

Reynolds number effects on aerodynamics forces of Kwangyang Bridge girder

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ABSTRACT: In this paper, the experimental results for twin box girder of the Kwangyang Bridge are presented in order to investigate the sensitivity of the Reynolds numbers on aerostatic force coefficient. High speed wind tunnel testing on 1:30 scale sectional model were carried out at the aeronautical wind tunnel in Korea Air Force Academy. The drag and lift coefficients revealed significant decrease of nearly 23% at supercritical region. The safety rail prevented the Reynolds number dependency of aerostatic force coefficients at negative angles of attack. In similar way, the boundary layer trip strip attached at bottom surface of girder reduced the Reynolds number dependency of aerostatic forces by fixing the location of flow transition. The pressure coefficients at girder surface near the gap significantly changed as the Reynolds number increase because of variation of the locations of flow separation and transition. The unbalanced burden of the drag force and lift forces at each box girder appeared in subcritical region was gradually resolved, and both boxes were almost equally loaded the forces at supercritical region.

KEYWORDS: Reynolds number, wind tunnel, suspension bridge, twin box girder.

1 INTRODUCTION

It is generally known that the flow around bluff and sharp edged bodies is independent of the Reynolds number, and the aerostatic forces measured at low speed wind tunnel testing may be directly applicable to the prototype bridge. The modern bridge girders are no longer sharp bluff body and are more likely streamlined section. The Reynolds number at ordinary wind tunnel tests of bridge girder has been generally 10^2 to 10^3 times smaller than that at actual bridges. Accordingly the aerostatic forces, especially drag force, of streamlined bridge sections seem to be no longer free from the Reynolds number.

Drag coefficients of some bridge girder sections were reported remarkably dependency of Reynolds number [1, 2]. In case of the Stonecutter Bridge girder, the drag force coefficient varied 30% according to wind speeds [3]. Considering the flexibility of long span bridges, those variations may significantly affect on structural and economical aspects of bridge design although the drag coefficients obtained at the low Reynolds number appear generally conservative for bridge design. Consequently there is some possibility of Reynolds number effects on girder of the Kwangyang Bridge that is extremely streamlined.

The Kwangyang Bridge, alternatively called as Yi Sun-sin Bridge, is located in south seashore of Korean peninsula which is frequently exposed to the typhoon at summer. During the Typhoon Maemi in 2003 passing nearby the bridge site, maximum instantaneous wind velocity was recorded 49.2 m/s at Yeosu Weather Station which is about 18km away from bridge site. Moreover the bridge superstructure locates 81m above sea level, and accordingly high wind is expected at the deck. Therefore the aerodynamic stability of the bridge is main concern of the design.

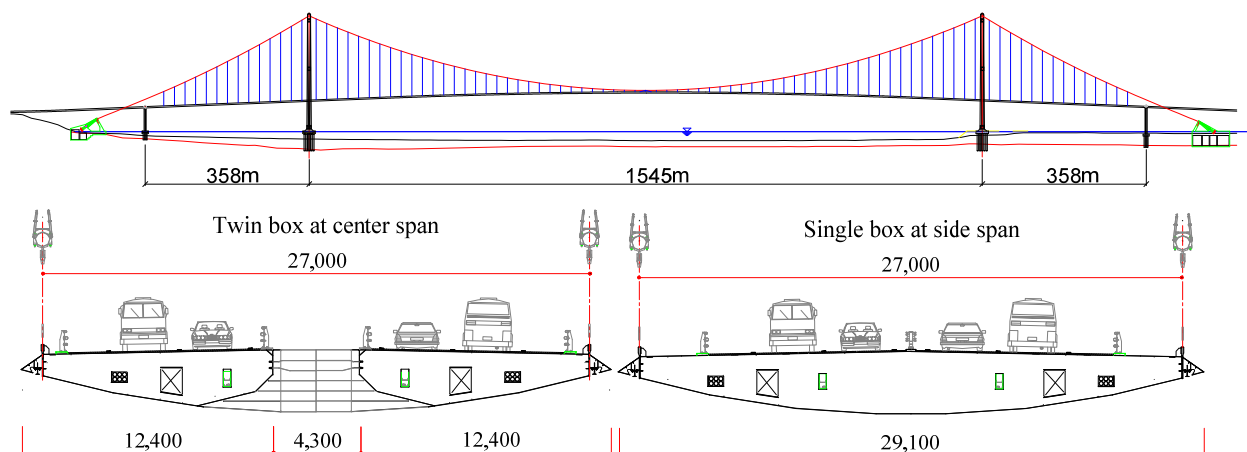


Figure 1. The Kwangyang Bridge.

