CHAPTER 4

WIND TUNNEL EXPERIMENTS

The present study includes simulation of characteristics of Atmospheric Boundary Layer (ABL) corresponding to an open terrain for conducting boundary layer wind tunnel test on a model of a section of a bridge deck corresponding to a geometric scale of 1:50. Experiments are carried out in the boundary layer wind tunnel (BLWT) facility at Structural Engineering Research Centre (SERC), Chennai, India. This chapter discusses on the experimental set up for static test and dynamic test, using the facilities developed for each test.

4.1 BOUNDARY LAYER WIND TUNNEL FACILITY AT STRUCTURAL ENGINEERING RESEARCH CENTRE (SERC)

Airline diagram of boundary layer wind tunnel is given in figure 4.1. The boundary layer wind tunnel facility can be viewed as an experimental facility wherein the wind flow is simulated in a controlled manner to represent the flow characteristics in the nature and the aerodynamic forces and responses of the model are investigated in a scientific manner. The BLWT at SERC, Chennai is a world-class facility with more capabilities. The overall length of the wind tunnel is 52 m. The tunnel has a bell mouth entry followed by an axial fan with a D.C Motor arrangement. The power of the fan-motor is 600 HP. An inlet diffuser is provided followed by a settling chamber with screens and a honeycomb to channelise the approach flow and to control the
whirls into a laminar flow. Since in this process it loses energy, it is deliberately sent through a contraction of 1:5 ratios, where after it enters the test section region. The size of the test section is 18m x 2.5m x 2.15m. Such a long test section is preferred to achieve natural development of equilibrium boundary layer.

The test section is provided with glass panels for easy visualization of experiment being carried out. A flexible ceiling arrangement is provided to achieve zero longitudinal pressure gradient. The test section is followed by a long diffuser and then by curved vanes for minimizing the static energy of the flow coming out of the test section. It is possible to generate wind speed from 0.5 m/s to 55 m/s in this wind tunnel. The test section has two turntables one on the upstream and another on downstream side to conduct experiments. While models can be tested at downstream table under simulated turbulent conditions, the upstream table is used for studies for models for uniform flow conditions. At entrance to test section, based on measurements, it has been found that the level of turbulence intensity is less that about 1% and the flow is uniform across the entire section.

Simulation or modelling of the characteristics of the natural wind inside the wind tunnel to a reduced scale is probably the foremost and important step in any wind tunnel experiment. In the present wind tunnel, special types of devices such as trip boards, roughness boards (wooden cubes) fixed on the tunnel floor are used to simulate necessary terrain conditions. Generally the most important measurements being carried out include that of mean and fluctuating wind velocities, pressures on surfaces of models and wind-induced response of the models. Hot-wire anemometer system is widely used for mean and fluctuating velocity measurements. The standard Pitot tube is used for measurement of mean velocity in the tunnel.
Smaller size accelerometers are used to measure the tip accelerations of models such as tall chimneys, towers etc, and strain gauges are used to measure base bending moment of the model structure both in along wind and associated directions. Hi-scan, differential types of pressure sensors are used for pressure measurement studies.

A basic requirement in all the BLWT experiments is that the model of a given building/structure should be immersed in the simulated boundary layer. Boundary layers as high as 1.2 m can be comfortably developed in this tunnel. Based on the flow simulation, the flow scale will be determined by comparing the simulated flow characteristics with that of similar flow characteristics established based on available benchmark full-scale experiments.

![Figure 4.1 Airline diagram of boundary layer wind tunnel at SERC](image)
4.2 SIMULATION OF ATMOSPHERIC WIND IN THE TUNNEL

For the purpose of wind tunnel application to civil engineering problems, the following similarity requirement has to be considered in the modeling of Atmospheric Boundary Layer:

- Simulation of mean velocity profile according to a terrain.
- Simulation of turbulence intensity profile, corresponding to the selected terrain.
- Simulation of spectrum according to a scale ratio.

When all the above three modeling criteria are satisfied, it is assumed that the atmospheric boundary layer in full scale has been simulated properly in the wind tunnel. On comparison with the standard theoretical spectrum, the length scale, \( L_{u,x} \) of the simulation is arrived. Terrain Category – 2 (Open terrain) is simulated in the wind tunnel using trip board followed by uniformly placed roughness elements. Using hot wire anemometer, velocity traces have been acquired and analysed to obtain mean velocity profile, turbulence intensity profile and power spectrum of longitudinal component of velocity for the simulated flow, based on Equations (4.1), (4.2) and (4.3), respectively. The measured spectrum is compared with the standard von-Karman’s spectrum. By matching the scalable wind spectrum which is obtained from the wind tunnel with that of von-Karman spectrum, the relation between frequency, \( 'n' \) and \( (nL_{u,x}/\bar{U}) \) is obtained and consequently the value of \( L_{u,x} \) is computed. On comparing the value of \( L_{u,x} \) in the model to that of in full-scale, a geometric model scale of 1:50 is obtained for the present study. Experimental details are explained in detail elsewhere (SelviRajan, 1999). The measured mean velocity profile, intensity of turbulence variation and spectrum of longitudinal fluctuating component of velocity are given in figures 4.2, 4.3 and 4.4, respectively (Cook, 1985).
\[
\frac{\bar{U}(z)}{\bar{U}(\delta)} = \left( \frac{z}{\delta} \right)^u
\]  
(4.1)

