

Dynamic wind actions on catwalk structures

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ABSTRACT: Wind tunnel tests and buffeting analyses were conducted to investigate wind induced responses of a catwalk structure of a suspension bridge. It was found from the wind tunnel tests that the Reynolds number effects on the aerostatic coefficients were negligible for the catwalk floor systems. Design formulae were proposed to estimate the aerostatic coefficients of catwalks with various solidity ratio and angle of attack. The buffeting analysis results revealed that tying the catwalk on an erecting main cable may be an effective structural countermeasure to reduce the lateral displacements of the catwalk.

KEYWORDS: Catwalk; Suspension bridge; Wind force; Wind tunnel test; Reynolds number.

1 INTRODUCTION

1.1 Catwalk system

Catwalk structures are temporary walkways that allow the erection of main cables in suspension bridges. As shown in Figs. 1 and 2, catwalk structures consist of a few ropes, wooden beams, wooden steps, and porous wire meshes at the bottom and sides. The ropes support a worker's weight, equipment for cable erection, and some wires forming main cable. The other components of catwalk are used for pedestrian comfort and safety. A pair of catwalk structures is generally installed along the main cables and linked at regular intervals by cross bridges.



Figure 1. Catwalk structure of Kwangyang Bridge.

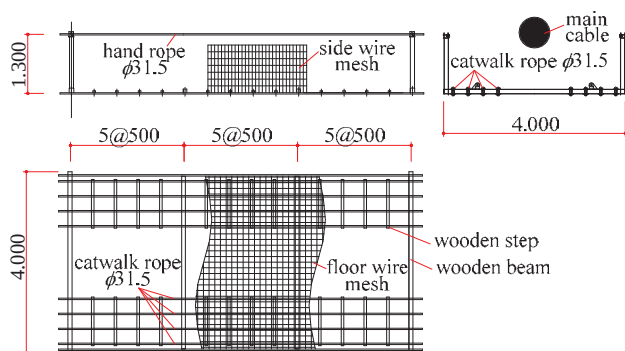


Figure 2. Details of the catwalk system.

The target model used in the present study was a catwalk structure derived from a design alternative of the Kwangyang Bridge, which has a main span length of 1,430 m (Fig. 1). The data used in this paper are not the actual properties of the Kwangyang Bridge catwalk but those of an alternative submitted to a design competition by DM Engineering Company.

As shown in Fig. 2, the width and height of the single side catwalk were 4.0 m and 1.3 m, re-

spectively. Each catwalk consists of 10 ropes with a diameter of 31.5 mm and a safety apparatus consisting of wire mesh, a wooden step, and a hand post. The solidity ratios of the side and bottom were 7% and 16%, respectively.

1.2 Previous research and research objective

The effects of wind on catwalk systems have not been well defined although many suspension bridges have recently been completed or are under construction worldwide (Tanaka 1998). Kawaguchi and Fukunaga (1995), Takeno et al. (1997), and Kitagawa (2004) suggested an erection plan for the catwalk structure in the Akashi Bridge. They assessed possible technical problems arising from the erection of the main cable such as the hauling system, erection sequence, static deformation, aerodynamic stability, arrangement of cross bridges, and vibration control measures. Matsuzaki et al. (1990) introduced the fabrication and erection of the prefabricated parallel wire strand used for most of the Honshu-Shikoku Bridges in Japan.

Shinichi et al. (1997) provided information for the design and construction of the catwalks for the Kurushima Bridges. They tested the effectiveness of stay ropes and guy ropes to mitigate vibrations of the catwalk using a 1/10 scaled structural model. Recently, Zheng et al. (2007) performed wind tunnel tests for the catwalks of the Runyang Bridges. Although they measured aerostatic force coefficients for various angles of attack and yaw angles, their tests were limited to a specific catwalk and did not provide general information for the aerodynamic forces acting on catwalk structures.

