

Wind-Tunnel Tests With the Chacao Double Suspension Bridge

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ABSTRACT: The proposed Chacao Bridge is planned for construction in Chile. The bridge is a double suspension bridge with both main spans exceeding 1 km. This paper presents selected results from the initial section model tests and the subsequent aeroelastic full-bridge model tests. The former was conducted at a scale of 1:60 and the latter at a scale of 1:215. Special attention is drawn to the aerodynamic stability of the bridge deck, where the cross-sections of the bridge deck in the 600 m centre portions of the main spans are different from the cross-section in the side span and in the vicinity of the pylons. It was found that the structure with a bluff deck cross-section outside of the 600 m centre part of the main spans reduces the critical wind speed. Further, it was found that the motions of the main spans appear to be uncoupled, and that instability only occurs in the longest span, with the shorter span remaining aerodynamically stable.

KEYWORDS: Aeroelastic full-bridge model, wind-tunnel tests.

1 INTRODUCTION

The proposed Chacao Bridge is a remarkable double suspension bridge planned to span the Canal de Chacao in Chile between the Island of Chiloé and the South American continent. The bridge is illustrated in Figure 1. The proposed bridge structure consists of two adjacent cable-suspended main spans. The northern span is 1100 m long and is flanked by a cable-supported side span of 340 m. The southern span is 1055 m and is flanked by a 140 m long pier-supported side span. The total length of the structure is 2750 m.

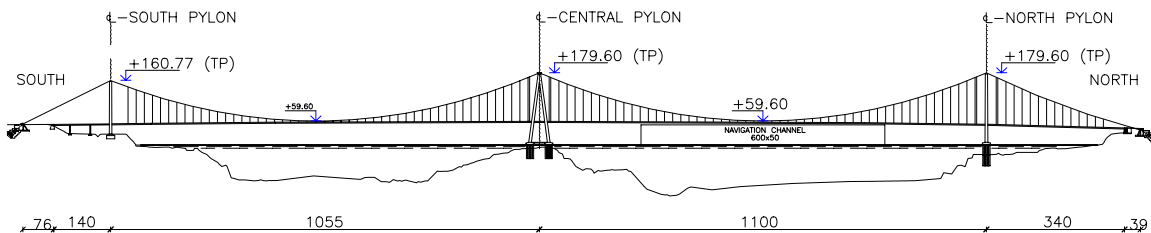


Figure 1. Elevation of the Chacao Bridge. Dimensions in m.

The central pylon and the pylon of the northern span are 180 m tall, whereas the pylon of the southern span is 161 m. The central pylon is founded on a submerged reef. The bridge deck, illustrated in Figure 2, is a steel girder of the closed box type. The deck is 23.8 m wide and 2.80 m deep.

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2.2 Full-bridge model

The full-bridge model tests were conducted to verify and elaborate on the observations made in the section model tests with respect to aerodynamic stability and buffeting response. Furthermore, the test programme for the full-bridge model tests included investigations of local wind screens, partial edge fairings on the bridge deck and yaw angle effects. The full-bridge model was designed and constructed at a geometric scale of 1:215. The tests were conducted in FORCE Technology's 13.6 m wide and 1.7 m tall boundary-layer wind tunnel. This wind tunnel, which has a maximum speed of about 7 m/s, is described in detail by Smitt *et al.* The aeroelastic full-bridge model in the wind tunnel can be seen in Figure 3.

Most of the tests were conducted in turbulent flow with a turbulence intensity at deck level of 6%-7%. Some tests were repeated in smooth flow, with a turbulence intensity of approximately 1%.



Figure 3. Photograph of the aeroelastic model in FORCE Technology's 13.6 m wide wind tunnel.

The bridge deck was continuous from the South Pylon to the North Abutment. At the South Pylon and the North Abutment, the bridge deck was restrained against transverse and vertical displacement and against rotation around the longitudinal axis of the deck. At each cross beam of the central pylon and at the North pylon the bridge deck was restrained in the transverse direction only.

3 SECTION MODEL TESTS

Prior to the full-bridge model tests, the aerodynamic behaviour of the bridge section was investigated through traditional two-dimensional section model tests. The dynamic properties of the two main spans are listed in Table 1. The deck mass modelled was 12600 kg/m and the mass moment inertia was 796600 kg·m²/m.

