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Experimental and numerical study on generation and mitigation of vortex-induced vibration of open-cross-section composite beam

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Abstract. Open-cross-section composite beam (OCB) tends to suffer vortex-induced vibration (VIV) due to its bluff aerodynamic shape. A cable-stayed bridge equipped with typical OCB is taken as an example in this paper to conduct sectional model wind tunnel test. Vortex-induced vibration is observed and maximum vibration amplitudes are obtained. CFD approach is employed to calculate the flow field around original cross sections in service stage and construction stage, as well as sections added with three different countermeasures: splitters, slabs and wind fairings. Results show that flow separate on the upstream edge and cause vortex shedding on original section. Splitters can only smooth the flow field on the upper surface, while slabs cannot smooth flow field on the upper or lower surface too much. Thus, splitters or slabs cannot serve as valid aerodynamic means. Wind tunnel test results show that VIV can only be mitigated when wind fairings are mounted, by which the flow field above and below the bridge deck are accelerated simultaneously.

Keywords: open-cross-section composite beam; vortex-induced vibration; splitters; slabs; wind fairings; velocity field; vorticity field

1. Introduction

The deck of modern long-span cable-stayed bridges can be made of purely steel, purely concrete or steel-concrete composite beam, which refers to a cross section consisting of a concrete floor mounted on longitudinal steel girders. The longitudinal steel girders can be single I-beam, box girder, or two I-beams locating on two edges of concrete floor, which is called open-cross-section composite beam (OCB). OCB is one of the most preferable choices for long-span bridges, due to four main reasons, a) low-weighted, b) economic, c) easily to construct and d) forced reasonably. It has been employed in a variety of completed bridges, such as Shanghai NanPu Bridge, YangPu Bridge, Fujian MinJiang Bridge.

With the increase in span length of bridge nowadays, the importance of bridge aerodynamic performance becomes more prominent. The shape of OCB tends to be ‘bluff’, making it easier to

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cause vortex induced vibration. For the purpose of enlarge the application area of OCB, non-structural aerodynamic means like wind fairings, splitters etc. can be added, to improve the aerodynamic performance.

Due to the complexity of flow field around OCB, few studies have been focused on the mechanism of generation and mitigation VIV of this type of sections. (Kubo *et al.* 2001, Kubo *et al.* 2002) found that the aerodynamic responses of OCB could be much suppressed by just moving the location of main steel girders inward and also setting solid crash barriers at inward location, without adding any specific appendages. Irwin (2008) undertook the sectional model wind tunnel test of Second Severn Bridge, and the experimental results showed that two vertical baffle plates mounted on the lower surface of bridge could be used to decrease the oscillation amplitudes. Zhitian *et al.* (2011) studied the effectiveness of a hybrid method combined with vertical baffle plates on the upper and lower surface in controlling the structural vibration. Guowei *et al.* (2015) modified the rectangular sections of barriers and rails into circular ones, and installed a set of sharp-angle wind fairings on the leading edge of floor and horizontal splitters at the tip of steel girder, which tend to be a valid approach verified by the wind tunnel test. However, the above authors used wind tunnel test as their unique research method, in which they could only observe the specific motion such as flutter or harmonic oscillation occurs or not, and analyze the detailed amplitude, phase, or spectra of structural motion. These experimental results could be used to check the validity of proposed aerodynamic countermeasures, instead of giving an insight into the physics nature of flow pattern.

Some scholars have done research on mechanism of mitigating VIV of streamlined bridge sections, including closed boxing girders. Zhou *et al*. (2015) found that crash barriers on the upper surface of deck with different geometrical shape have different impact on the flow field pattern around the bridge section, resulting in different VIV responses. Nagao *et al.* (1997) studied the effects of position and size of handrails on bridge VIV responses by means of smoke wire method and surface pressure measurement and considered that handrails with high solidity ratio would amplify the amplitude of vertical VIV response. Francesco (Ricciardelli *et al.* 2002) analyzed the flow pattern around the bridge deck during vortex-induced oscillation by surface pressure distribution, lift, drag and pitching moment, response amplitude and wake velocity field obtained from the wind tunnel test. Sarwar and Ishihara (2010) compared the flow field around the bridge sections with and without aerodynamic means using CFD results, and concluded the change of flow pattern due to the addition of aerodynamic means. Li *et al*. (2011) used hybrid CFD method based on force vibration technology to studied fluid field characters of twin-box grid and mechanics of countermeasures. Most authors above focus their study on streamline deck section. OCB is seldom studied because of its complex flow field induced by bluff characteristic of deck geometry.

