Wind and Structures, Vol. 11, No. 3 (2008) 179-192

DOI: http://dx.doi.org/10.12989/was.2008.11.3.179

The effect of Reynolds numbers on the steady state aerodynamic force coefficients of the Stonecutters Bridge deck section

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(Received August 8, 2005, Accepted July 5, 2007)

Abstract. In a wind tunnel experiment employing a reduced scale model, Reynolds number (Re) can hardly be respected. Its effects on the aerodynamics of closed-box bridge decks have been the subject of research in recent years. Stonecutters Bridge in Hong Kong is a cable-stayed bridge having an unprecedented central span of 1018m. The issue of Re sensitivity was raised early in the design phase of the deck of Stonecutters Bridge. The objective of this study is to summarise the results of various wind tunnel experiments in order to demonstrate the effect of Re on the steady state aerodynamic force coefficients. The results may provide an insight on the choice of scale for section model experiments in bridge design projects. Computational Fluid Dynamics (CFD) analysis of forces on bridge deck section was also carried out to see how CFD results are compared with experimental results.

Key words: Stonecutters Bridge; Reynolds number; aerodynamic force coefficients; CFD.

1. Introduction

Reynolds number (Re) is a non-dimensional parameter defined as the ratio between the inertia force to viscous force, viz., $\mathrm{Re} = \rho UL/\mu$ where ρ is the density of fluid, U is the mean velocity of flow, L is a typical dimension and μ is the viscosity of fluid. In a wind tunnel experiment employing a reduced scale model, Re can hardly be respected. Its effects on the aerodynamics of closed-box bridge decks have been the subject of research in recent years. Schewe and Larsen (1998), Kubo, *et al*. (1999), Matsuda, *et al*. (2001) have reported a marked dependence of drag coefficient and Strouhal number on Reynolds number. This effect is believed to be directly linked to

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the influence of Re on the separation and reattachment regions of the boundary layer of bluff bodies (Larose, *et al.* 2003).

The issue of Re sensitivity was raised early in the design phase of the deck of Stonecutters Bridge. The deck section of the winning reference scheme for the Stonecutters Bridge is a twin girder structure comprising two 20.6 m wide box girders arranged in parallel in a horizontal plane and separated by a 13.1m wide vent (see Fig. 1). The individual box girders, which were designed with well-rounded soffit plates, were interconnected by heavy cross-beams at 18m intervals. Aerodynamically, the well-rounded soffit plates indicated a Re dependence of the flows similar to what is known from flow about a circular cylinder. At low $Re \approx 0.2 \times 10^6$ which is typical for conventional section model tests, the separation point may be expected to be located slightly upwind of the deepest point of the box leading to a wide vortex street wake and thus high aerodynamic drag. At high $Re \approx 7 \times 10^7$, typical of the prototype bridge, the separation point on the box soffit might be considerably downwind of the deepest point on the box girder, yielding a narrow vortex street wake, Fig. 1. The different flow patterns expected at model scale and full-scale Re would, in turn, yield lower drag coefficient and different vortex shedding characteristics of the prototype bridge than that inferred from a conventional wind tunnel section model (Schewe and Larsen 1998). Moreover, the uncertainty of the location of the separation points would make it difficult to position guide vanes for mitigation of vortex shedding response correctly, should aerodynamic studies prove them necessary.

Hence, the aerodynamic investigation of Stonecutters Bridge has naturally included the study of

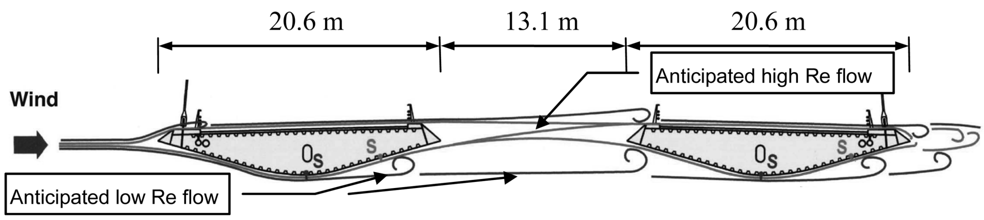


Fig. 1 Conceptual flow about the Stonecutters Bridge deck at high and low Reynolds numbers

the effect of Re on the reference scheme. In addition to aerodynamic considerations, the reference scheme deck shape caused concern in relation to manufacture. In particular the reference scheme geometry would render the welding of the bottom joint between the cross-beam and the lower tangent point of the soffit plate extremely impractical.

In view of these concerns, it was decided to draft alternative cross sections which would respect the overall aesthetic qualities of the reference scheme, but resolve the concerns raised above. A comparison of the reference scheme (R) deck and the alternative scheme (AJ) deck finally adopted for the detailed design of Stonecutters Bridge is shown in Fig. 2. It is noted that the AJ-section features a rounded soffit plate starting at the nose which then changes into an inclined flat panel at the deepest point of the section. On the upwind girder, the knuckle line between the rounded soffit and inclined inner panel ensures a well defined separation point before the flow will enter a region of inverse pressure gradient. Thus the width of the upwind section wake and thus drag coefficient should become independent of Re. Whether this is the case is the main subject of this study.