Table 1. Prototype frequencies for section model

Span	f_{vertical} [Hz]	$f_{\text{torsional}}$ [Hz]	freq. ratio [-]
North span	0.131	0.387	2.96
South span	0.150	0.424	2.82

For buffeting, stability and aerodynamic derivatives tests, the frequencies of the North span (the longer span, where the lowest stability limit would be expected) was simulated, whereas investigations related to vortex-induced oscillations were investigated with the properties of the South span (the shorter and lighter span).

The critical wind speed for the onset of divergent response, such as flutter, was determined for a number of conditions. All tests were conducted for three angles of wind incidence: 0° , -3° (“nose down”) and $+3^\circ$ (“nose up”). The results are presented in Figure 4a.

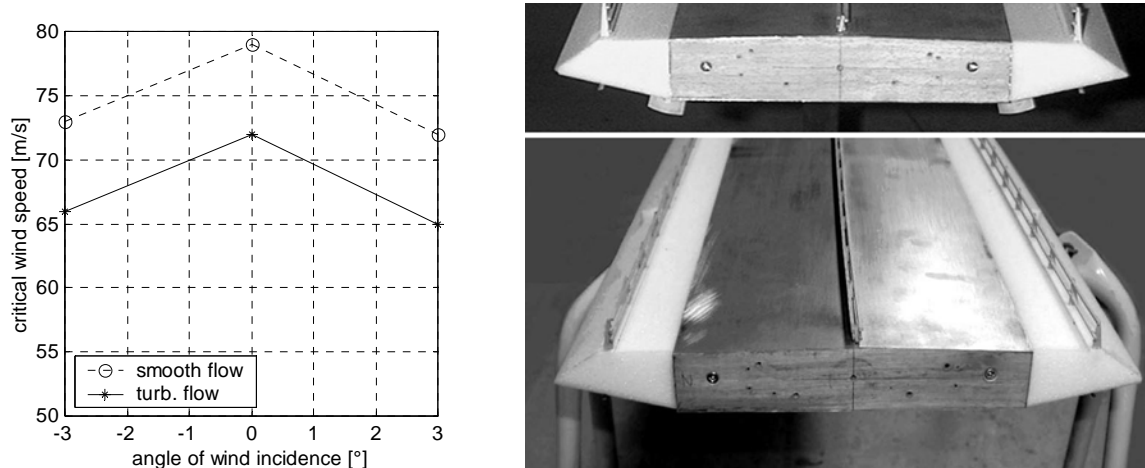


Figure 4. a) Critical wind speeds for onset of instability determined in the section model tests and b) photograph of the 1:60-scale section model (lower photo: section without guide vanes; upper photo: section with guide vanes).

It is seen from figure 4a that the critical wind speeds exceed the requirement of 58 m/s for all angles of incidence. Furthermore, it is found that stability limit is about 10% higher in smooth flow compared to turbulent flow. Finally, it can be seen that with wind angles of incidence of -3° or $+3^\circ$, the stability limit decreases by 8% to 11%, with the largest reduction for positive angles of wind incidence.

It was demonstrated in the section model tests that guide vanes mounted on the lower corners (or knuckle points) of the section have a mitigating effect on potential vortex shedding induced oscillations. The guide vanes were mounted at a distance of 0.5 m from the girder and had a cord length of 1.5 m. The effects of such guide vanes have been reported elsewhere for similar sections, see A. Larsen *et al.* It was documented in subsequent section model tests, that the guide vanes have only a marginal affect the stability limit (i.e., the critical wind speed for onset for divergent oscillations) and the static load coefficient. In turbulent flow the stability was slightly higher with guide vanes. It was also found that continuous wind screens along the section model reduces the stability limit considerably.

4 FULL-BRIDGE MODEL TESTS

The full-bridge model was designed according to similarity of the Froude Number at a geometric scale of 1:215. The scale of 1:215 was chosen to obtain a full utilization of the width of the wind tunnel (13.6 m) and this scale results in a velocity scale of $1:\sqrt{215}$ (i.e., about 1:14.7). The main focus of the tests was to verify the critical wind speeds obtained in the section model tests and to determine the buffeting behaviour of the structure. The aerodynamic behaviour of the structure was investigated at two yaw angles, 0° and 30° relative to the perpendicular to the deck axis. The yaw angle of 30° corresponds to the North end being upwind.

The bridge was tested with and without wind screens installed on the bridge deck near the pylons. The wind screens, with a porosity of 50%, have the purpose of diminishing the wake gusts from the pylon legs, which could induce uncomfortable buffeting on passing vehicles. Due to the potential scale effects, the guide vanes were not included in the full-bridge model tests.