This paper takes a cable-stayed bridge equipped with typical OCB as an example. Sectional model wind tunnel test is carried out and vortex induced vibration with considerable amplitude is observed. CFD simulation is employed to calculate the flow field around the original section. Results of CFD are analyzed to find the cause of VIV. Furthermore, three kinds of aerodynamic means are proposed to mitigate the vibration phenomenon. The modification of flow field pattern around the section by different aerodynamic means is compared. Validity of three aerodynamic means are verified through the wind tunnel test.

2. Wind tunnel test and CFD settings

2.1 Wind tunnel test settings

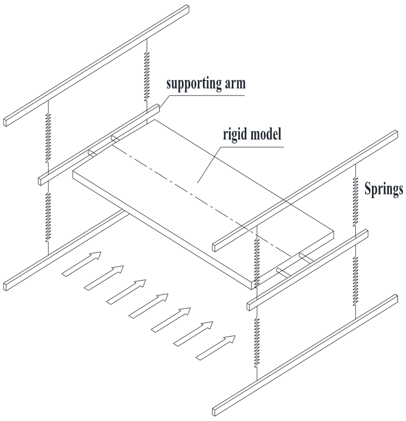
Wind tunnel test is conducted in TJ-1 laboratory of Tongji University. Fig. 1(a) shows the case of original bridge deck model and Fig. 1(b) to 1(d) show cases of bridge deck added with splitter, slabs and wind fairings, respectively. As shown in Fig. 1(e), sectional rigid model is supported by eight springs, whose ends are fixed in the tunnel wall. By setting reasonable structural mass and mass moment of inertia, as well as the rigidity of springs, vertical and torsional frequency of the bridge deck model can be achieved corresponding to the 1st order vertical and torsional frequency of prototype full bridge.

(a) Sectional rigid model and suspending system

(b) Model added with wind fairing

(c) Model added with slabs

(d) Model added with splitter



(e) Sketch of testing device

Fig. 1 Wind tunnel test models

According to the similarity requirements of sectional model design, frequency ratio λ_f and wind speed ratio λ_v are determined. The relationship of main parameters between real bridge and sectional model are shown in Table 1.

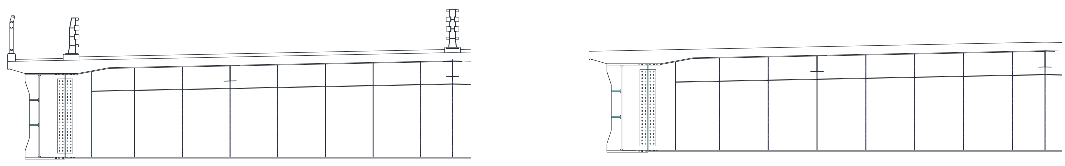
Cross sections of bridge deck model in servicing stage and construction stage are shown in Figs. 2(a) and 2(b) respectively. The main structure is composed of two steel longitudinal girders and a concrete floor. Structure members are connected with shearing studs, as well as several steel transverse girders distributing in equal space along the bridge direction. Cross section which considers the existence of crash barriers and pedestrian guard rails is the one in servicing stage, while the cross section which does not is in construction stage. Two sets of models have different mass system, stiffness system and natural frequencies. All of the experiments are conducted in the uniform flow.

2.2 CFD settings

In order to understand flow behavior around the section and mechanism on improvement of vortex induced vibration, CFD techniques are employed as a supplementary tool of wind tunnel test. 2-dimensinal circular computational domain is established with bridge deck sections locating in the center. Diameter of the circular domain is set as 40 times width of bridge deck to guarantee that outer boundary is far enough from the wall boundaries. In the near wall region, layers of block-structured girds with fine size are generated, to simulate the wall bounded flow characteristics, while a coarser mesh is used for the region far from the solid walls. Total number of grids adds up to 400,000.

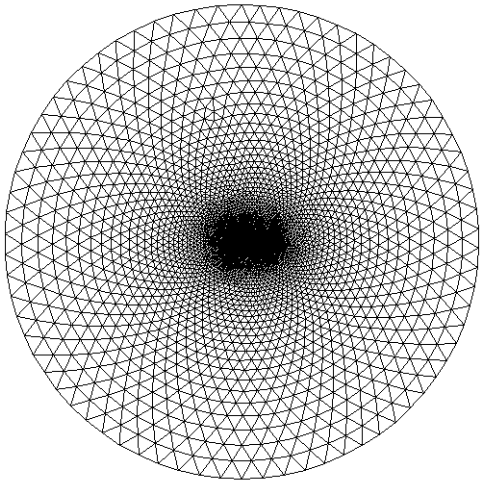
Table 1 Similarity scales and setup parameters for sectional model wind tunnel tests