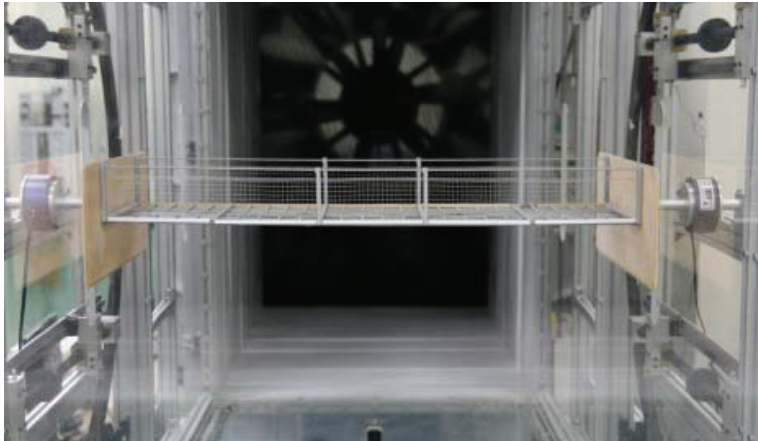
As a countermeasure to mitigate the lateral vibration of catwalks, additional storm ropes have been used to stabilize catwalk structures, which are sensitive to wind action due to their flexibility. The use of storm ropes, however, is associated with some disadvantages such as a protracted construction period, inconvenient navigation, and anchorage problems (Akiyama et al. 1999). Recently, additional guy ropes parallel to catwalk ropes or horizontal ropes connecting each catwalk have been adopted to reduce the horizontal vibrations caused by wind as well as by catwalk use (Hojo et al. 1995).

As summarized above, limited research has been conducted concerning the aerodynamic characteristics of catwalk structures. In particular, Reynolds number effects of porous catwalk structures have not been investigated. In this study, wind tunnel tests of two different scale models were performed in order to investigate the effects of the Reynolds number, main cable, and solidity ratio. Parameter studies of structural properties of catwalks and countermeasures to vibration were performed to examine the wind induced responses of catwalks by applying buffeting analysis in the time domain. This paper summarizes the technical results obtained from wind tunnel tests and buffeting analyses of catwalks.

2 EXPERIMENTAL SETUP

The parallel catwalks along the bridge axis are assumed to be aerodynamically independent of each other, because the porous catwalks were separated by more than 20 m. Consequently, wind tunnel tests were only conducted for a single catwalk.

Two rigid models with scale of 1/14 and 1/4 were fabricated and tested in wind tunnels to obtain the aerostatic force coefficients of the catwalk floor system. The solidity ratios of the model were varied by replacing porous wire mesh tied at steel frame. In order to investigate the Reynolds number effects, the aerostatic force coefficients of two different scaled models were measured at various wind velocities ranging from 5 to 30 m/s, which correspond to 1/84 to 1/4 of the Reynolds number of the actual catwalk.



(a) 1/14 scale model in the small wind tunnel
Figure 3. Catwalk models in the wind tunnels.



(b) 1/4 scale model in the large wind tunnel

Fig. 3 shows the catwalk models installed on external force balances in the wind tunnels. The wind tunnel tests were carried out in two wind tunnels at the KOCED Wind Tunnel Center at Chonbuk National University in Korea. The 1/4 scale model tests were performed at the high speed test section of a closed return type wind tunnel. The size of the test section was 5.0 m wide $\times$ 2.5 m high $\times$ 20 m long, and the maximum wind speed was 31 m/s. The 1/14 scaled model was tested at the small wind tunnel with a test section of 1.0 m wide $\times$ 1.5 m high $\times$ 5 m long. The turbulent intensities of the large and small wind tunnels are less than 1% and 0.5% respectively.

The aerostatic forces acting on the models were measured using a pair of JR3 force balances that were capable of reading three forces and the associated three moments. The mean wind speed was measured using a pitot tube and a pressure transducer. The angle of attack was varied from -10 degree to +10 degree at 1 degree intervals. The correction for blockage effect was not done because blockage ratio of the models was less than 1%. The forces and moments were transformed into non-dimensional aerostatic coefficients using the following equations.

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 H}, \quad C_L = \frac{L}{\frac{1}{2}\rho V^2 H}, \quad C_M = \frac{M}{\frac{1}{2}\rho V^2 H^2} \quad (1)$$

where, D is the drag force, L is the lift force, M is the pitching moment, V is the free stream wind speed, ρ is the air density and H is the height of the catwalk.

3 EXPERIMENTAL RESULTS

3.1 Effects of the Reynolds number

The Reynolds number effects on the aerostatic coefficients were investigated using the two different scale models under uniform wind flow. The Reynolds numbers of the actual catwalk range from 4.3×10^5 to 2.6×10^6 , while those of the scale models ranged from 3.1×10^4 to 6.5×10^5 . The height of catwalk models was used for reference length evaluating the Reynolds numbers.

