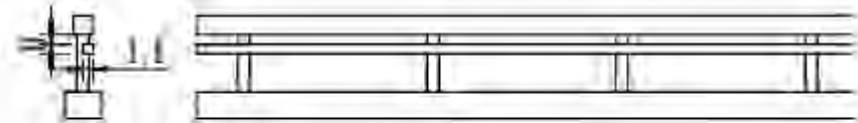


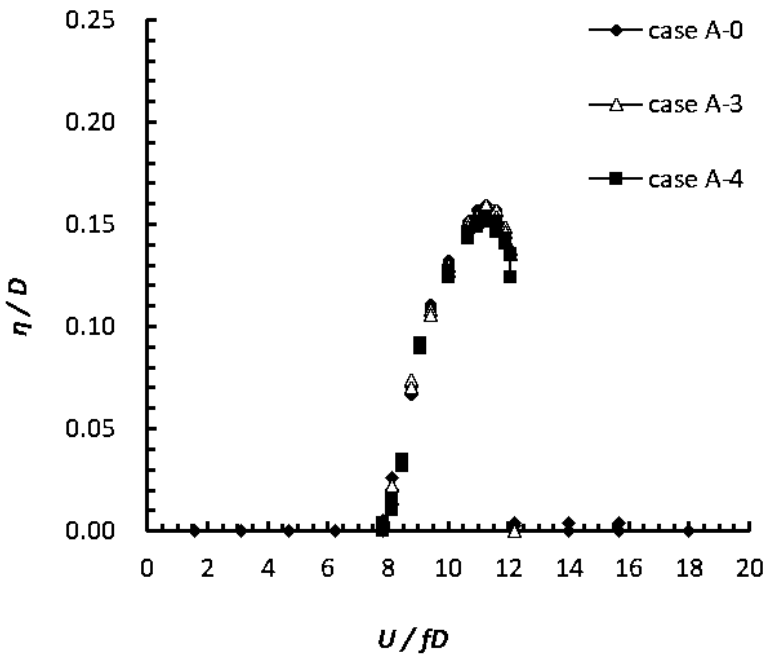
(b)