Parameters		Unit	Prototype	Scales	Model(target)	Model(measured)
Length	L	m	104.4	λ_L = 1:60	1.74	1.74
Width	B	m	28	λ_L = 1:60	0.467	0.467
Depth	D	m	3.78	λ_L = 1:60	0.063	0.063
Mass	m	kg/m	40900	λ_m= 1:60^2	11.36	11.36
Frequency	f_h	Hz	0.3178	λ_f =6.67:1	2.119	2.202

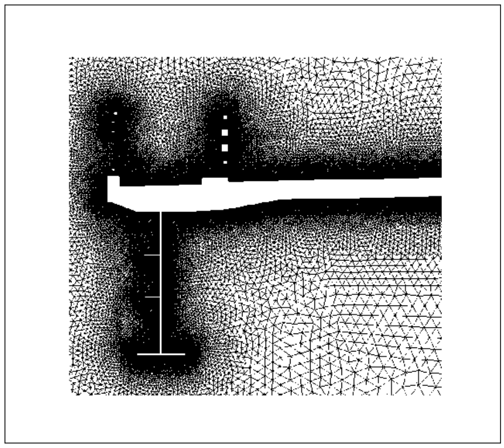


(a) Servicing sections (b) Construction sections

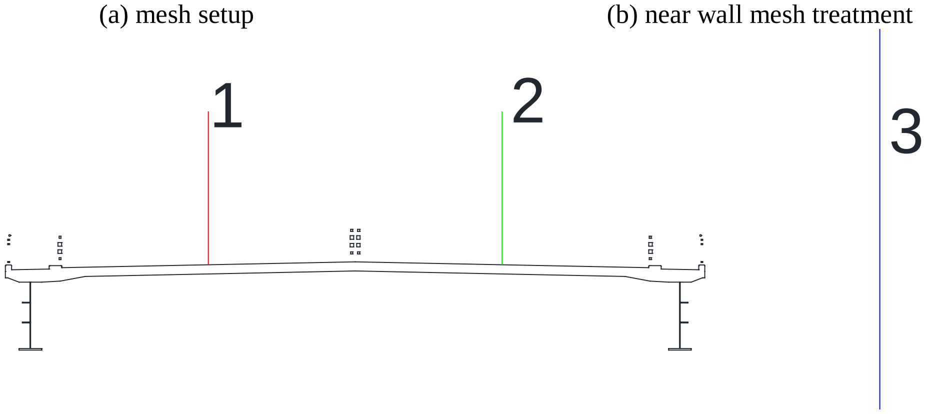
Fig. 2 Cross section of bridge deck model



(a) mesh setup



(b) near wall mesh treatment



(c) Monitoring Line 1,2 and 3

Fig. 3 Mesh setup and monitoring lines

The boundary condition of left semicircle is set as velocity inlet, with the x-direction wind speed equal to 4m/s, corresponding to the maximum harmonic vibration amplitude occurred in the experiment case of original section. Wind velocity direction is set as 0°、+3°、-3°with respect to the level. +3°means the wind flows from lower to upper when going from left to right. The right semicircle is set as pressure outlet, with the gauge pressure value equal to 0. SST model is chosen to simulate turbulence flow field. In the process of computation, three vertical lines with each having 50 points are chosen to monitor flow field structure in the vicinity of section. Line 1 stands at the upper surface of left-half deck to monitor the flow field above the upwind deck part. The second line locates on the upper surface of right-half deck to record the characteristics of flow field above the right-half deck. The third line is set downstream of the section to read the wake flow structures.

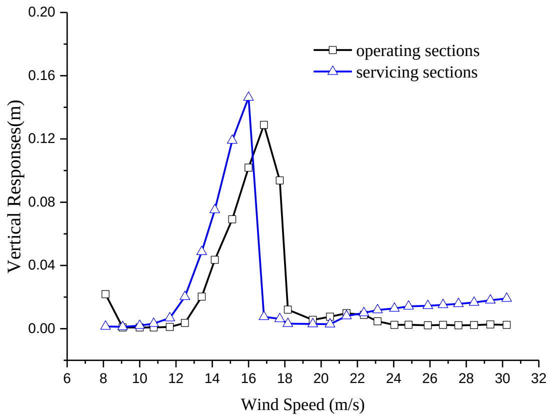


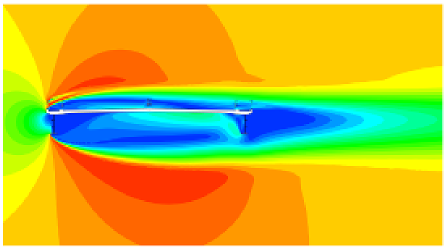
Fig. 4 Vertical VIV responses of prototype section