The well rounded soffit of the reference design was removed by adopting the revised cross section AJ. However, the effectiveness of the guide vanes in suppressing vortex shedding response is a key

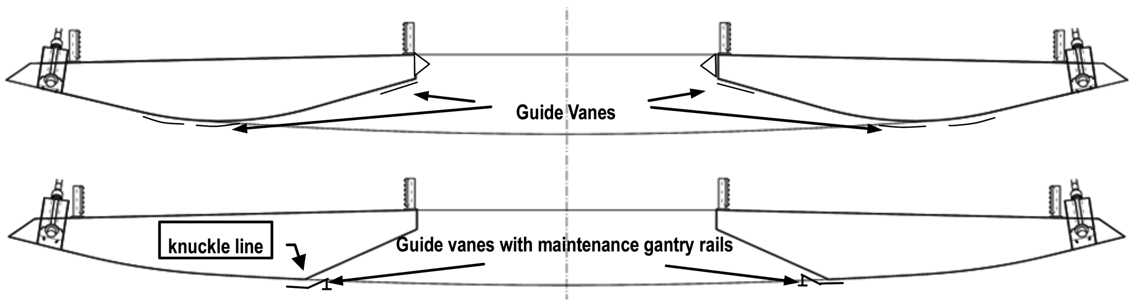


Fig. 2 Reference scheme (Top R-section) and final alternative (Bottom AJ-section) and guide vane configurations investigated

design issue and is also Re dependence. Hence, a number of wind tunnel experiments employing a range of Re were implemented under the project. Section models of scales 1:80, 1:20 and 1:200 were employed and this paper will summarise the findings of these experiments. The results may provide an insight on the choice of scales for section model experiments in bridge design projects. CFD analysis on forces on deck section was also carried out to see how CFD results are compared with experimental results.

2. Wind tunnel experiments

During the design stage of the project, the following rigid section model experiments were conducted:

(1) 1:80 scale section model experiments conducted in the Danish Maritime Institute of Denmark (DMI, which was later renamed as FORCE-technology);
(2) 1:20 scale section model experiments conducted in the National Research Council of Canada (NRCC); and
(3) 1:200 scale section model experiments conducted in FORCE-technology (FT) of Denmark.

Whilst the experiment employing the 1:200 scale section model was conducted purely to evaluate the drag and lift coefficients of the deck of Stonecutters Bridge, the other 2 series of experiments employing 1:80 and 1:20 scales were conducted to evaluate both the static and dynamic performance of the Stonecutters Bridge deck. In this paper, focus would be put in the effect of Re on the steady state aerodynamic force coefficients.

The mean drag, lift and torsional aerodynamic forces acting on the sectional models were directly measured with load cells and normalised to provide static force coefficients. To depict the rate of change of the coefficients with angle of wind incidence, the tests were conducted for a range of angle of wind incidence. Some tests were performed in both smooth and turbulence flows whilst some were performed in smooth flow only. In order to compare the results on an equal basis, only smooth flow results will be discussed. A typical force coefficient is defined as follows:

$$C_{D,L} = \frac{\bar{F}_{D,L}}{\bar{q}Bl} \text{ and } C_M = \frac{\bar{M}}{\bar{q}B^2 l} \tag{1}$$

where C is an aerodynamic force coefficient, $\bar{F}$ is a time-averaged (mean) aerodynamic force, $\bar{M}$ is a mean overturning moment, $\bar{q}$ is the mean wind velocity pressure at deck level, where $\bar{q} = \frac{1}{2}\rho\bar{U}^2$, ρ is the air density in Kg/m^3, $\bar{U}$ is the mean wind velocity at deck level in m/s. B is the overall bridge deck width and l is the model span length. The subscripts D, L and M refer to the drag, lift and overturning moment, respectively.

2.1. 1:80 scale section model tests

A number of cross sections including the original reference scheme (R), alternative schemes (A1 and A3) and finally alternative scheme (AJ) have been studied. As the other series of wind tunnel experiments under different Re were conducted for section AJ only, this section will also focus on the results related to section AJ only.

2.2. Experimental conditions

The AJ bridge deck model was manufactured to a geometrical scale of 1:80 (Larsen 2001). The model construction utilised a light foam material covered by a thin carbon fibre skin in order to produce a stiff section model (Leung, *et al*. 2004). This was done in order to allow a stiffer spring suspension system and thus allow a higher Re for the vortex shedding tests. The AJ model reproduced major deck furniture such as parapets, cross-beams and stay anchor casings. The guide