Fig. 4 shows that the Reynolds number effects on the aerostatic force coefficients were not significant for the catwalk floor systems. Lift coefficient and pitching moment coefficient were also found to be independent to the Reynolds number. In summary, the Reynolds number effect on aerostatic force coefficients of the catwalk system is negligible.

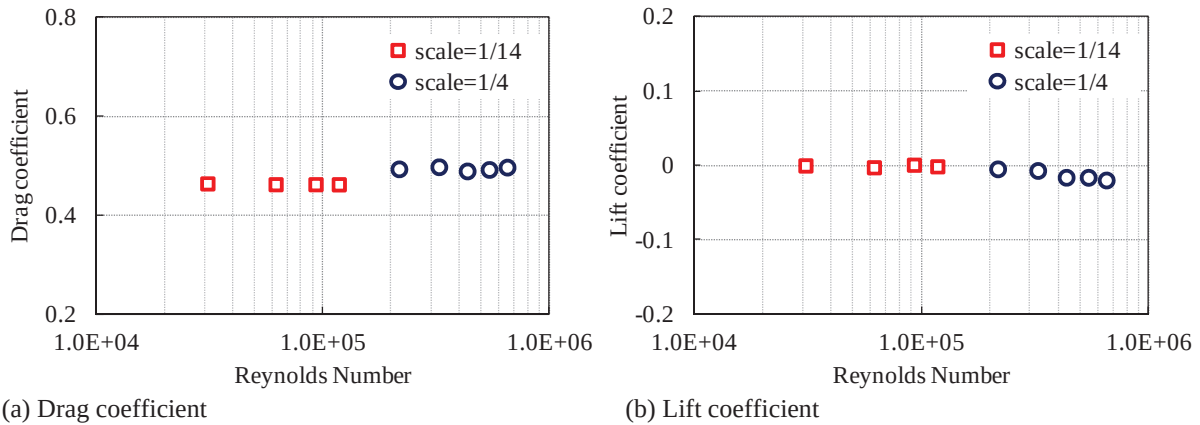


Figure 4. Aerostatic force coefficient as a function of Reynolds number.

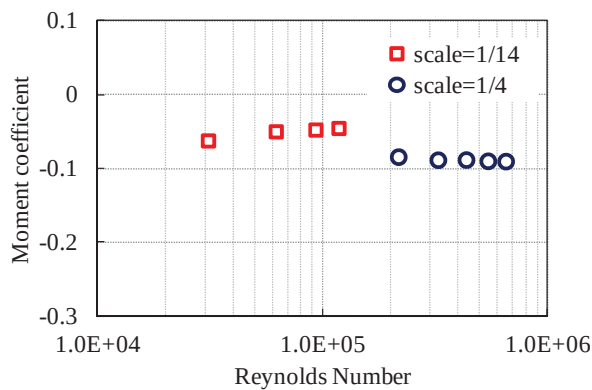


Figure 4.



Figure 5. Catwalk with the main cable at its center.

3.2 Effects of the main cable

As the main cable erection work nears completion through air spinning, a strand bundle is placed inside of the catwalk, as shown in Fig. 5. Differences in the displacements between the main cable and the catwalk structure can occur under high winds because of discrepancy in stiffness. Consequently, the location of the main cable within the cross section of the catwalk shifts from the center point to the quarter point of the catwalk. These conditions were simulated in the wind tunnel tests, and the effects of the main cable presence on the aerostatic coefficients of the catwalk structure were investigated.

Fig. 6 shows the aerostatic coefficients of the catwalk without and with the main cable at the center point and quarter point. Although the aerostatic coefficients were slightly reduced in the presence of the main cable, the effects of the main cable on the aerostatic coefficients of the catwalk are negligible from a practical point of view.

3.3 Effects of the solidity ratio

The solidity ratios of a catwalk vary over a wide range depending on suspension bridges. The bottom solidity is generally higher than the side solidity. In order to investigate the effects of the solidity ratios on the aerostatic coefficients, wind tunnel tests were performed for solidity ratios

of the floor system ranging from 9% to 23.5% at the side and from 16% to 30.5% at the bottom. Most of the catwalk floor systems surveyed in this study was within the above ranges. The solidity ratios of the test model were changed by tying a proper porous wire mesh to frame of model.