One particular concern was the potential coupling or beating between the two main spans during flutter vibration, due to the two fairly close torsional frequencies, see Table 2.



Figure 5. a) Photograph of the 1:215-scale full-bridge model at 30° yaw angle with the authors and b) graphical illustration of the full-scale structure.

The prototype eigenfrequencies provided by the Client are listed in Table 2 together with the model scale target and obtained frequencies. It should be noted that some of the frequencies are slightly revised, compared to those available at the stage of the section model tests (Table 1). Table 2 also lists the span with the maximum modal displacement.

Table 2. Prototype Frequencies (MS for model scale).

Mode	mode number	prototype [Hz]	MS target [Hz]	MS obtained [Hz]	Span
1 st lateral	1	0.069	1.01	1.06	South
2 nd lateral	2	0.073	1.07	1.15	North
1 st vertical	4	0.129	1.89	1.96	North
2 nd vertical	5	0.153	2.24	2.40	South
3 rd vertical	6	0.159	2.33	2.51	North
1 st torsional	33	0.387	5.67	5.58	North
2 nd torsional	35	0.422	6.19	6.17	South

The modes listed in Table 2 each represent the first symmetrical mode for each span (except the 3rd vertical mode, which is the second symmetrical vertical mode for the North span).

The structural damping was 0.9% - 1.0% of critical for the first lateral mode, 0.4% - 0.5% for the second lateral mode, about 0.4% for the vertical modes and 0.2% for the torsional modes.

The full-bridge model tests showed, as expected, that tapered wind screens located in the vicinity of the pylon did not influence the aerodynamic stability or the overall behaviour of the bridge deck, whereas wind screens (continuous along the model) were proven to significantly reduce the critical wind speed in the section model tests.

The bridge deck was fitted with non-structural edge fairings to obtain a streamlined cross-section, see Figures 2 and 7. However, in the course of testing, it was decided by Icuatro-COWI to pursue the possibility of only applying the triangular edge fairings in the central parts of the main spans. Consequently, the full-bridge model tests were conducted with two configurations of the bridge deck. In one configuration, the bridge deck cross-section was identical to the one tested in the section model tests all along the bridge. In the other configuration, the bridge deck near the pylons and in the side spans was of a more bluff type, in which the edge fairings (or

wind fairings) were not installed, and only in the central 600 m (2 x 300 m) of the two main spans was the bridge deck equipped with edge fairings (see Figure 6). A comparison of the deck section with and without wind fairings is shown in Figure 7.

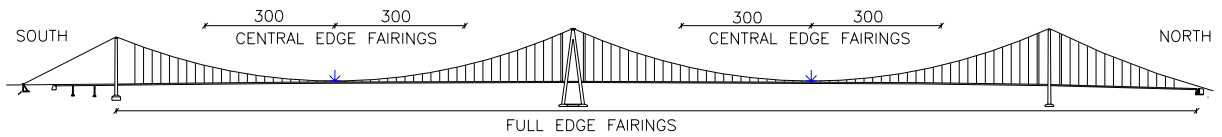


Figure 6. Portions of deck equipped with “full” or “central” edge (or wind) fairings. Dimensions in m.

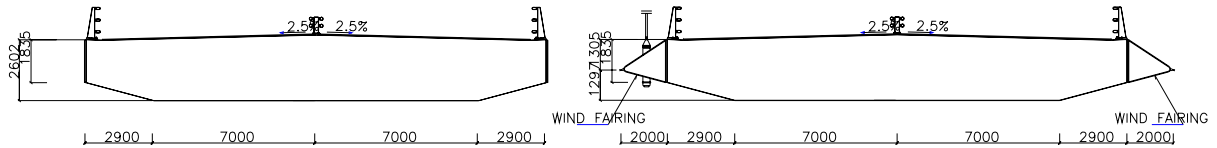


Figure 7. a) Bridge section without and b) with wind fairings. Dimensions in mm.

5 PRESENTATION OF SELECTED RESULTS

The most essential part of the testing was to demonstrate adequate critical wind speed for onset of divergent oscillations. The critical wind speeds determined in full-bridge model tests are listed in Table 3.

Table 3. Determined critical wind speeds, U_{cr} , for onset of divergent response.