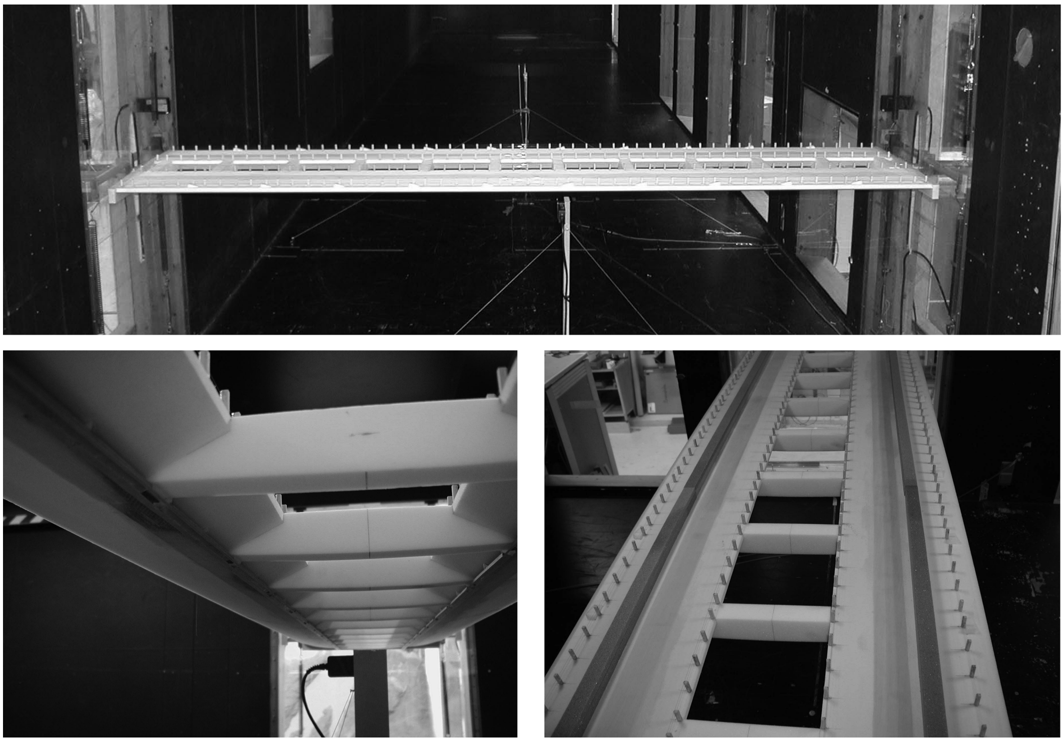


Fig. 3 AJ section model in the DMI 2.6 × 1.8 m boundary layer wind tunnel (top). Details of guide vanes (bottom, left) and AJ with traffic models on the roadway (bottom, right)

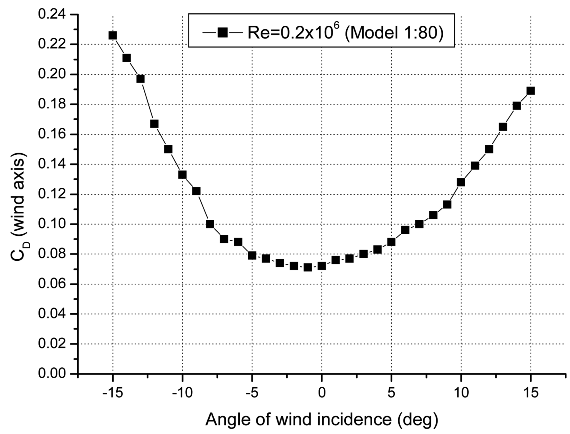
vanes and maintenance gantry rails were manufactured from thin strips birch wood and were attached to the soffits by means of pin connections, thus making mounting and dismounting easy. Pictures of the AJ section model are shown in Fig. 3. The static tests were conducted in smooth flow and turbulent flow with vertical turbulence intensity at deck level of about 15% and at mean wind speed of about 8 m/s in turbulent flow and 12 m/s in smooth flow. The Re based on the width of one box (19.5 m) is therefore in the order 0.2×10^6. Only tests under smooth flow condition will be presented in this paper.

2.3. Steady state wind load coefficients

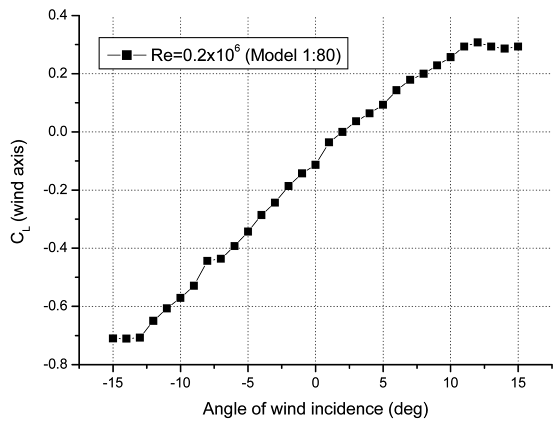
The steady state wind loads were measured for the AJ deck shape including guide vanes. Fig. 4 shows the detailed load coefficient curves as measured for the AJ section.

2.4. 1:20 scale section model tests

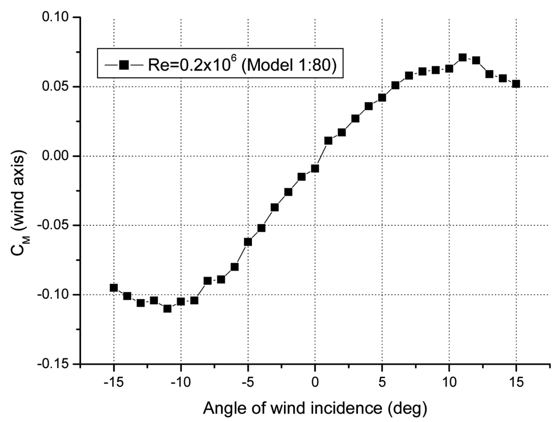
The main objectives of the 1:20 scale high Reynolds Number section model test programme was



(a) Drag Coefficients



(b) Lift Coefficients



(c) Moment Coefficients

Fig. 4 Steady state wind load coefficients measured for the AJ cross section (1:80 scale) in smooth flow