The objective of present study is to investigate the sensitivity of aerostatic force coefficients of twin box girder of the Kwangyang Bridge according to the Reynolds numbers. This paper presents the 1:30 scale sectional model testing conducted at aeronautical wind tunnel in Korea Air Force Academy. Comparison with the results at low Reynolds number obtained in KOCED Wind Tunnel Center in Chonbuk National University is also provided.

2 TEST SETUP

The ordinary section model tests with scale of 1:70 were performed at the KOCED Wind Tunnel Center in Chonbuk National University during the design of the Kwangyang Bridge. The general results for aerodynamic design of main span girder can be found at Ref [5]. Those were, however, tested at low Reynolds number which was less than 4.8×10^5 (based on total girder width). Moreover smooth ventilation of air flow through narrow gap of 4.3m needs to be confirmed from the high speed wind tunnel tests, because different flow structure around guide vane according to wind speeds was observed at the Stonecutter Bridge.

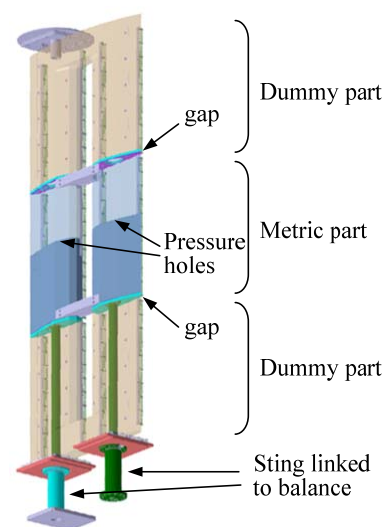


Figure 2. 1/30 scale model at wind tunnel in Korea Air Force Academy

The mid-size aeronautical wind tunnel at Korea Air Force Academy was used in present investigation in order to test at high wind speeds (high Reynolds numbers). Size of the test section was 3.5m(W)×2.45m(H). Contraction ratio was 7.3:1, maximum wind speed was 92m/s, and turbulent intensity was less than 0.038% at 74m/s. This closed circuit wind tunnel equipped boundary layer removal system and external pyramidal balance.

A 1:30 scale section model weighed over 250kg was made by aluminum and steel to resist high wind speed. Length and width of the model were respectively 1.94m and 1.0m which represented 72m of actual bridge girder. As shown in Figure 2, the model consists of three parts, one metric part and two dummy parts. Aerodynamic forces acting on metric part were measured by external pyramidal balance through two stings penetrating dummy part. Electric line sensors were attached at the gaps to warn the contact between metric part and dummy parts. Wind pressures were measured from 92 pressure holes in metric part. The pressure tubes were connected to pressure measurement system (PSI-8400).

Table 1 shows the experimental cases: girder without safety railing (case1), girder with safety railing (case2), girder with safety railing and boundary layer trip strip (case3). Case1 simulated the girder at construction stage where safety rails were generally not installed. Case2 and Case3 represented the girder at completion stage. The boundary layer trip strip is an artificial roughness added to the wind tunnel model in order to fix the location of transition from a laminar to turbulent boundary on the model [6]. The thickness of trip strip used in present investigation was 0.29mm. The trip strip was added on the bottom surface at 1.1m (at prototype) away from leading edge of the girder.

Table 1. Experimental Cases

Test case	Stage	Installation		Wind speed (m/s)	Angle of attack (deg)
		Safety rail	Trip strip		
Case1	Construction	×	×	10~45	+3 ~ -3
Case2	Completion	○	×	10~70	+5 ~ -5
Case3	Completion	○	○	10~45	+5 ~ -5

3 TEST RESULTS

3.1 Aerostatic force coefficients

Figure 3 shows the aerostatic force coefficients of the girder normalized by full girder width. As can be seen in the figure, the aerostatic force coefficients obtained from the 1:70 scale model well correspond with those measured from the 1:30 scale model at low Reynolds number. As Reynolds number (Re) increase gradually, the drag and lift coefficients revealed significant decrease of nearby 23%, while pitching moment coefficients were relatively consistent. The drag coefficient at $Re=1.5 \times 10^5$ (based on full girder width) was 0.083 but dropped to around 0.064 at $Re=7 \times 10^5$ and kept consistent. The lift coefficient also dropped from -0.096 to -0.347. The critical Reynolds number in present girder was found to be $2 \times 10^5 \sim 7 \times 10^5$ that is near the range of wind speeds at ordinary section model tests.