Case A-3



Case A-4



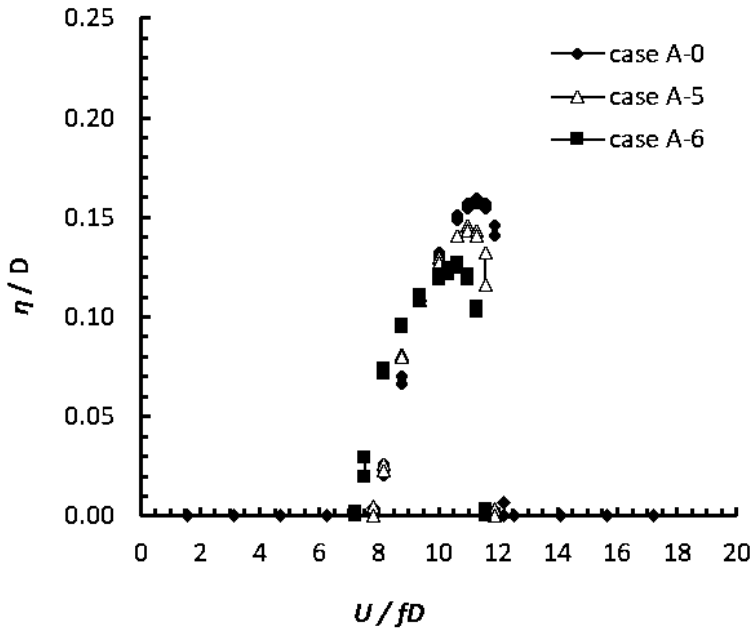


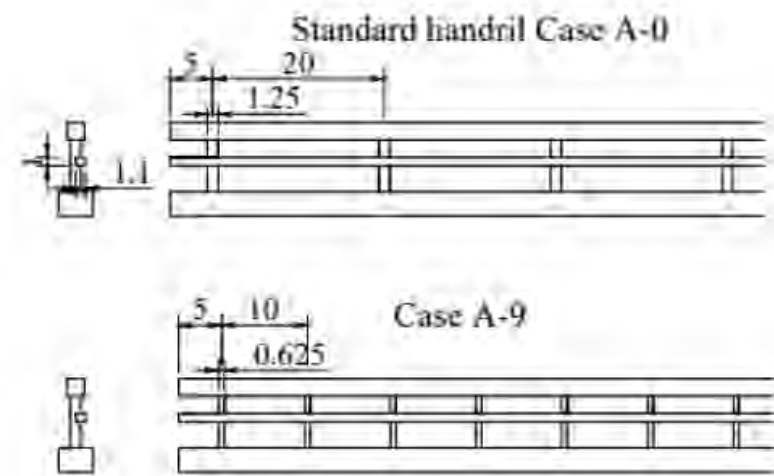
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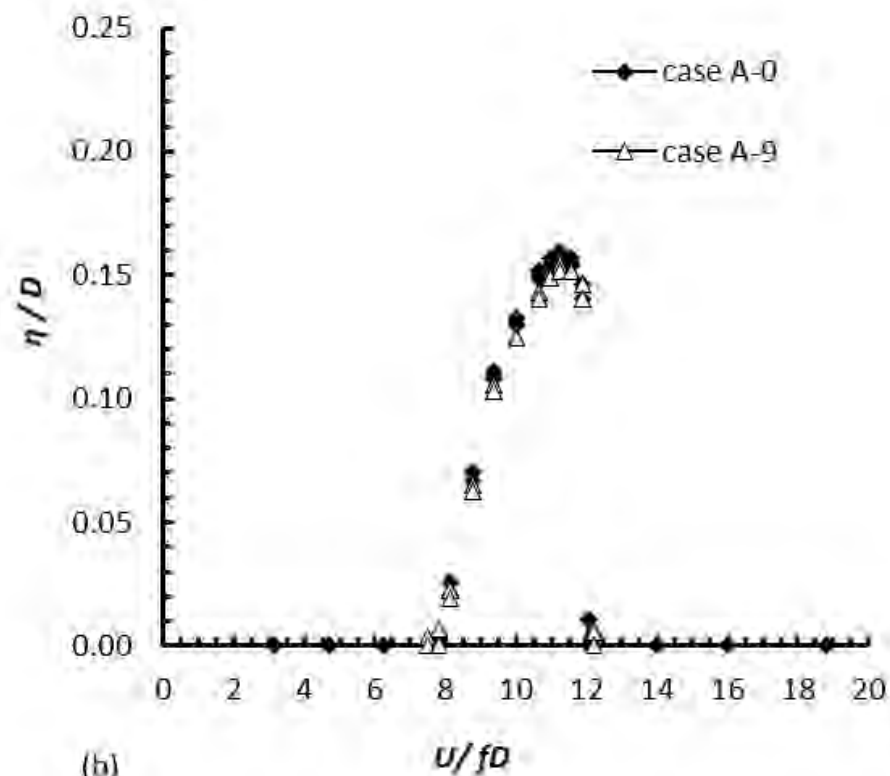
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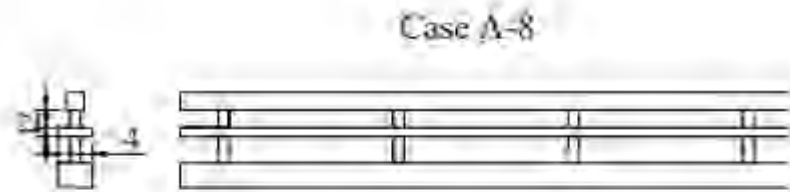
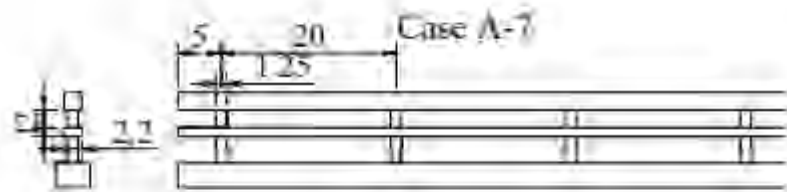