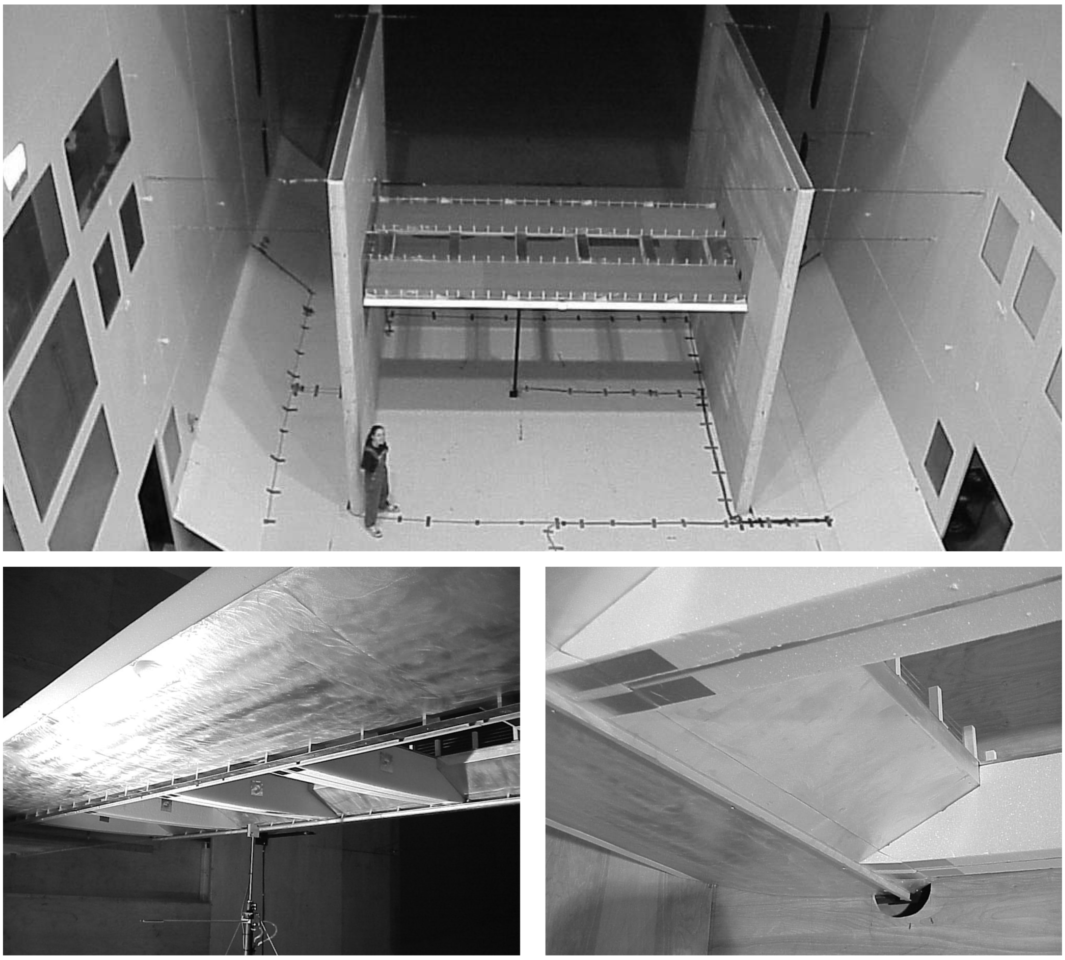


Fig. 5 1:20 AJ section model suspended in the NRCC 9×9 m low speed wind tunnel (top). Details of guide vanes option 4(bottom, left) and maintenance gantry rails (bottom, right).

to establish the following data for the AJ cross section for Stonecutters Bridge:

(1) Steady state aerodynamic force coefficients in smooth flow condition
(2) Vortex induced response in smooth flow
(3) Investigation of the ability of guide vanes to mitigate vortex induced response and the effect of mounting maintenance gantry rails directly at the soffit.

This paper will focus on the first objective.

2.5. Experimental conditions

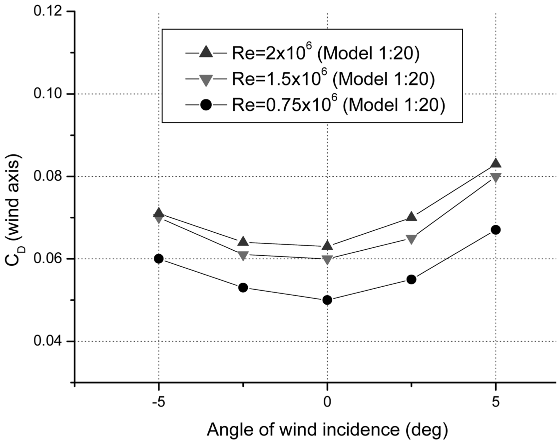
The AJ bridge deck model was manufactured to a geometrical scale of 1:20 (Larose 2001). The model construction utilised an aluminium frame construction filled by light foam material to provide the external shape of the AJ cross section and covered by a thin aluminium skin (Leung, *et al*. 2004). The 1:20 AJ model re-produced major deck furniture such as parapets, cross-beams and stay anchor casings. The guide vanes and maintenance gantry rails were manufactured from thin strips of aluminium and were attached to the soffit by means of pin connections, thus making mounting and dismounting easy. Pictures of the AJ section model are shown in Fig. 5. All tests were done in smooth flow for five angles of wind incidence (±°5, ±2.5°, 0°) and for several wind speeds between 5 and 40 m/s corresponding to Re based on the width of one box in the order of 0.5×10^6 to 2.5×10^6.

2.6. The steady state wind loads

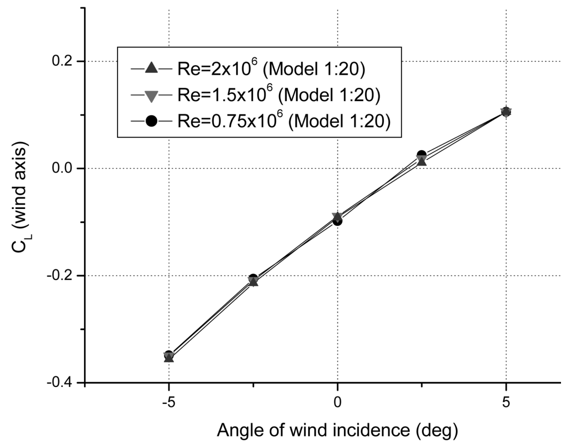
The steady state wind loads was measured for the 1:20 scale AJ deck shape including guide vanes. Fig. 6 shows the detailed load coefficient curves as measured.