It is noticeable that the safety rail significantly influences to the drag and lift coefficients regardless of the Reynolds number. The drag coefficient without safety rail (Case1) was almost half of that with safety rail (Case2 & 3). These represent that any obstacles attached at leading edge of the girder strongly change the drag and lift coefficients.

Higher pressure drag as compared to skin friction drag at low Reynolds number region introduces additional drag. As Reynolds number increases, the transition point has moved forward and drag has reduced accordingly. Two distinct features depending on Reynolds number are the

location of boundary layer transition and the location of separation. A boundary layer trip strip is a tool used for making transition to occur earlier than it is [6]. Unfortunately the girder with the boundary layer trip strip (Case2) was not tested at the critical Reynolds number region. The effect of the trip strip on the Reynolds number independency is not identified in the range of the tested Reynolds number.

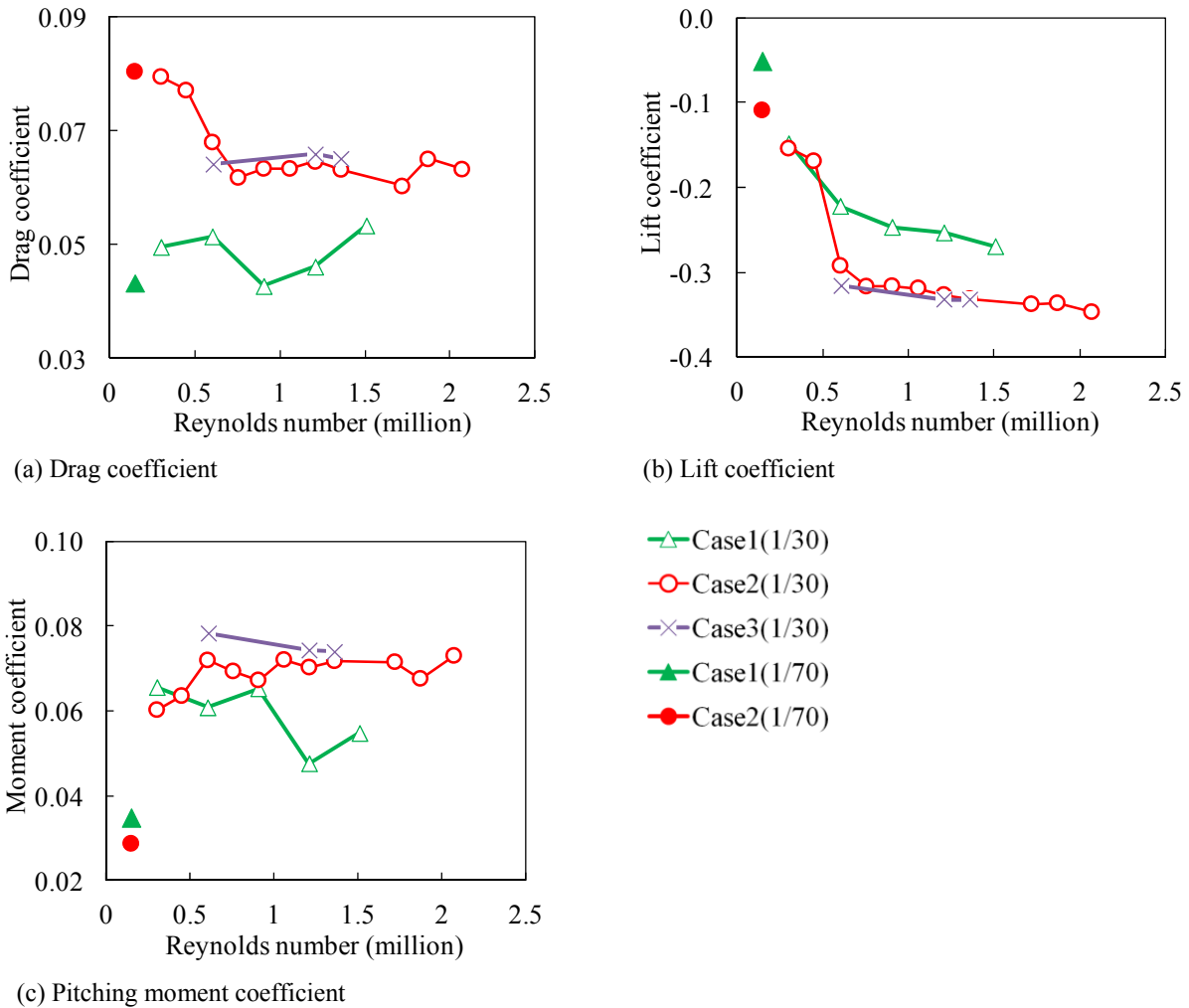
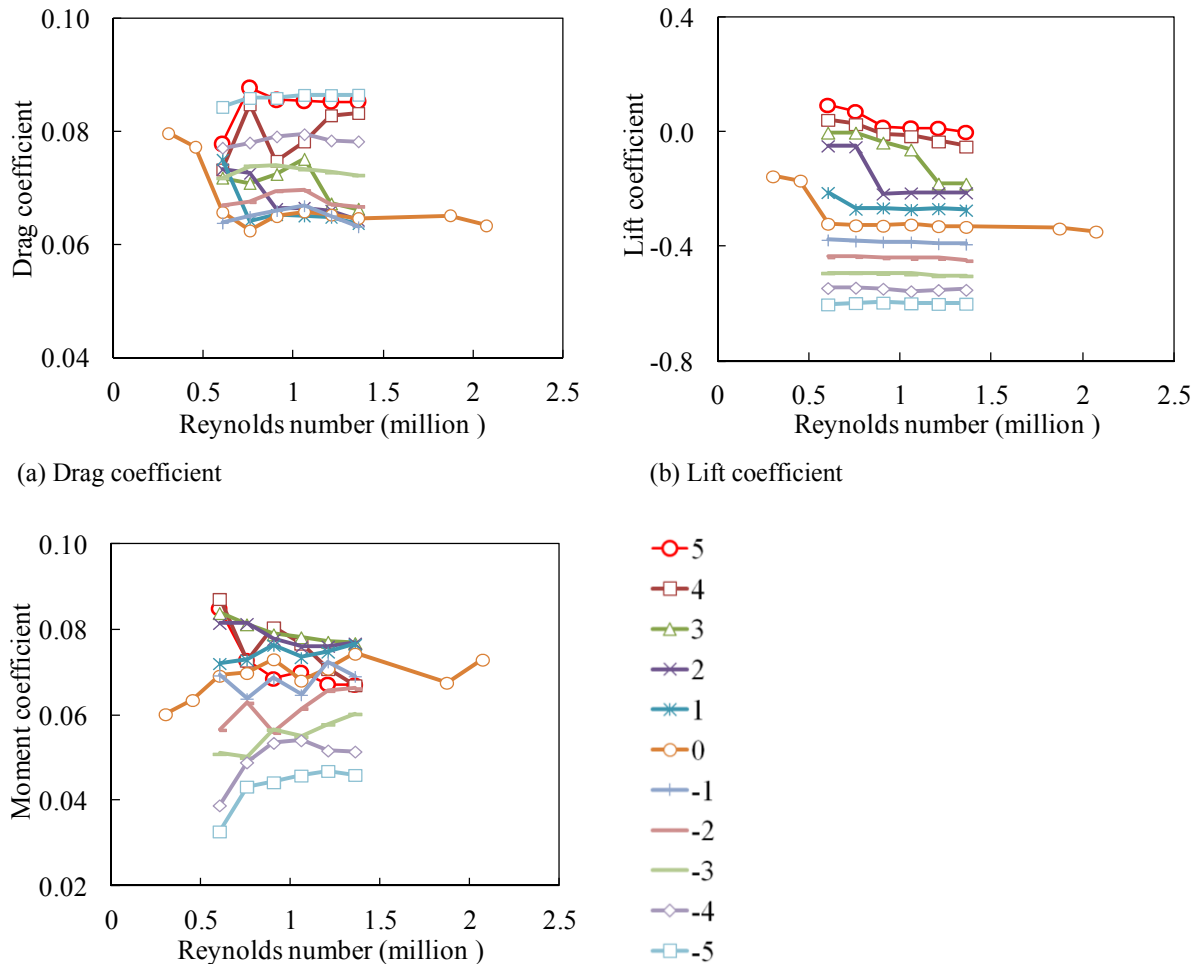