3. Experimental and preliminary numerical results

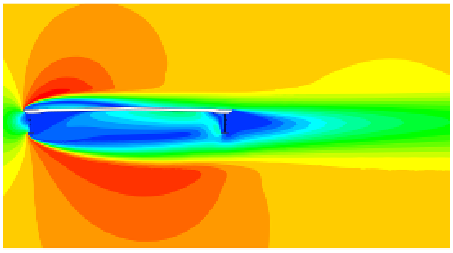
During the wind tunnel test of original cross sections in servicing stage and construction stage, vertical VIV is observed. Vertical responses of both cases at 0 degree attack angle are shown in Fig. 4. It can be observed that vertical oscillation of sections in servicing stage occurs in the wind speed range of 13.4–16.8 m/s, with the peek amplitude of 0.13 m, and VIV lock-in range of sections in servicing stage is 12.5–16.0 m/s, with the peek amplitude of 0.15 m. If VIV occurs, it can result in uncomfortable sense for driving and structural fatigue. Experimental results show that it is not the crash barriers or pedestrian guard rails that induces structural oscillations, because both sections with and without handrails have experienced this problem. Existence of barriers and rails can magnify the amplitude of oscillations. This characteristic is quite different from streamlined box grids. While for streamlined box sections, it is always the handrails that increases the bluffness of sections and cause VIV.

Time-averaged velocity and vorticity field of sections in servicing and construction stage are obtained from CFD simulations. It can be seen from Fig. 5 that upstream edges of both cross sections tend to be bluff due to the concrete floor and steel girder. Flow starts to separate on the upstream edge of floor and steel girder flange, and reattach on the upper surface of floor deck. The flow separation, reattachment, and vortex shedding cause unsteady aerodynamic pressure acting on sections. If the total force frequency arrives close to the natural frequency of structure, the bridge starts to vibrate.

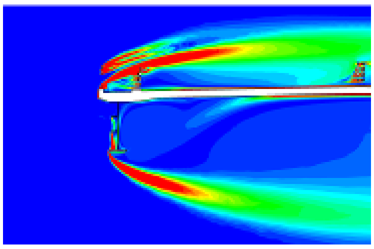
In order to study attack angle influence and find the most adverse attack angle of original section, both numerical simulation and wind tunnel experiments are carried out at +3 and -3 degree. Mean X-velocity contour of +3 and -3 degree are shown in Figs. 6(a) and 6(b). Profile of X-velocity at Line 1 and Line 2 as functions of distance from deck are compared in figure c) and d). Both X-velocity profile at Line 1 and Line 2 indicate that flow velocity is greater at -3 degree while results of +3 degree are minimum. This imply that flow separation of +3 is stronger than other two angles and cause more severe unsteady vortex induced force acting on deck upper surface. Wind tunnel results shown in Fig. 6(e) further proved that +3 degree is the most adverse attack angle.



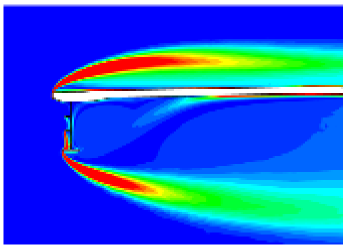
(a) X-velocity contour of servicing sections



(b) X-velocity contour of construction sections

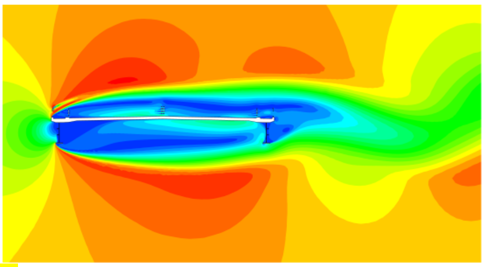


(c) Vorticity contour of servicing sections

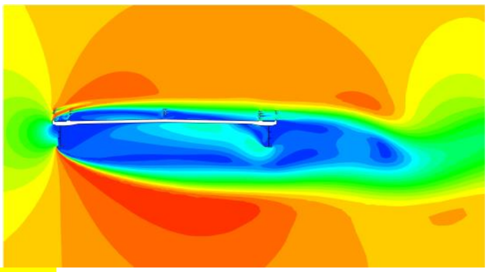


(d) vorticity contour of construction sections

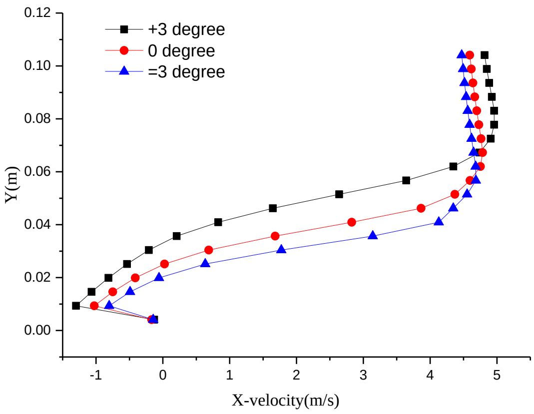
Fig. 5 Velocity and vorticity contour of sections of original section