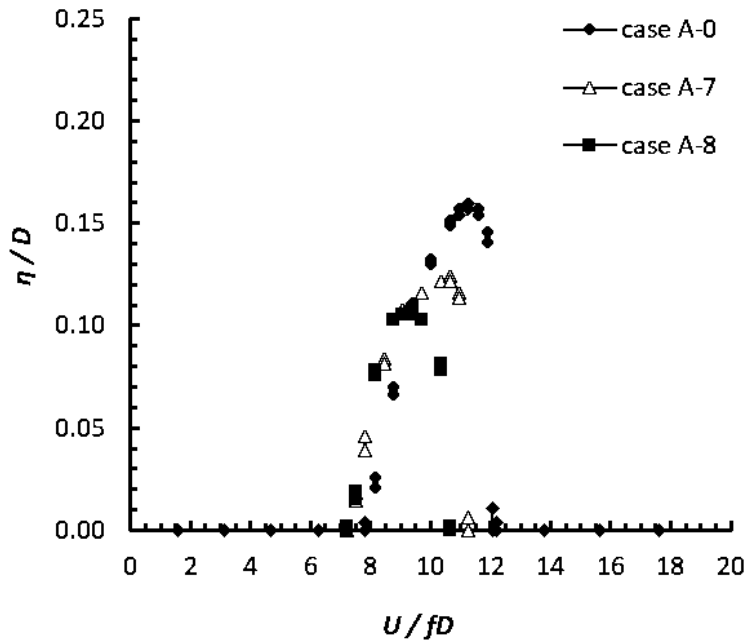


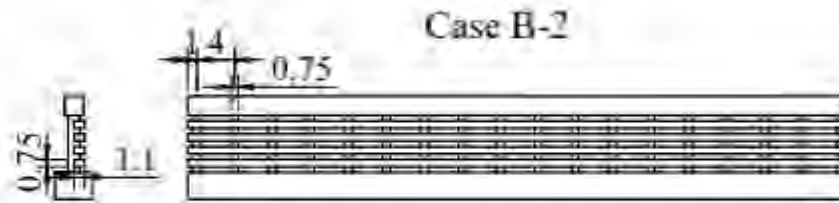
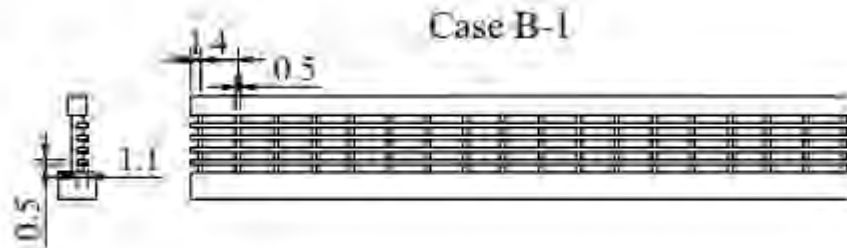
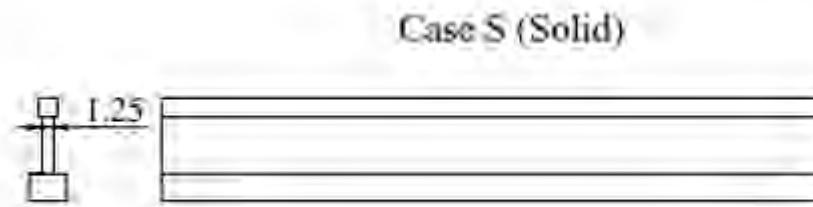
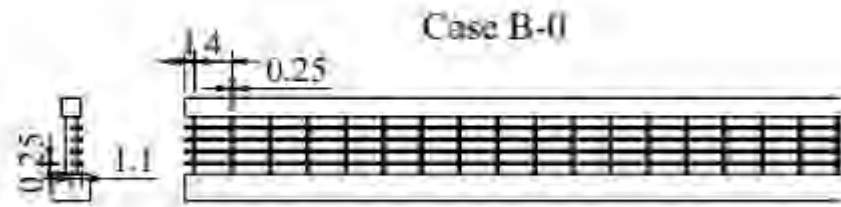
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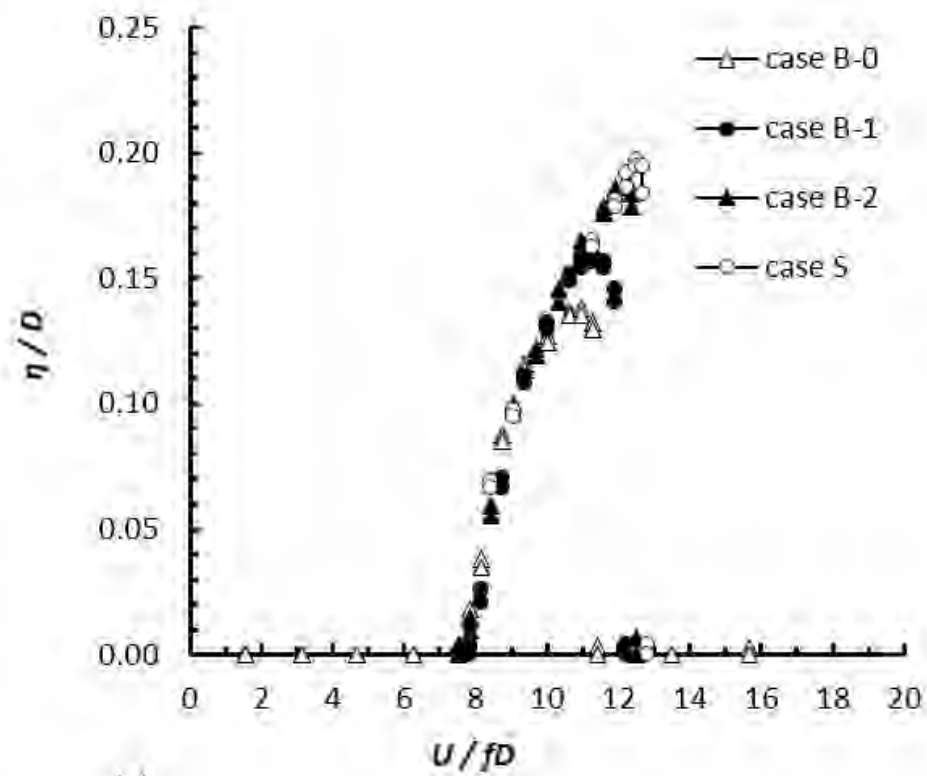