Figure 3. Aerostatic force coefficients at 0° angle of attack

The girder without safety rail definitely revealed the Reynolds number dependency on its aerostatic force coefficients. The tendency is, however, slightly different at the girder with safety rail. Figure 4 shows the aerostatic force coefficients of the girder with safety rail (Case2) according to angle of attack and the Reynolds number. The Reynolds number dependency was observed at zero and positive angles of attack (nose up), yet was not observed at negative angles of attack (nose down). In negative angles of attack, the location of separation on the bottom surface of the girder might be dependent on the Reynolds number. The location of separation did not, however, change because of the safety rail equipped at leading edge when the girder was inclined to negative angles of attack. The safety rail might fix the location of boundary layer transition and the location of separation.

When carefully watching the drag and lift coefficients shown in Figure 4(a) and (b), sudden drops of the coefficients are observed at certain angles of attack, e.g. 2° and 3° . Those drops already occurred at 0° angle of attack moved forward to higher Reynolds number in positive angles of attack. These represent that the critical Reynolds number changes according to angles of attack generally moved to higher value at high positive angle of attack.



(c) Pitching moment coefficient
Figure 4. Aerostatic force coefficients of girder with safety rail according to angle of attack

As mentioned earlier, the effectiveness of the boundary layer trip strip which was not clearly identified because the tests were carried out at super critical Reynolds number. This effectiveness can be observed in the delayed critical Reynolds number at high positive angle of attack. The sudden drop of the drag and lift coefficients at the critical region occurred at the girder was eliminated at the girder by patching the boundary layer trip strip at its bottom surface. This removal of critical region from the test ranges represent that the trip strip effectively fix the location of transition from a laminar to turbulent boundary on the model, and can be used for simulating the high Reynolds number effect at low wind speed.

3.2 Pressure distributions

Figure 5 shows pressure coefficients along girder section. Pressure coefficient heading outside the box represents negative pressure (suction) and inside means positive. As can be seen in Figure 5(a) for girder without safety rail (Case1), the pressure coefficients at front edge of the leeward box change from negative to positive as the Reynolds number increase. This inconsistency of pressure coefficients is probably a result of moved locations of separation and boundary layer transition as wind speed up. These variations of pressure coefficients result in the Reynolds number dependency of the aerostatic force coefficients.

In case of girder with safety rail (Case2) at low Re, the pressure distribution of leeward box did not change much. However, the pressures at rear and mid bottom surface of windward box were changed at critical Re. The uniformly distributed negative pressures were observed at rear bottom surface of windward box in low Re. As wind speed increases, the strong negative pressure peaks were observed at folded edge of bottom surface above the critical Re.