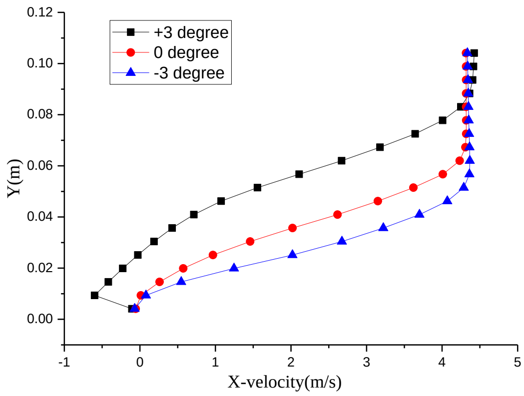
(a) X-velocity contour of attack angle at +3°



(b) X-velocity contour of attack angle at -3°



(c) X-velocity profile of Line 1



(d) X-velocity profile of Line 2

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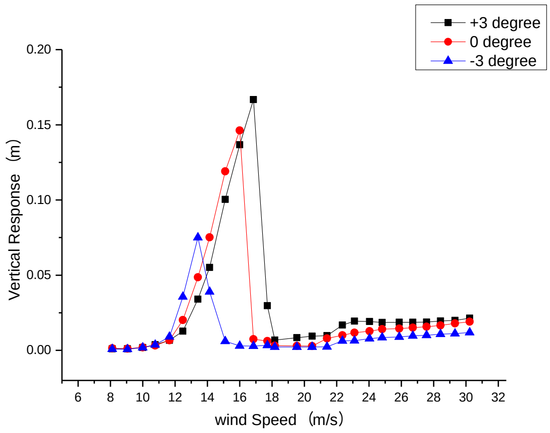


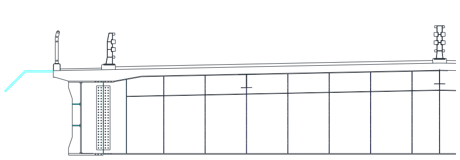
(e) Wind tunnel results of different attack angle

Fig. 6 Numerical and experimental results of different attack angles

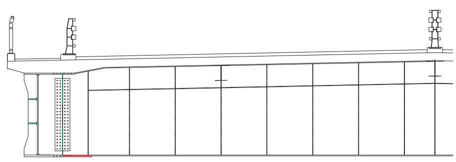
4. Scheme proposed to suppress VIV

4.1 details of scheme

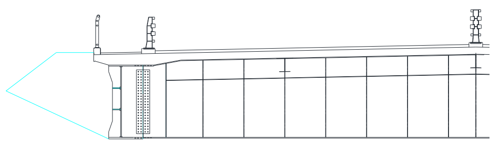
According to CFD results shown above, some aerodynamic means must be added to smooth the turbulent flow field around the upper surface and lower surface of sections. Three schemes are proposed, 1) splitters are installed on the side of deck (Fig. 7(a)); 2) slabs are installed inward of steel girders flange (Fig. 7(b)); 3) wind fairings are installed on the side of web of steel girders (Fig. 7(c)). The function of splitters is to reduce the flow separation on the upper part of upstream edge. Slabs allow flow reattach on it to improve flow field behavior in the lower side of sections. Wind fairings can help to smooth the flow field on the upper and lower surface of sections simultaneously.



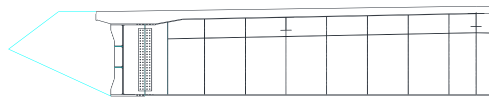
(a) servicing sections added with splitters