The test results are shown in Fig. 6. It is clear from the figures that the side solidity ratio strongly affects the drag and moment coefficients but not the lift coefficient. In addition, the lift coefficient is only influenced slightly by the bottom solidity ratio but the drag and moment coefficients are not. From the above results, it is found that the drag and moment coefficients are a function of side solidity ratios, yet the lift coefficients are a function of bottom solidity ratio.

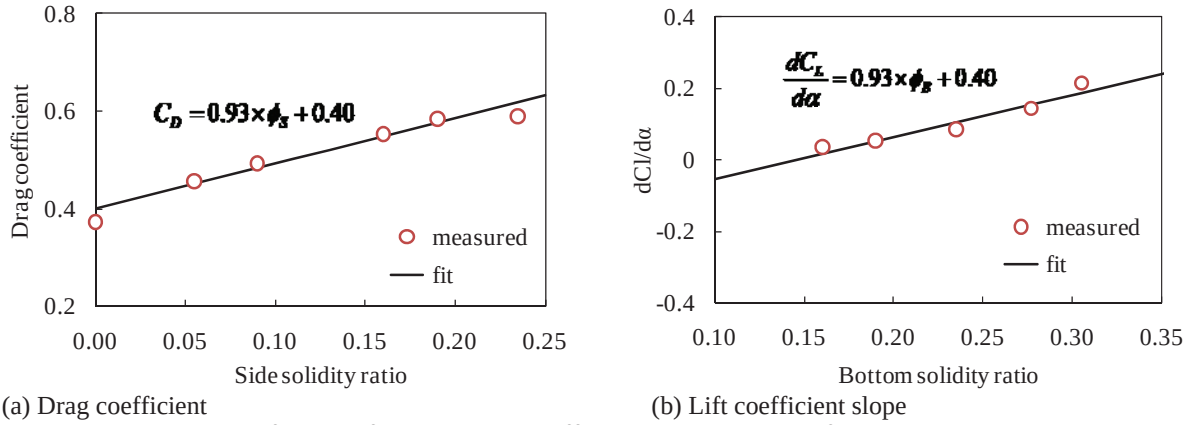


Figure 6. Aerostatic Best fit lines of the aerostatic coefficients at attack angle of 0°.

3.4 Design formulae for aerostatic coefficients

From the results of wind tunnels tests for various solidity ratios of the catwalk, it is clear that the aerostatic coefficients are affected mostly by the solidity ratio of the floor system. As shown in Fig. 6, the drag coefficient and moment coefficient are almost linearly proportional to the side solidity ratio. Therefore, the following linear fit equations are proposed to estimate the aerostatic coefficients of a catwalk at attack angle of 0 degree as functions of the solidity ratios.

$$C_D = 0.93 \times \phi_s + 0.40 \quad (2a)$$

$$C_M = -0.32 \times \phi_s - 0.06 \quad (2b)$$

$$\frac{dC_L}{d\alpha} = 0.93 \times \phi_b + 0.40 \quad (2c)$$

$$C_L \approx \frac{dC_M}{d\alpha} \approx 0 \quad (2d)$$

where α is angle of attack, ϕ_s is the side solidity ratio, and ϕ_b is the bottom solidity ratio. In addition, the best fit equations for drag coefficients as a function of angle of attack and solidity ratio are given as follows.

$$C_D(\alpha, \phi_s) = 1.674 \times 10^{-3} \alpha^2 + 2.862 \times 10^{-4} \phi_s^2 + 0.470, \quad \phi_b = 16\% \quad (3a)$$

$$C_D(\alpha, \phi_b) = 1.977 \times 10^{-3} \alpha^2 + 1.597 \times 10^{-5} \phi_b^2 + 0.493, \quad \phi_s = 9\% \quad (3b)$$

4 WIND INDUCED RESPONSES

4.1 Structural modeling and buffeting analysis

The catwalk structural system was modeled using finite element based structural analysis software developed by DM Engineering Co. Isolated catwalk system neglecting the flexibility of the supporting towers was adopted at the analysis. The catwalk ropes were modeled by an elastic catenary element and cross bridges were modeled by a frame element. A total of 10 ropes at each side of the catwalk were considered to behave coincidentally and were modeled as a single equivalent rope. The inertial effects of the wood steps, hand posts, and wire meshes were considered and their stiffness were neglected in the analysis.