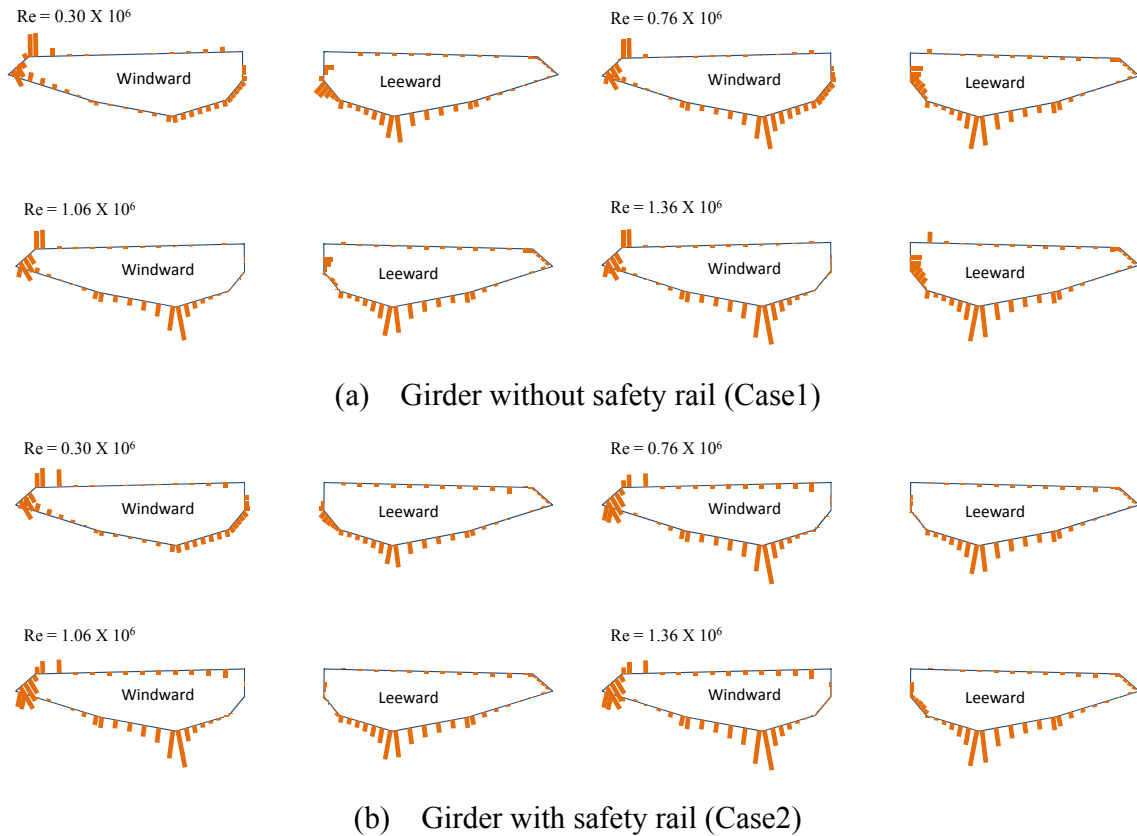
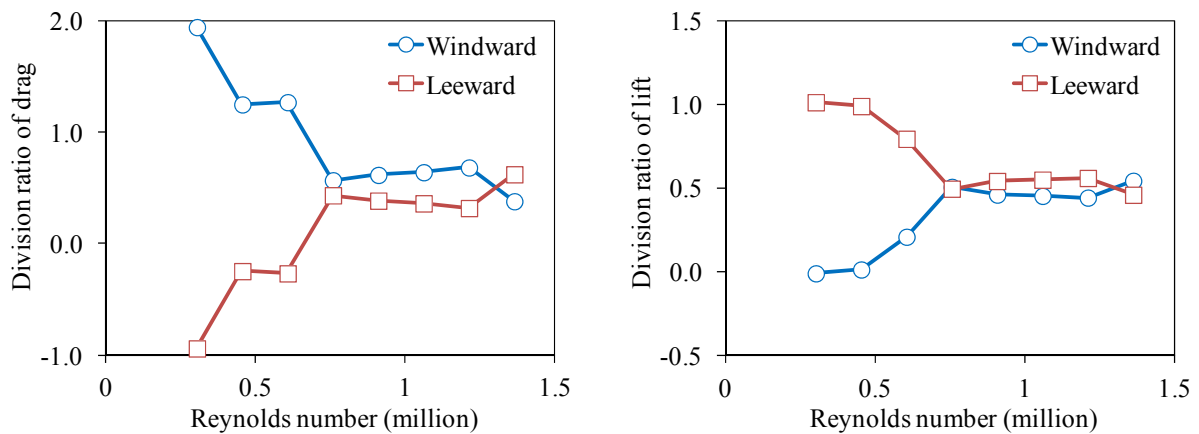