Yaw angle	Flow	Wind fairing	Wind screens	U_{cr} [m/s]
0°	turbulent	central	off	63
0°	turbulent	central	on	63
0°	turbulent	full	on	68
0°	smooth	central	off	72
0°	smooth	central	on	72
30°	turbulent	central	off	70
30°	turbulent	central	on	70
30°	smooth	central	off	74

The instabilities were generally observed to develop in the North span. It is seen from Table 3 that the critical wind speeds are 8% - 10% higher with wind coming from a yaw angle of 30° compared to wind perpendicular to the bridge axis.

The only directly comparable results between the section model tests and the full-bridge model tests are the stability limits determined in turbulent flow. In the section model a critical wind speed of 72 m/s was estimated, whereas 68 m/s was found in the full-bridge model, i.e., 5-6% lower in the latter case.

Unfortunately, no section model data are available for the bluff section, i.e., the bridge deck without wind fairings.

Figure 8 shows the RMS (root-mean-square) of deck displacement (or rotation) at South and North mid-span, respectively, for the two deck configurations. Figure 9 shows the RMS of deck displacements or rotation at South and North mid-span, respectively, for the wind coming from 0° and 30°. Figure 10 shows examples of the time histories of the mid-span displacements and

rotations at a wind speed corresponding to critical wind speed. The time histories shown in Figure 10 were recorded for the 30° case in smooth flow.

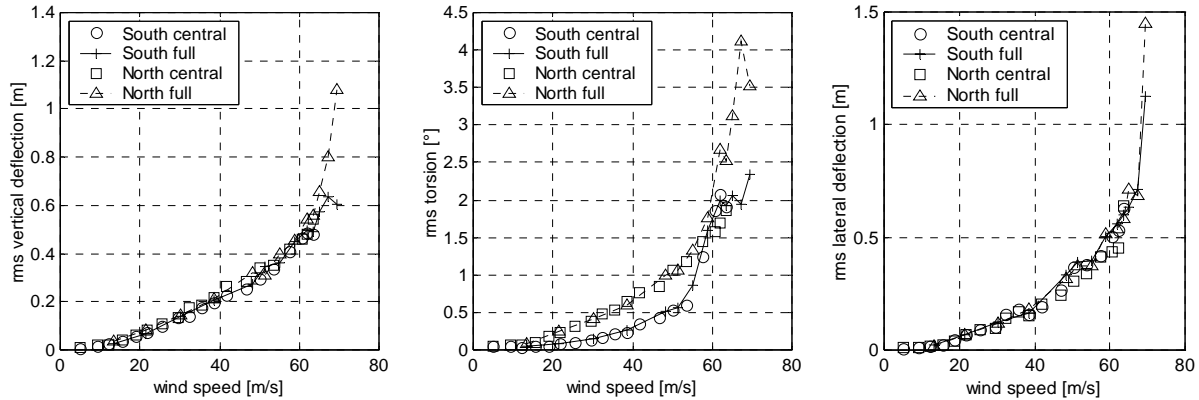


Figure 8. Vertical, torsional and lateral RMS displacement or rotation at mid span (North and South span) with central and full edge fairings, respectively. Wind speed corresponds to mean wind at deck level. Yaw angle is 0°.

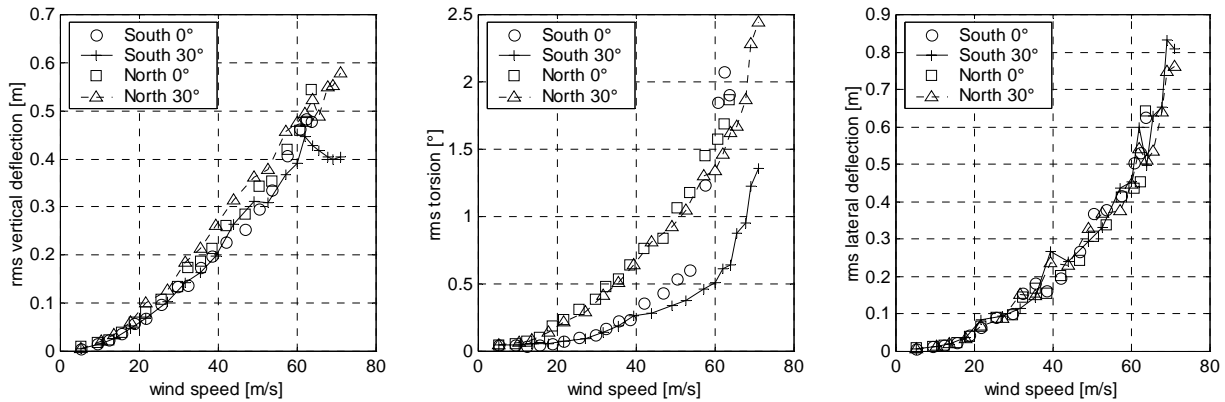


Figure 9. Vertical, torsional and lateral RMS displacement or rotation at mid span (North and South span) with wind from 0° and 30°, respectively. Wind speed corresponds to mean wind at deck level. Central wind fairing.