To find the unstrained length and initial tension of ropes for the initial equilibrium configuration, present study used the TCUD (target configuration under dead loads) method that was an iterative numerical approach based on the Newton-Raphson method. Detail description of the TCUD method can be found in the reference (Kim and Lee 2001). By using the computed unstrained length and initial tension, the initial nonlinear static analysis was firstly conducted in order to include the influence of self weight on the deformations and internal forces of the catwalk structure, and then the free vibration analysis was done at next. The natural frequencies of the lowest four lateral modes were found to be 0.049 Hz, 0.097 Hz, 0.146 Hz, and 0.195 Hz. The lowest four vertical modes were 0.137 Hz, 0.194 Hz, 0.231 Hz, and 0.275 Hz.

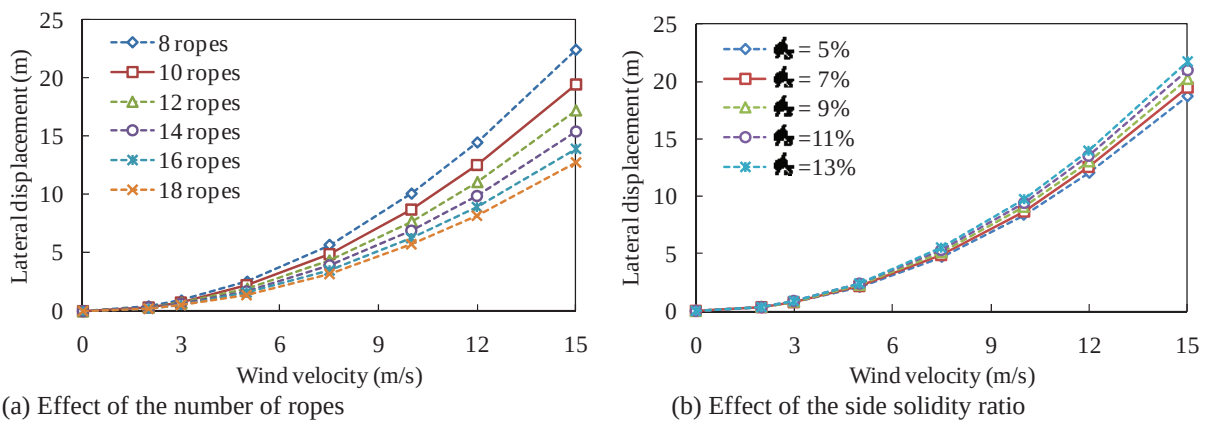


Figure 7. Static lateral displacements of the catwalk under wind loads.

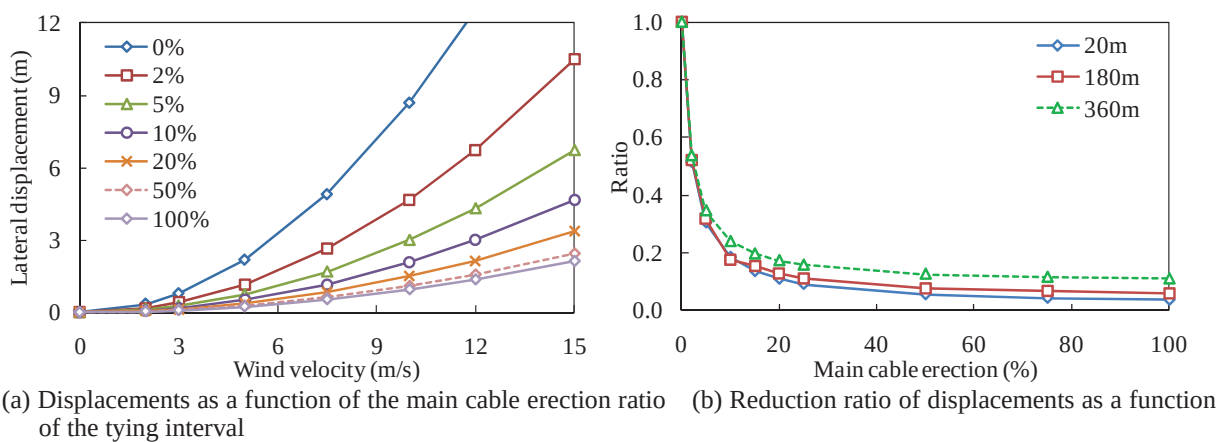


Figure 8. Static lateral displacements of the catwalk tied to the erecting main cable.