2.7. 1:200 scale section model tests

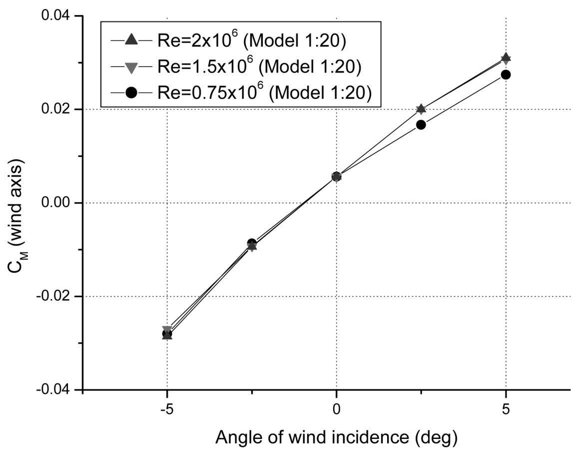
During the full bridge aeroelastic model tests employing a geometric scale of 1:200 at the Monash



(a) Drag Coefficients



(b) Lift Coefficients



(c) Moment Coefficients

Fig. 6 Steady state wind load coefficients measured for the AJ cross section (1:20 scale) in smooth flow wind tunnel, it was found that the mean lift force was an upward force, which was not in line with all earlier wind tunnel test results. It therefore triggered this study to evaluate the drag and lift coefficients at the same scale and shape employed for the deck of the full bridge model (1:200).

2.8. Experimental conditions

The coefficients were determined by wind tunnel tests in smooth flow (Larsen 2004). The model was tested at three angles of wind incidence, namely, -2.5deg, 0deg and +2.5deg. As there is no need to conduct dynamic tests at this scale, the model was primarily produced from plastic (polyamide PA 2200 with a density of 900-950 Kg/m^3) by means of rapid prototyping using the SLS-method (Selective Laser Sintering). FORCE Technology's workshop made fittings for the gauges and the internal stiffening of the model plus details on the deck (cable anchorages and railing (simple steel braces). Dimensions of the steel braces simulating the railings were estimated based on the photographs in Fig. 7, which was taken during the full aeroelastic model test.

Based on the photograph, FORCE Technology estimated the dimensions of the steel braces simulating the railings as a Ø1 mm wire with a length of 84mm and a distance of 5.5mm above the deck surface. The model was fitted with such steel braces in the position of the railings. Further, the model was fitted with Ø5 mm and 5mm tall "cylinders" simulating the screws used for attachment of the cable wires. Owing to the small dimension of guide vanes, it was decided that they would not be modelled as for the full bridge aeroelastic model of the same scale.

The model had a length of 0.99 m and was hollow and stiffened by two U-shaped aluminium-profiles. The model had a frequency in vertical bending of about 15 Hz when installed in the gauges.

The tests were conducted at an average mean wind speed of 7 m/s. The Re based on the width of one box (19.5 m) is therefore in the order 0.05×10^6. Photograph of the model is shown in Figs. 8

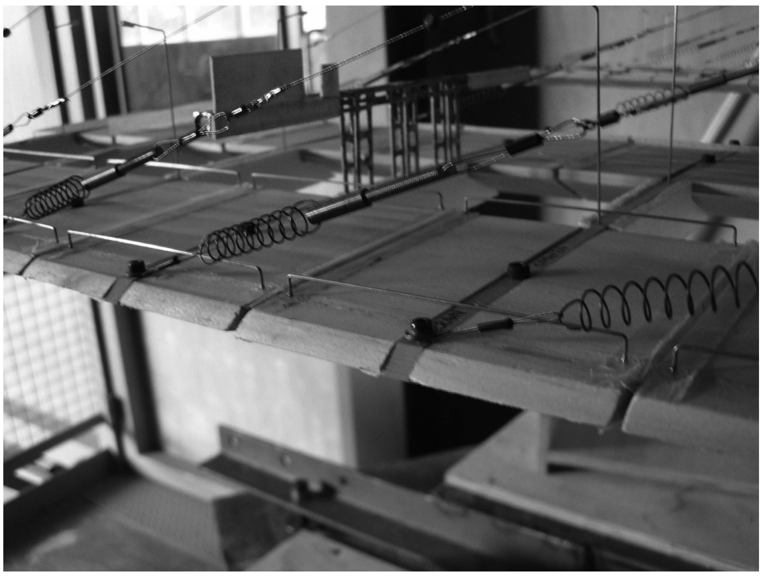


Fig. 7 Photograph of the deck in aeroelastic full bridge model with steel braces simulating railings