(b) servicing sections added with slabs

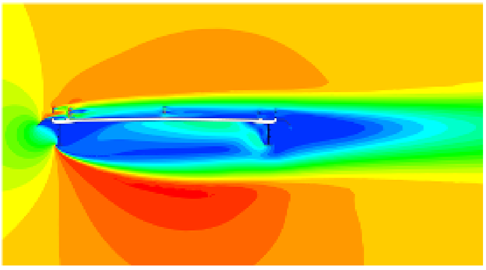


(c) servicing sections added with wind fairings

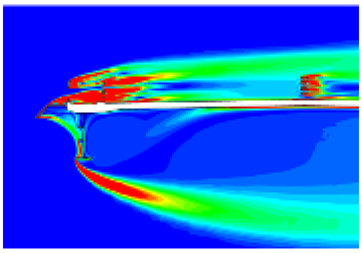


(d) construction sections added with wind fairings

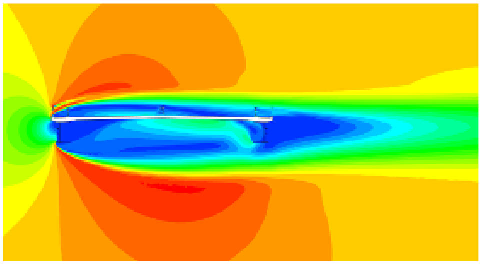
Fig. 7 Scheme proposed to suppress the VIV



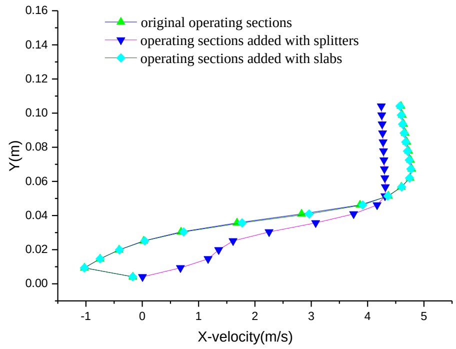
(a) X-velocity contour of sections added with splitters



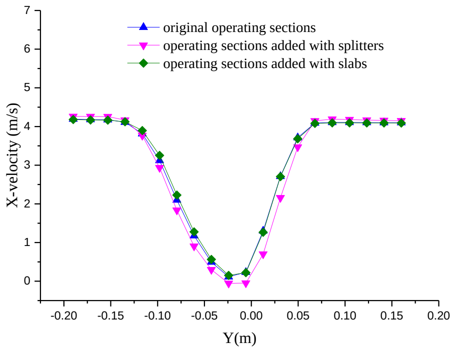
(b) Vorticity contour of sections added with splitters



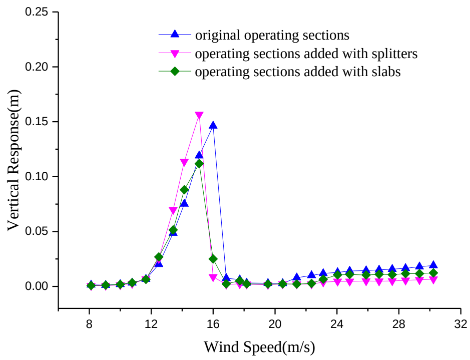
(c) X-velocity contour of sections added with slabs



(d) X-velocity profile of Line 1



(e) X-velocity profile of Line 3



(f) Vertical VIV response of prototype section

Fig. 8 Numerical and experimental results of sections added with splitters and slabs

4.2 Splitters and slabs

CFD results of countermeasures proposed above are shown in Fig. 8. Comparing Fig. 5(a) to Fig. 8(a), it can be observed that the 'blue' region(represent low value of velocity) above the upper surface of deck is reduced when splitters are mounted, meaning that velocity magnitude of flow field at this position is enlarged. This also can be verified by Fig. 8(d), in which the X-velocity profile as function of distance from deck surface at Line 1 is demonstrated. The mean flow X-velocity near the surface of original section deck is negative, meaning there is a recirculation zone at this position. On the contrary, mean flow X-velocity at the same position of sections added with splitters turns to be positive, meaning that recirculation zone has disappeared, instead of which is a more smooth flow field.

Wind tunnel test of sections added with splitters is undertaken then. Experimental results are shown in Fig. 8(f). It can be seen that the maximum vibration magnitude value is not reduced when added with splitters, meaning that VIV cannot be suppressed by only smoothing the flow field above the upper surface of deck.

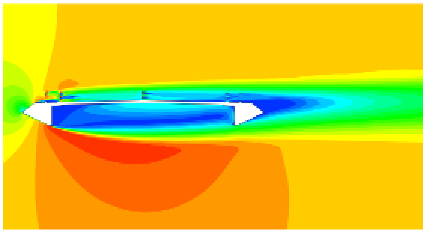
Installing slabs inward bottom plates of steel I-girders, as extension of bottom flange, can be treated as a valid way to mitigate VIV of OCB (Guowei *et al.* 2015). Flow field of sections added with slabs is shown in Fig. 8(c). It can be seen that the existence of slabs has little impact in neither the upper and lower flow field (see Fig. 8(c)) nor wake region width (see Fig 8.e). Wind tunnel test results of sections added with slabs show that the existence of slabs can reduce vibration amplitude slightly. Therefore, slabs cannot be used individually for OCB discussed in this paper, but as a supplementary way with other countermeasures, such as wind fairings and splitters.