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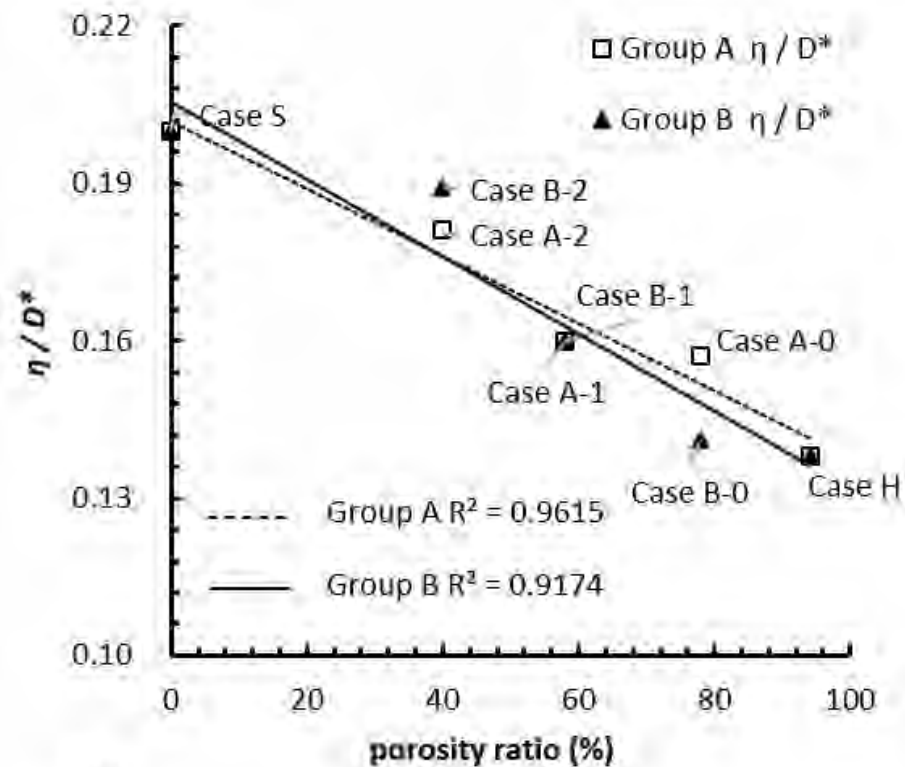