The horizontal and vertical components of turbulent wind velocities were generated by the ARMA technique considering special correlations along the bridge axis (Cao et al. 2000). Wind velocities were generated every 50 m along the bridge axis. A modal analysis combining the free vibration data and buffeting forces was performed to compute the catwalk displacements under turbulent winds. In the quasi-steady theory, the instantaneous forces acting on the moving catwalk structure are almost identical to the static forces at the same effective attack angle, and the phase lag between wind and moving body velocity is not considered. Aerodynamic damping was evaluated from the forced vibration tests (Kwon and Lee 2009).

4.2 Static responses

Fig. 7 shows the static lateral displacements of the catwalk under wind loads. The displacements gradually decrease as the number of ropes increases. However, the cross bridge intervals had a minor effect on the static lateral displacements. Static displacements slightly increased as the side solidity ratio was increased. This is because the drag coefficient increased by only 20% as the side solidity ratios increased from 5% to 13%.

Fig. 8(a) shows the static lateral displacements of the catwalk as a function of main cable erection completion. As the main cable erection was close to completion, the significantly increased stiffness of the main cable contributed to reduce the lateral displacement of the tied catwalk. Fig. 8(b) shows the effect of the tying interval between the catwalk and main cable on the lateral displacement. The lateral displacement can be effectively reduced by tying down the catwalk and main cable, regardless of the tying interval if the stress level of tying material is acceptable.

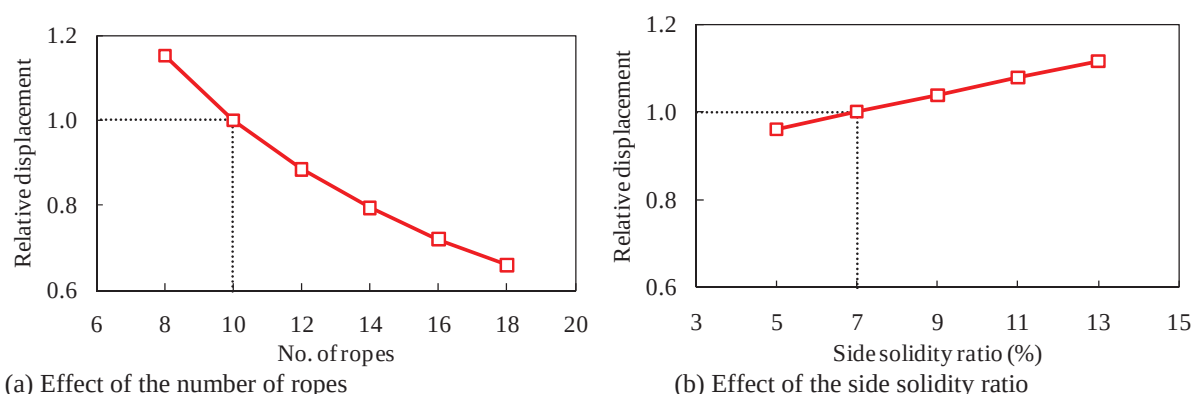


Figure 9. Relative dynamic lateral displacements of the catwalk under turbulent winds.

4.3 Dynamic responses

Relative dynamic lateral displacements of the catwalk are given in Fig. 9. To allow a relative comparison of each structural type, the lateral displacements of the catwalks were normalized by dividing by the lateral displacement of the generic catwalk shown in Fig. 2. The dynamic displacements were significantly reduced as the number of ropes was increased. The cross bridge slightly contributed to reduce the lateral displacements. However, increasing the number of cross bridges may not be an effective way to reduce the lateral vibrations. The dynamic displacements also slightly increased as the side solidity ratio increased, as in the static evaluation results. In conclusion, the reduction of dynamic displacements can be effectively accomplished by increasing the number of ropes, that is, stiffening. However, the effect of the cross bridge interval on the vibration reduction is not significant.

5 CONCLUSIONS

Wind tunnel tests and buffeting analysis were performed in order to investigate wind induced responses of catwalk structures of a suspension bridge. The main findings of the present study are as follows.

The wind tunnel tests revealed that the Reynolds number effects on the aerostatic coefficients were negligible for the catwalk floor systems. The aerostatic coefficients of the catwalk were found to be consistent for practical purposes, regardless of the presence of the main cable inside the catwalk. Simple design formulae that are functions of the solidity ratios were proposed to estimate the aerostatic coefficients of the catwalk. It was found from the buffeting analysis that static and dynamic lateral displacements of the catwalk significantly decreased as the number of ropes increased. Lateral displacements were effectively reduced by tying down the catwalk and erecting a main cable.

6 ACKNOWLEDGEMENTS

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