\[I_u = \frac{u'(z)}{\bar{U}(z)}
\]  
(4.2)

\[
\frac{nS_u(n)}{\sigma_u^2} = \frac{4x_u}{\left(1 + 70.78x_u^2\right)^{3/2}}
\]  
(4.3)

where

- \(x_u\) = \(\frac{n L_{ux}}{\sigma_u}\)
- \(L_{ux}\) = turbulence length scale along the wind direction
- \(\sigma_u^2\) = the square of the rms intensity
- \(n\) = frequency
- \(\alpha\) = power law exponent
- \(\delta\) = boundary layer thickness
- \(I_u\) = turbulence intensity level
- \(\bar{U}(z)\) = mean velocity at height \(z\)
- \(u'(z)\) = rms component of fluctuating velocity at height \(z\)

and

- \(S_u(n)\) = power spectral density function in frequency domain
Figure 4.2 Mean velocity profile

Figure 4.3 Turbulence intensity profile
Figure 4.4 Comparison of Measured Spectra with Karman Spectrum

4.3 EXPERIMENTS USING STATIC TEST RIG

Long-span suspension bridges or cable-stayed bridges are highly susceptible to wind excitations because of their inherent structural flexibility and low damping ratios. The aerodynamics of such structures is characterized by separated flow and turbulent wakes exhibiting widely varying degrees of flow organizations (Cermak, 1979). As wind separates and flows around a bridge deck, vortices are formed at the windward edge of the bridge. These vortices then roll in an alternating pattern, along the top and bottom sides of the bridge deck. Vortex shedding is considered as a problem when the accelerations caused by the motions disturb the users of the bridge. Vortex-induced oscillations do not cause sudden collapse, but the structure must be designed for critical velocity against vortex shedding, since large visual displacement occurs at resonant and in a long run it results in long-term fatigue damage. Wind tunnel testing of bridge deck sections is generally
carried out in conventional low speed wind tunnels by adopting common model scales ranging between 1:50 and 1:100 for practical reasons (Peter King, 2003a). In the present study, a sectional model of a typical bridge deck has been instrumented with pressure taps at a particular section and wind tunnel test has been conducted for different wind speeds.

4.3.1 Pressure measurement on model to evaluate Strouhal’s number

Measurement of dynamic pressure fluctuations on a bridge deck enables a better understanding of the flow pattern around the bridge deck in terms of flow separation and also in the evaluation of correlation of pressures, across the width of the deck. The section model was instrumented with pressure ports across the section at \( x/L \approx 0.15 \) from one end, where \( x \) is the distance from the end and \( L \) is the length of the deck. A total of 26 pressure ports were distributed on the top and bottom faces of the model, as shown in figure 4.5. The pressure data were acquired at a sampling frequency of 500 Hz for a duration of 10 seconds. The model was tested for 0° wind inclination angle and for four different wind speeds of 4.74, 8.12, 11.64, and 15.04 m/s, measured at the level of the model. The characteristic of the flow in the wake of the bridge deck has been further investigated using pressure spectra and the shedding frequencies have been evaluated. The Strouhal’s number which is not available for the selected cross section of the bridge deck is primarily computed and further compared with those cross-sections available in literature.

A rigid sectional model is generally used in airflow as an almost immobile object to measure time-averaged loads for the whole model or transducer forces or pressure data including everything except for motion dependency. A section model is a span-wise representative segment of a full-scale structure. In the present study, the model-to-full-scale ratio is selected as
1:50. The bridge sectional model under consideration has a length of 980 mm, width of 260 mm and deck thickness of 7 mm (Figure 4.5).

**Figure 4.5 Locations of pressure taps for Strouhal’s number**

### 4.3.2 Pressure measurement on model to compute force coefficients

Additional pressure taps are provided to compute the values of drag, lift and moment coefficients for various wind angles, as shown in figure 4.6 (Photo 4.1). Deck surface pressures at the chosen cross section are measured for four different wind speeds corresponding to $0^\circ, \pm 3^\circ, \pm 6^\circ, \pm 9^\circ, \pm 12^\circ$, and $\pm 15^\circ$, wind inclination angles. Mean pressure distribution and the statistical values based on the pressure trace are computed.