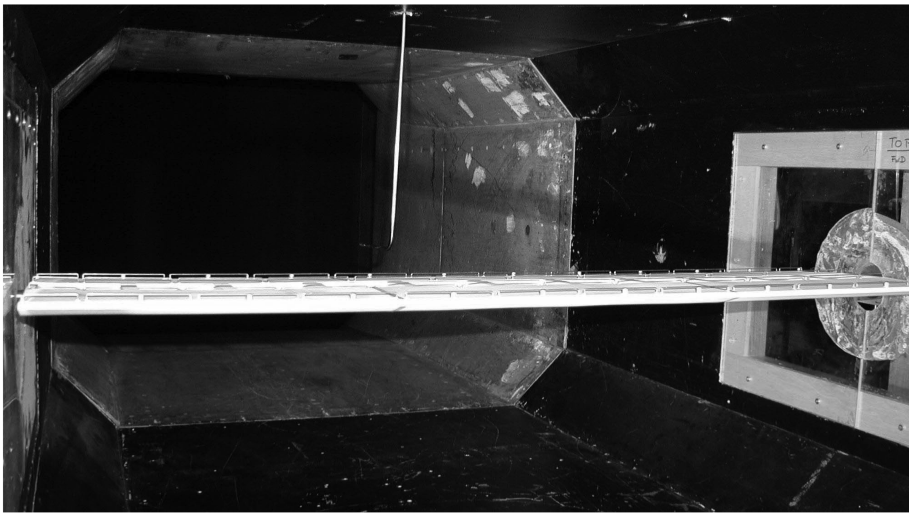


Fig. 8 Photograph of the section model in tunnel

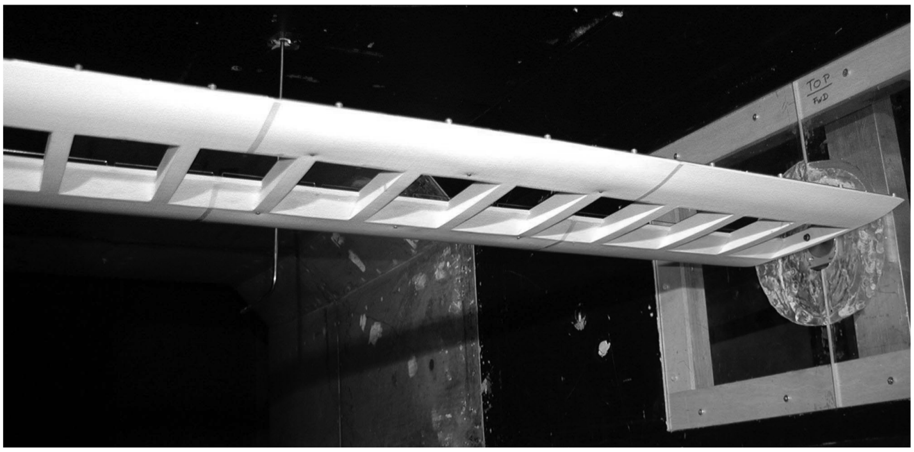


Fig. 9 Photograph of the underside of section model in tunnel

and 9 below.

The average drag and lift force coefficients are given in the Table 1. The corresponding values found in the 1:80 scale section model are listed for comparison.

Table 1 – Steady state wind load coefficients measured for the AJ cross section (1:200 scale) in smooth flow

	C_D	C_D	C_L	C_L
Wind incidence \ Scale	1:200	1:80	1:200	1:80
-2.5°	0.059	0.072	-0.271	-0.217
0°	0.054	0.072	-0.113	-0.113
+2.5°	0.054	0.077	0.016	0.018

3. Computational fluid dynamics (CFD)

3.1. Random discrete vortex method (RVM)

In this study, RVM method was used in the evaluation of aerodynamic force coefficients for the deck section of Stonecutters Bridge, as a comparison. Two distinct features can be revealed in studying the unsteady separated flow about bluff bodies, either stationary or in time dependent motion. They are vortex shedding and vortex motion (Zhou, *et al*. 2003). The shedding of vorticity in the near wake of the body and the development of vortex motion will have a direct influence on the aerodynamic forces on the bluff bodies by balancing the change of fluid momentum along the body surface. Hence, it is possible to identify the inherent mechanism of the fluid forces on the body by investigating the complicated flow structure and vortex motion in the near wake.

The input to RVM simulations is a boundary panel model of the two-dimensional deck section contour. The output of RVM simulations is time-progressions of surface pressure and section loads in terms of body axes. In addition, maps of the induced velocity fields and vortex positions at prescribed time steps are available. Vortex blob strength of 0.005 and Reynolds number of 2E5 are adopted in the simulations. Apart from zero degree angle of attack, ±1°, ±3° and ±5° are adopted. Each simulation was run for 15 non-dimensional time units $T = tU/D$, where t is the time, U the wind speed and D the width of the chord of one girder. A non-dimensional time increment $\Delta T = 0.01$ was adopted throughout the simulations.

Surface pressure distribution was computed from the local flux of surface vorticity at each time step. The surface pressure of the deck section was integrated along the contour to yield time traces of aerodynamic forces in the lateral, vertical and torsional direction (body axes). A complete derivation of the RVM method in determining aerodynamic forces due to pressure distribution is given in Chen, *et al*. (2006). Steady-state force coefficients are obtained from time averages of simulated loads on deck models and are normalised according to the following:

$$C_{x,z} = \frac{\bar{F}_{x,z}}{\bar{q}D} \text{ and } C_m = \frac{\bar{M}}{\bar{q}D^2} \tag{2}$$

where C is an aerodynamic coefficient, $\bar{F}$ is a time-averaged (mean) aerodynamic force, $\bar{M}$ is a mean overturning moment, $\bar{q}$ is the mean wind velocity pressure at deck level, where $\bar{q} = \frac{1}{2}\rho\bar{U}^2$, ρ is the air density in Kg/m^3, $\bar{U}$ is the mean wind velocity at deck level in m/s. D is the width of the chord of one girder. The subscripts x, z and m refer to the lateral, vertical and torsional direction, respectively. To transform the force coefficients into wind axes and to normalise the forces by the overall deck width in lieu of the width of one chord, the force coefficients obtained by RVM have to be adjusted as follows:

$$C_D(\alpha) = C_x(\alpha) \times \frac{19.5}{53.3} \times \cos\alpha + C_z(\alpha) \times \frac{19.5}{53.3} \times \sin\alpha \tag{3}$$

$$C_L(\alpha) = -C_x(\alpha) \times \frac{19.5}{53.3} \times \sin\alpha + C_z(\alpha) \times \frac{19.5}{53.3} \times \cos\alpha \tag{4}$$

$$C_M(\alpha) = C_m(\alpha) \times \left(\frac{19.5}{53.3}\right)^2 \tag{5}$$

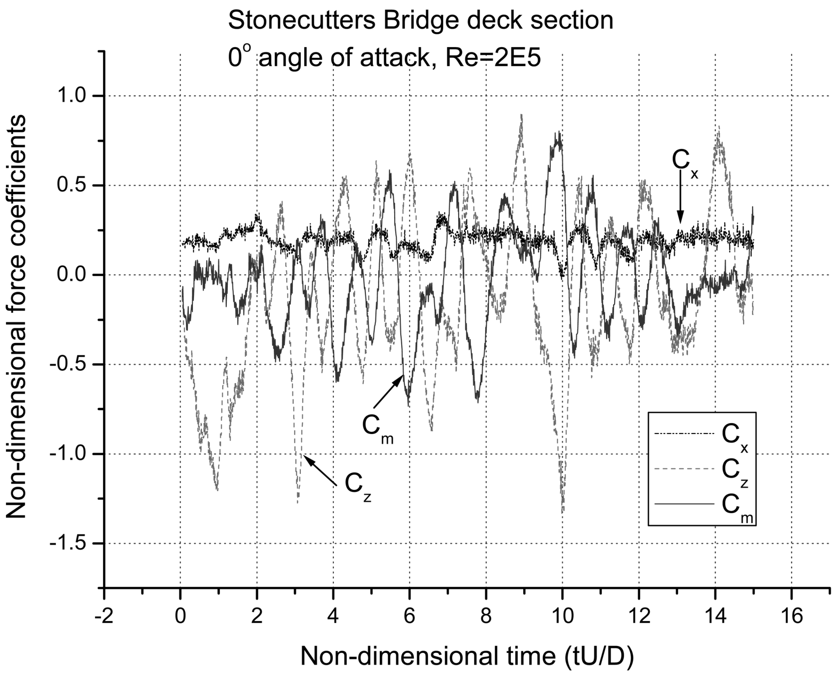


Fig. 10 Time traces of the development of C_x, C_z and C_m for Stonecutters Bridge deck section

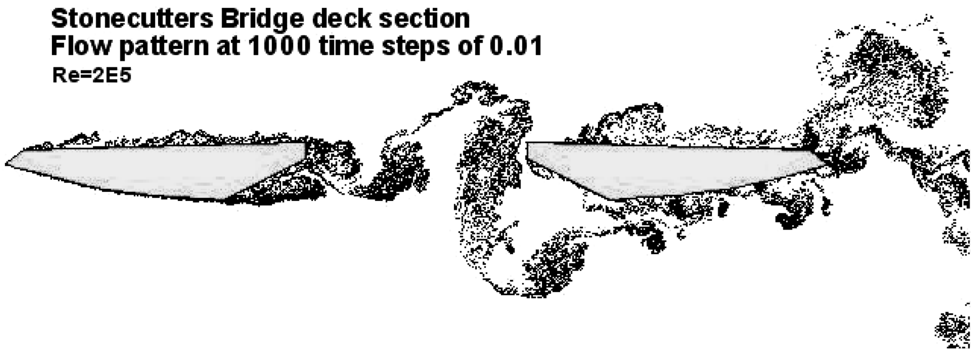
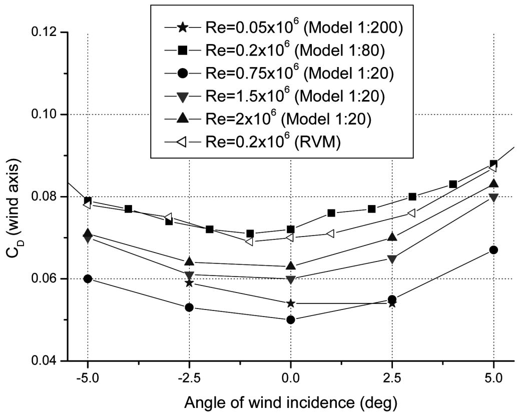


Fig. 11 Flow pattern at 1000 time steps of 0.01 for Stonecutters Bridge deck

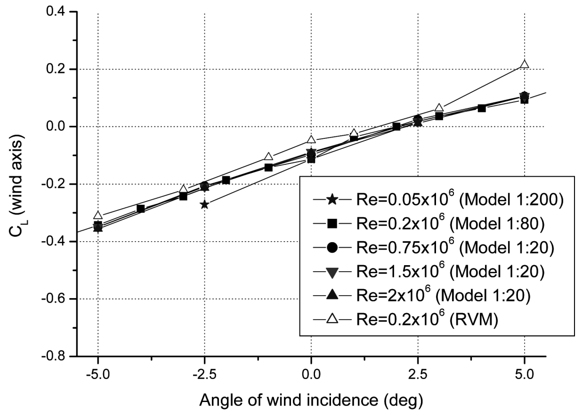
Fig. 10 shows an example of the simulated time traces of C_x, C_z and C_m obtained from RVM analysis for Stonecutters Bridge deck section. The C_x trace settles quite quickly at a value of around 0.19, the C_z and C_m traces develop distinct oscillations about the zero-value axis. The flow pattern can be visualised by plotting the spatial position of the individual vortex particles. See Fig. 11.