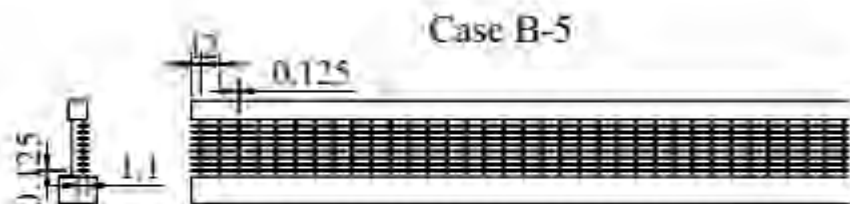
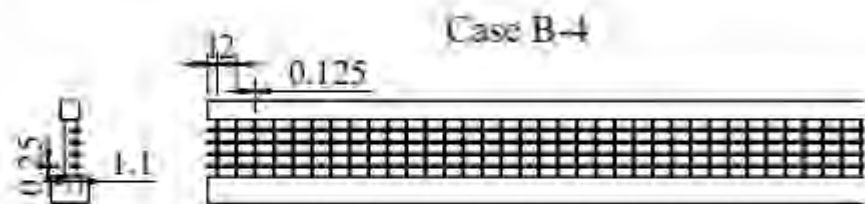
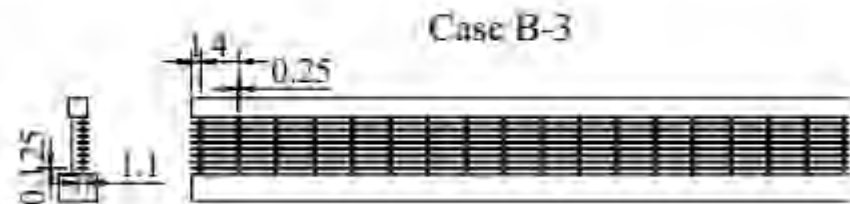
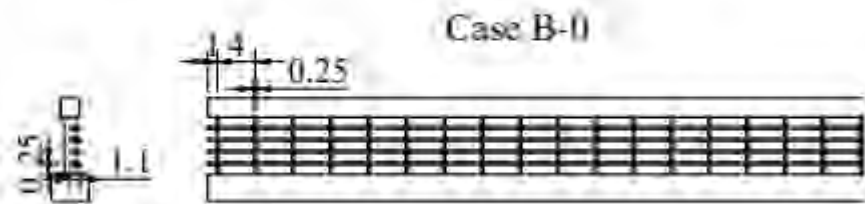