**Figure 4.6 Locations of pressure taps for force coefficients**
4.3.3 Force measurement to compute force coefficients

The supporting plates to mount the bridge deck model were used such that the central bore of 10 mm threaded hole held the model horizontally through long bolts that were used to connect the load cell and the bridge deck model. The perfect zero angle of attack was checked using a leveling meter. The bridge deck can be rotated with respect to the oncoming flow to measure the variation in the forces with angle of attack, between +15° and -15°. The measurements of wind angle are checked using a rotation meter. The load cells were initially fixed to a portal frame at a required height and the bridge deck model was located within the parallel members of the frame inside the wind tunnel as shown in Photo 4.2. The two ends of the model were equipped with load cell through long bolts from the supporting plate in order to channel the wind over the deck in a two-dimensional manner. The moment measurement system was fixed on the left side of the flow and the measurement system consisting of drag and lift had hinged support at the other end of the model, as shown schematically in figure 3.10. The frames
supporting the rig are initially mounted inside the wind tunnel. The vertical frames are of box section. On one of the vertical frames, the static rig measuring moment is attached. On the other vertical frame, the rig measuring drag and lift is attached. The section model of the bridge deck is suitably assembled between the test rigs. Wind tunnel test is carried out on the section model of cable stayed bridge deck under simulated open terrain flow as shown in Photo 4.2. The overall force coefficients are measured using the developed load cells. To validate the designed load cells, the force coefficients evaluated based on pressure measurement are compared with those evaluated based on force measurement.

**Photo 4.2 Test set-up inside wind tunnel for 0° wind**

### 4.4 EXPERIMENTS USING DYNAMIC TEST RIG

Most of civil engineering structures are of un-streamlined and hence theoretical treatment is un-amenable to such structures. The oscillations are characterized by the mutual interaction of aerodynamic force, \( F_a(t) \), with inertial force \( (m \ddot{x}) \), viscous force or damping force \( (c \dot{x}) \), and elastic force \( (kx) \), occurring due to structural motion, i.e,
Linearization of the governing equation is considered to solve the stability problems. The tendency of modal coupling is examined using mode shapes. In stability problems, the modes of vibrations only are of interest, unlike response problems where the absolute values of stresses and deformations are required to be determined. Aeroelastic instability occurs when the aerodynamic force increases rapidly with the wind speed, while the elastic stiffness is unaffected by the increased wind, leading to excessive deflections that are divergent in character (Diana et al., 2004). Hence the aeroelastic design focuses on rigidity, damping characteristics and aerodynamic shape.

Section model tests on bridge decks are regularly conducted in boundary layer wind tunnels to check the aerodynamic stability of the cross section. In the present study, a section model of a cable stayed bridge deck with a geometric scale ratio of 1:50 is tested under simulated open condition. The sectional model is supported on the dynamic test rig using springs and air dampers at both the ends as shown in Photo 4.3. After hanging the model elastically at a height of 770 mm from the floor of the wind tunnel, a mini shaker which is capable of providing excitations at frequencies from 5 Hz to 1000 Hz is connected to the bridge deck model using a flexible spring such that the supporting conditions for the deck are unaltered. The shaker is connected to a function generator for obtaining harmonic excitation. The function generator can also be used to vary amplitude. Even-distribution of the input energy over the required range of frequency is ensured for the sectional model. For the present study, constant RMS amplitude of about 0.1 Volt is maintained throughout all test cases. The circuit diagram of the above setup is shown in figure 4.7. The model is instrumented with an accelerometer.
and strain gauges at both the ends to measure vibrations. The data are acquired at a sampling rate of 1000 Hz for a duration of 10 second.

**Figure 4.7 Circuit Diagram of the Test Setup for Vertical / Torsional Vibrations**

The selected spring constant as obtained by spring combinations for each square frame is experimentally found to be 4367 N/m in the vertical direction, as can be seen from figure 4.8. The measured vertical and torsional natural frequencies are about 10.27 Hz and 20.43 Hz, and the corresponding damping coefficients are 0.0043 and 0.0401, respectively.

**Figure 4.8 Computation of stiffness for an end square frame**
Experiments are conducted under simulated open terrain conditions for four different mean wind speeds, \( \bar{U} \) of 4.5, 6.0, 8.0 and 9.5 m/s, measured at the height of the bridge deck model. The sectional model is subjected to forced vibrations with a fixed value of amplitude and for five different frequencies between 5 and 25 Hz at 5 Hz interval using the external shaker. Following three test cases have been carried out:

1. In the first case, forced vertical excitation alone is given to the model which has both vertical and torsional degrees of freedom.

2. In the second case, coupled vertical and torsional excitation is given to the model by keeping the exciter eccentrically at a distance of 40 mm from the leeward edge of the bridge deck model.

3. In the third case, the vertical degree of freedom is restrained using stiff vertical rods connected to the central bolts on either side of the deck model (Figure 3.17) and the model is allowed to have only torsional degree of freedom, and is excited eccentrically at the same distance as mentioned in the test case 2.

The sectional model is always kept horizontal for all test cases, which correspond to zero angle of wind attack. Torsional motion and coupled vertical and torsional oscillations of the bridge deck are measured using an accelerometer and the four load cells. The stability of the bridge deck is studied based on measured spectral and damping characteristics.
SUMMARY

The experimental details on simulation of boundary layer in wind tunnel, measurement of pressure and force coefficients on static sectional model of a bridge deck using static test rig and measurement of dynamic characteristics for the same bridge cross section studied using dynamic test rig are explained in this chapter. The experimental set-up for both the tests are dealt separately in detail.