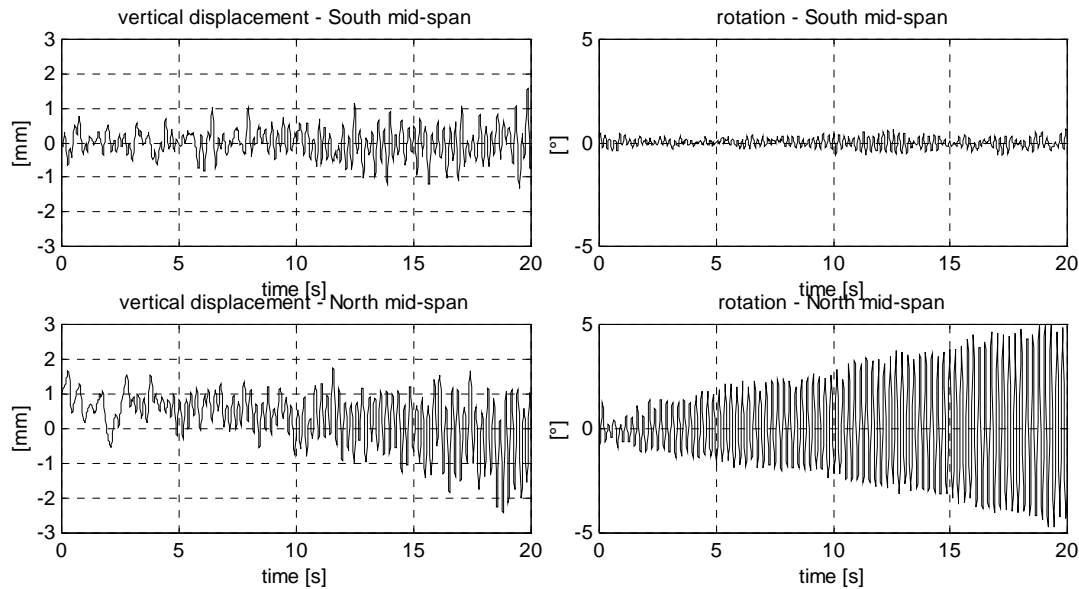


Figure 10. Time series of vertical displacement and rotation at mid span (North and South span) at critical wind speed. Wind speed corresponds to mean wind at deck level. Displacements and time in model scale.

6 SUMMARY AND CONCLUSIONS

The aerodynamic behaviour of a unique double suspension bridge has been addressed through traditional two-dimensional section model tests and through aeroelastic full-bridge model tests. The basic aerodynamic information was provided through tests of the 1:60 scale section model, i.e., ensuring that the selected geometry provided adequate resistance against divergent oscillations. However, a number of issues could only be investigated in full-bridge model tests. These items were, e.g., potential coupling between the motions of the two main span, especially at critical wind speeds, the effect of varying deck cross-section along the spans, yaw angle effects and effects of local wind screens. The full-bridge model was constructed at a geometric scale of 1:215.

Selected results of the tests have been presented. It was found that changing the side span deck cross-section and the deck cross-section near the pylons to a bluffer type, affects the critical wind speed, but this was acceptable in the present case. Further, it was found that the aeroelastic responses of the main spans were not coupled during divergent responses.

7 ACKNOWLEDGEMENT

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8 REFERENCES

- 1 S.O. Hansen and E.G. Sørensen, A new boundary layer wind tunnel at the Danish Maritime Institute, *J. Ind. Aerodyn.*, 18 (1985) 213-224.
- 2 L.W. Smitt and M. Brinch, A new wide boundary layer wind tunnel at the Danish Maritime Institute. *Proc. Aerodynamics of Large Bridges*, A. Larsen (Ed.), Copenhagen, 1992, Balkema.
- 3 A. Larsen, S. Eisdahl, J.E. Andersen & T. Vejrum, Vortex shedding excitation of the Great Belt suspension Bridge, *J. Ind. Aerodyn.*, 88 (2000) 283-296.