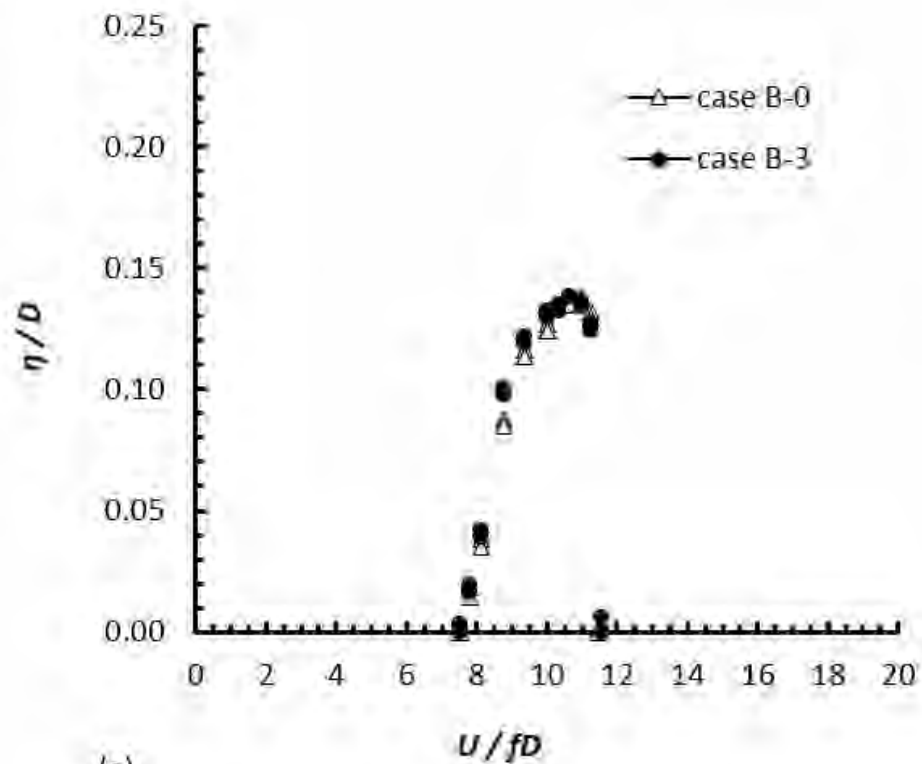


(a)

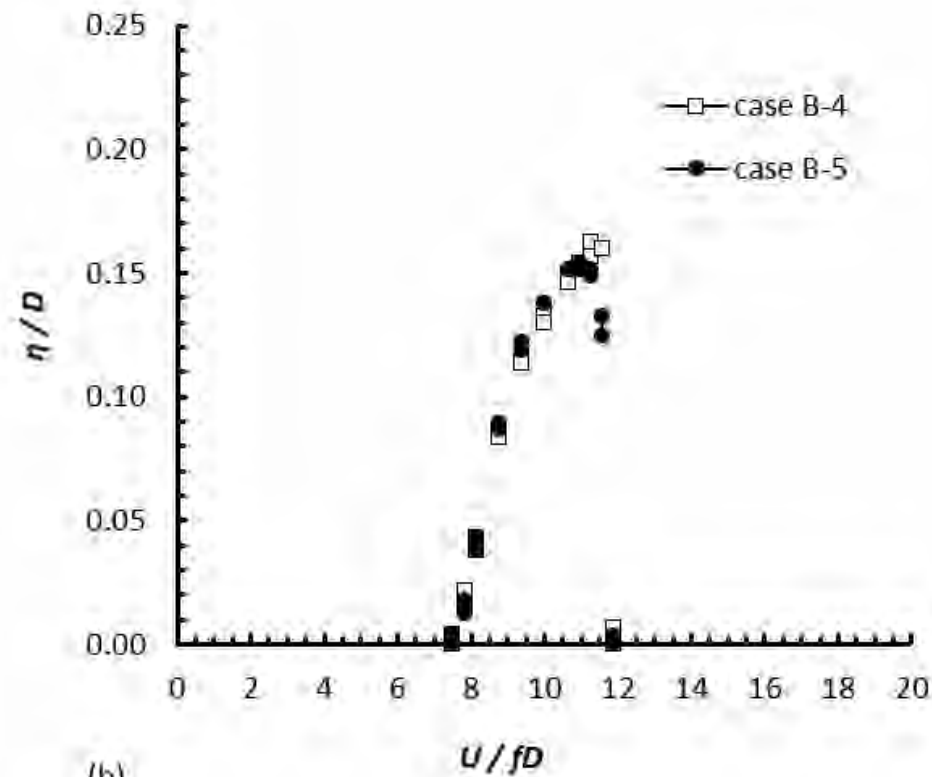


(b)