4.3 Wind fairings

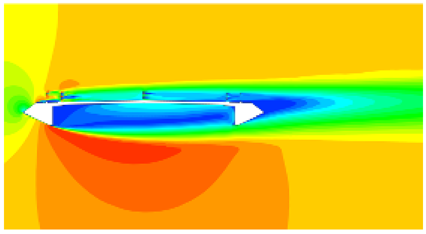
Furthermore, a more valid way to entirely mitigate VIV of OCB is proposed. That is, wind fairings with a sharp angle are mounted outward of two steel girders. This aerodynamic means can make OCB more streamlined at the upstream and downstream edges to reduce flow separation above and below the bridge deck simultaneously (comparing Fig. 9(a) with Fig. 5(a)). Fig. 9(c) shows the X-velocity profile of Line 1. It can be seen that when added with wind fairings, negative X-velocity profile of near wall region in upwind lane turns to be positive and the flow accelerate effect is better than case of splitters. Fig. 8(d) shows the X-velocity profile of Line 2. It can be seen that X-velocity of near wall region in the downwind lane is also increased. Wind tunnel test results of sections added with wind fairings are shown in Fig. 9(f). There is no VIV phenomenon observed during the experiment of case of wind fairings, meaning that when the X-velocity of flow field above and below the bridge deck is accelerated due to the existence of wind fairings, VIV can be eliminated.

CFD simulation and wind tunnel test of construction sections with and without wind fairings are also undertaken to confirm the validity of wind fairings. Fig. 9(b) shows that the ‘blue’ region above and below the bridge deck has been reduced when wind fairings are mounted. X-velocity of near wall region of both upwind and downwind lane are positive; meaning the flow separation in that region is reduced. Fig. 9(e) shows the X-velocity of Line 3, downstream of the sections. The width of wake becomes narrow when wind fairings exist. There is no VIV phenomenon occurred with respect to construction sections added with wind fairings in wind tunnel test.

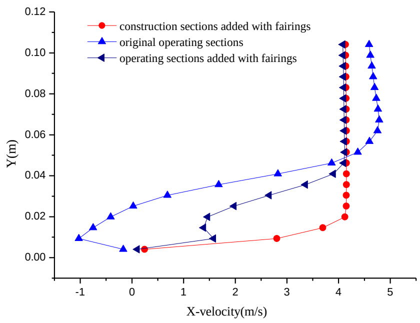
Section added with wind fairing is studied at +3 degree of attack angle to further assure the effectiveness of means to mitigate VIV. Numerical results in Fig. 10(a) show that with the help of wind fairs, x-velocity on the upper surface of deck at +3 degree are much faster that that of original section at both monitor line 1 and 2. Wind tunnel results proved again that wind fair can successfully mitigate VIV for both servicing and construction sections at +3 degree attack angle.



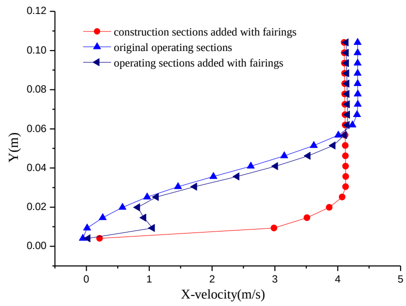
(a) X-velocity contour of servicing sections added with wind fairings



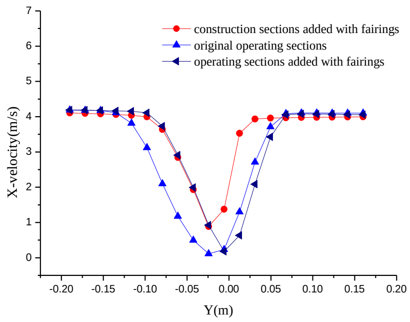
(b) X-velocity contour of construction sections added with wind fairings