4. Summary of results

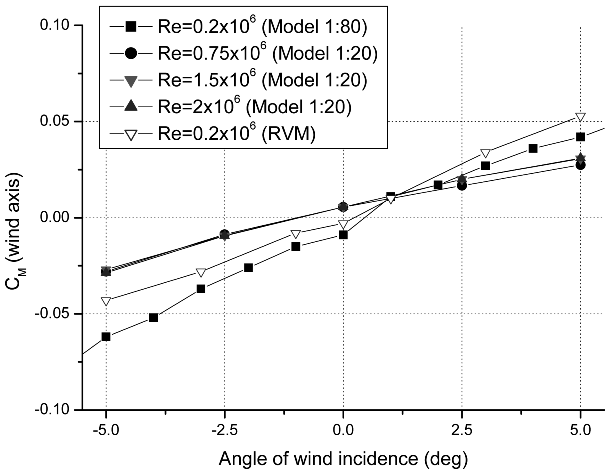
The force coefficients of Stonecutters Bridge deck section obtained under various wind tunnel tests employing section model of three different scales under five different Re together with that obtained from RVM method were plotted in Fig. 12.



(a) Drag Coefficients



(b) Lift Coefficients



(c) Moment Coefficients

Fig. 12 Steady state wind load coefficients measured in wind tunnel experiments and calculated by RVM

For C_L, it is noted from Fig. 12 (b) that the lift coefficient is almost unaffected by Re as C_L obtained from the 1:20 model tests at different Re corresponds very well with the C_L obtained from the 1:80 scale tests (Hui and Larsen 2002). There is only slight variation for C_L obtained from the 1:200 scale tests at -2.5 degree angle of attack (nose down). RVM C_L was also found to be close to the wind tunnel experimental results.

For C_M, the 1:20 scale results display little Re dependence yielding a moment slope $dC_M/d\alpha =$ 0.34, whereas the 1:80 scale results indicate a 60% increase in moment slope to $dC_M/d\alpha = 0.55$ and a slight off-set at $\alpha = 0^o$. For C_M, the RVM results are close to the wind tunnel results (1:80 model) conducted under a similar Re.

The drag coefficient displays the most interesting Re-dependence. At $\alpha = 0^0$ and $\text{Re} = 0.2 \times 10^6$, $C_D = 0.072$ (1:80 scale model). By increasing Re about four times reaching $\text{Re} = 0.75 \times 10^6$ (1:20 scale model), the drag drops dramatically by 34% to $C_D = 0.048$. Doubling the Re to $\text{Re} = 1.5 \times 10^6$ yields a substantial drag recovery to $C_D = 0.060$ and further increase to $\text{Re} = 2.0 \times 10^6$ yields

$C_D = 0.063$, approaching the low Re case. This behaviour of C_D as a function of Re is very similar to that well known from the circular cylinder going from high C_D at sub-critical Re through very low C_D at the drag crises to yield almost sub-critical C_D values at super-critical Re. The drag coefficient corresponds to the 1:200 scale model at $Re = 0.05 \times 10^6$ was found to be 0.054, which was a bit lower than expected. However, it should be noted that the modelling of the 1:200 scale section model was quite different from that of 1:80 and 1:20. For example, there was no guide vanes for the 1:200 model and the parapets were modelled differently. These all accounted for the unexpectedly low drag coefficient for this model. From Fig. 12 (a), it is noted that the RVM C_D runs very close to the wind tunnel results (1:80 model) which were also obtained at a similar Re.

5. Concluding remarks

Wind tunnel experiments were conducted to evaluate the steady state aerodynamic force coefficients for the deck of Stonecutters Bridge. Owing to various reasons, experiments at different stages of the project were arranged such that 3 different model scales had been adopted. Opportunities were taken to study the effect of Re on the forces of the Stonecutters Bridge deck. Five Re ranges from 0.05×10^6 to 2×10^6 were adopted. Results were plotted in Fig. 12.

For the range of Re studied in this exercise, the following observations can be made:

(1) lift coefficients were virtually unaffected by Re;

(2) there was minor effect in moment coefficients in that the coefficients obtained from 1:80 model (lower Re) indicate a steeper gradient and a slight off-set at $\alpha = 0^0$.

(3) Drag coefficients displays the most interesting Re-dependence. The drag coefficients obtained from the 1:80 scale section model was close to that obtained from high Re.

(4) Based on the above observation, the adoption of a model scale of around 1:80 is considered reasonable in determining the steady state aerodynamic force coefficients for design purposes, as it would give slightly more conservative drag coefficients.

(5) The steady state aerodynamic force coefficients were also obtained by numerical simulations using RVM method. Good agreement was established between the simulation results with that of wind tunnel results employing a geometric scale of 1:80 under Re=2E5.

Acknowledgements

The authors wish to express their gratitude to the Director of Highways of HKSAR, Ir C.K. Mak, for his permission to publish this paper. Views expressed in the paper are entirely those of the authors. Furthermore, the experimental work done by DMI, NRCC and FORCE - technology wind tunnels is also acknowledged.

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