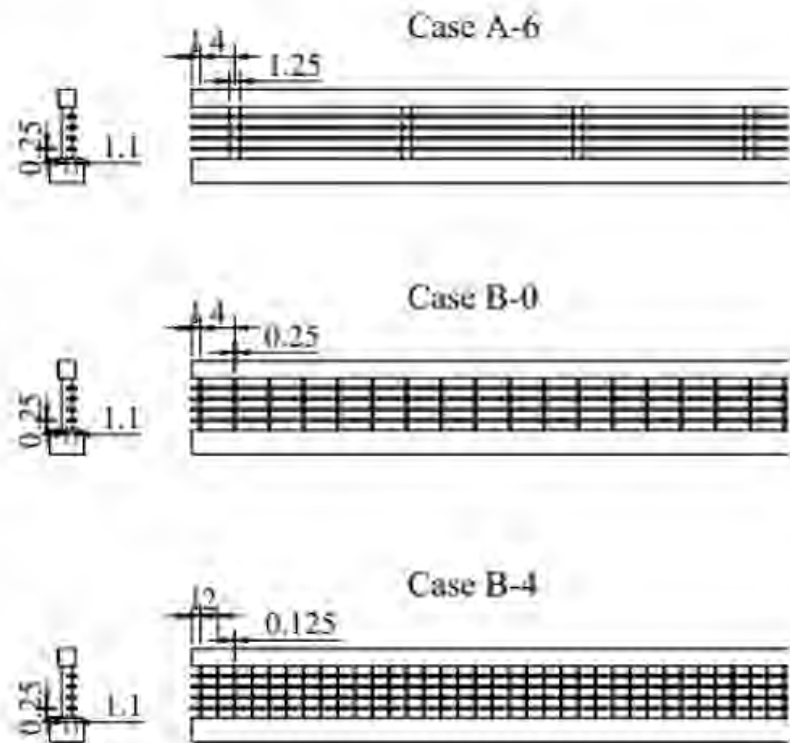




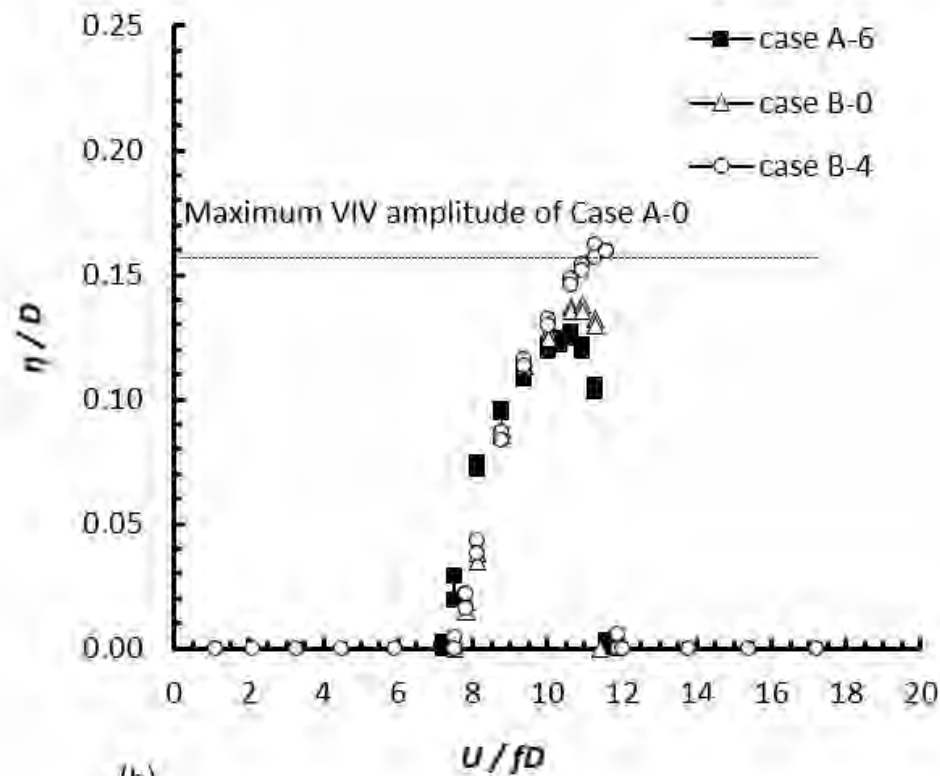
(a)



(b)



(a)



(b)