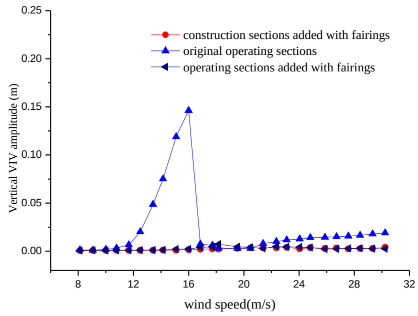
(c) X-velocity profile of Line 1



(d) X-velocity profile of Line 2

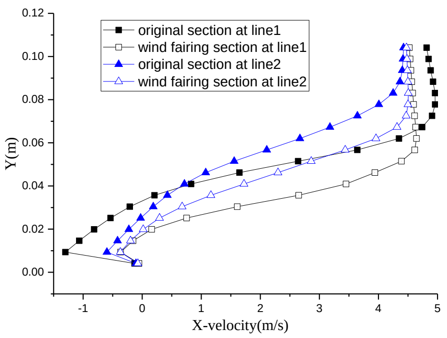


(e) X-velocity profile of Line 3

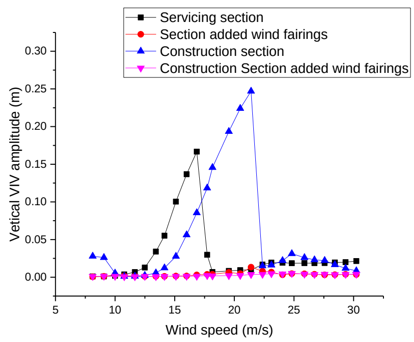


(f) Vertical VIV response of prototype section

Fig. 9 Numerical and experimental results of sections with wind fairings

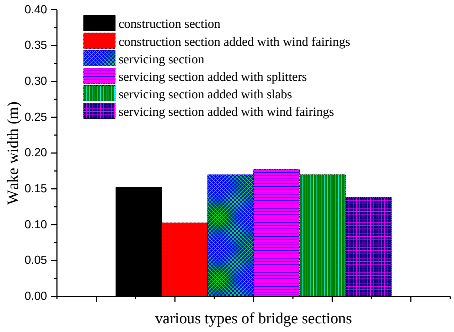


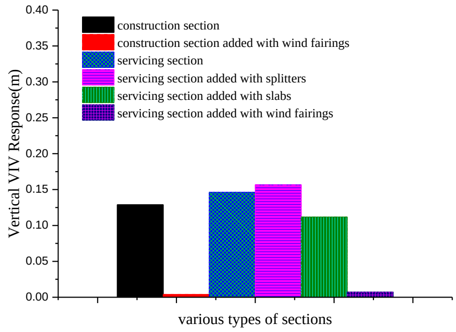
(a) X-velocity profile of Line 1 and Line 2 at +3°



(b) Vertical VIV response at +3°

Fig. 10 Comparison of results of sections with wind fairings at +3 degree





(a) Wake width (b) Vertical VIV response

Fig. 11 Wake width versus vertical VIV response

4.4 Wake width versus VIV amplitude

Fig. 11(a) shows the width of wake of various types of bridge sections, including original sections and sections added with wind fairings, splitters and slabs. The wake width is defined as the length of region on Line 3 in which flow X-velocity does not exceed 0.95 times far field velocity. Fig. 11(b) shows the maximum amplitude of vertical VIV observed during the wind tunnel test procedure.

From Figs. 11(a) and 11(b), the maximum amplitude of vertical VIV with respect to each type of sections has strongly positive relationship with the wake width of this section, namely, the narrower the wake behind the section is, the lower the VIV amplitude tend to be. The construction section added with wind fairings and servicing section added with wind fairings are a good case in point. It is also found that the servicing section added with splitters has a smaller vertical VIV amplitude than original section, due to the smoothing of flow field above the upper surface of bridge deck. But as the splitters have little impact on the turbulent flow field on the lower surface of deck, it cannot mitigate the VIV phenomenon significantly.

5 Conclusions

A cable-stayed bridge equipped with typical OCB was taken as an example in this paper to conduct sectional model wind tunnel test. Vortex-induced vibration lock-in wind speed and amplitudes were obtained. CFD approach was employed to calculate the flow field around the original cross sections in servicing stage and construction stage, as well as sections added with three means - splitters, slabs and wind fairings.

a) Upstream edge of OCB tends to be ‘bluff’ , which makes it easier for flow to separate, causing severe unstable aerodynamic forces acting on the section, leading to VIV phenomenon. Both the crash barriers and pedestrian guard rails have little influence on the generation of vortex induced vibration.

b) Splitters can only smooth the flow field on the upper surface. Slabs cannot smooth the flow field on the upper or lower surface too much. Therefore, splitters or slabs cannot serve as valid aerodynamic means if used alone. Wind fairings can accelerate flow field above and below the bridge deck, making great contributions on eliminating vortex shedding, resulting in mitigating vortex induced vibration.

c) The amplitude of VIV is positive relation to the section wake width, meaning that if wake width can be decreased by the use of aerodynamic means, which reduces the flow separation, then the vibration phenomenon can be mitigated.

d) A method combined with CFD simulation and wind tunnel test, can be employed to analyze aerodynamic problem of bridge deck, find the essential cause of the problem, and propose reasonable aerodynamic means to optimize aerodynamic performance of bridge deck.

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