Figure 5. Mean pressure coefficients at 0° angle of attack

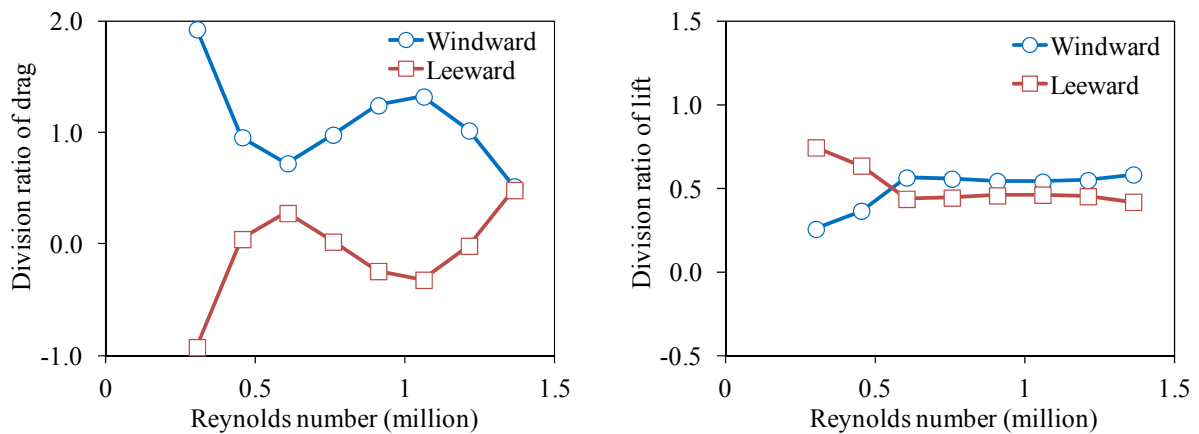
3.3 Aerostatic forces acting on each twin boxes

The aerostatic force sharing ratios between windward box and leeward box are given in Figure 6 as a function of the Reynolds number. The forces were evaluated by integrating the measured pressures along girder sections. At the low Re in subcritical region, the windward box burdened the drag force mostly, yet the leeward box mostly burdened the lift force. It is interesting that the drag force and lift force acting on the leeward box were respectively negative and almost zero at subcritical region.

This unbalanced division of forces was gradually reduced at critical region, and then force ratio was almost equal in both sides of boxes at supercritical region of the Reynolds number. Figure 7 shows the aerostatic force coefficient and division ratio of forces between windward box and leeward box at supercritical region, $Re=1.36 \times 10^6$. Accordingly it is reasonable to assume in design of twin box girder that the aerostatic forces acting on each boxes can be equally divided into the windward box and leeward box.

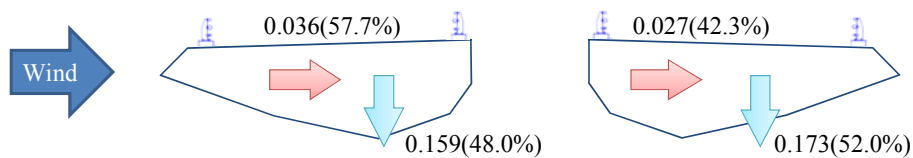


(a) Girder without safety rail (Case1)

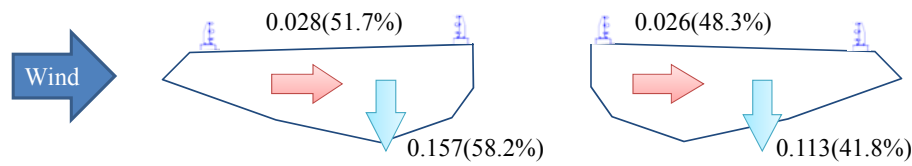


(b) Girder with safety rail (Case2)

Figure 6. Division ratio of aerostatic forces between windward box and leeward box according to Reynolds number



(a) Girder without safety rail (Case1)



(b) Girder with safety rail (Case2)

Figure 7. Aerostatic force coefficients and division ratio at supercritical region ($Re=1.36 \times 10^6$)

4 CONCLUSIONS

The sensitivity of the Reynolds numbers on aerostatic force coefficients of twin box girder were investigated through ordinary section model tests and high speed tests at aeronautical wind tunnel. Main finding obtained from the tests are summarized as follows:

- The Reynolds number dependency of aerostatic force coefficients were observed at present streamlined twin box girder. The drag and lift coefficients revealed significant decrease of nearly 23% at supercritical region. This Reynolds number dependency was only observed at positive angles of attack (nose up) because of the safety rail.
- The boundary layer trip strip was found to reduce the Reynolds number dependency of aerostatic forces by fixing the location of flow transition. The trip strip can be used to simulate the flow structure at supercritical region in low wind speed.
- The pressure coefficients at bottom rear surface of windward box girder and at frontal face of the leeward box girder significantly changed as the Reynolds number increase because of variation of the locations of flow separation and transition.
- The windward and leeward box girders respectively burdened most of the drag force and lift force at subcritical region. This unbalanced division of forces at each box girder was gradually resolved, and both boxes almost equally divided the forces at supercritical region.

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