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Research Paper

ESTIMATION OF DESIGN WIND FORCES FOR A TALL BUILDING BASED ON WIND TUNNEL STUDY

A Anjana Susan John[1]* and S Selvi Rajan[2]

Corresponding author:* ***A Anjana Susan John* ✉ *anjanasusanjohn89@gmail.com*

This paper demonstrates how structural engineers can benefit from cost-effective wind tunnel studies to obtain critical structural performance issues that otherwise cannot be found very accurately through analysis. In the present study, a 1:100 scale rectangular building model with plan dimensions of 10 cm x 20 cm and height of 70 cm has been considered for pressure measurement studies in a boundary layer wind tunnel under open terrain condition. The measured pressures have been integrated to evaluate mean force coefficients along the body fixed axes (X and Y) and also along drag (in the direction of wind) and lift (in the direction perpendicular to wind) coefficients. Design forces are computed by Codal procedure and its comparison with the forces obtained from pressure studies of the present work has been done. In the present case, experimental test results showed good comparison with the Codal values for along-wind force.

Keywords: Wind tunnel, Codal procedure, Tall building, Along-wind force, Open terrain, Wind load

INTRODUCTION

In India, in recent decades, the application of wind engineering to civil engineering structures has become popular and the state-of-the-art has improved considerably. Wind engineering requires a multifaceted approach to provide solutions to various wind-sensitive problems. It involves various fields such as (i) Fluid dynamics (ii) Probability and statistics and (iii) Structural dynamics. Wind, in general, has two main effects on tall buildings: First, it exerts forces and moments on the structure and its cladding, and second, it distributes air in and around the building, mainly termed as Wind Pressure (Kumar, 2011).

NEED FOR WIND TUNNEL STUDY

Modern tall buildings are being constructed widely with high strength and light weight materials. As a result, the sensitivity of these buildings to dynamic excitation by wind has increased.

[1] Student, Saintgits College of Engineering, Kottukulam Hills, Pathamuttom, Kottayam, Kerala.
[2] Chief Scientist, Wind Engineering Lab, CSIR-SERC, Chennai.

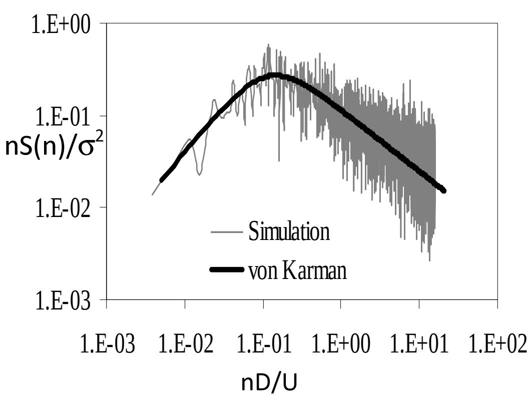
Wind forces govern the design of these buildings. Hence, reliable estimation of wind loads on these structures becomes important. Besides, modern buildings are usually cladded with glass panels. Presently, wind tunnel testing is the most reliable method to predict wind loads on such buildings and is being practiced all over the world. For the calculation of wind loads, pressure measurement study is essential. The designers use Codal provisions (IS: 875-Part 3) for calculating wind pressure and wind load. The pressure coefficients for buildings with regular configuration that are given in the IS code are based on wind tunnel experiments. For buildings having irregular configuration, wind tunnel experiments are recommended for calculating pressure coefficients. The simulation of boundary layer with proper terrain condition also plays a major role in pressure measurement.

The magnitude of wind loads on tall buildings depends on various building parameters, viz., building geometry in plan and its variation along the height of the building, and building height and aspect ratio, and also wind characteristics such as angle of wind incidence, terrain condition, and presence of surrounding structures (Harikrishna *et al.*, 2013). Currently, most of the codes provide pressure/force coefficients for evaluating wind loads on regular- shaped buildings with rectangular/square plan shape, and with various plan side ratios and aspect ratios (Lin *et al.*, 2005). These coefficients mostly correspond to the cases of wind direction perpendicular to any face of the building and are mainly derived from pressure/force measurement- based model studies in wind tunnels, which are considered to be reliable tools in evaluating wind loads on buildings. Further, codes do not recommend force coefficients for all oblique angles of wind incidence that make wind tunnel experiments more advantageous and a better choice for economic design. Experiments are essential in the development of current guidelines and design procedure for wind loads on structures. Wind tunnel experiments are also used as alternative for codes of practice in cases outside the scope of these codes or when it is assumed necessary to obtain the wind loading more precisely. The choice whether or not to perform wind tunnel experiments can be based on reasons of safety or economy. It was generally observed that the quasi-steady approach in the Codal procedure has led to conservative gust response factor in comparison to experimental results (Gianni and Francessco, 2010).

SIMULATION OF TERRAIN

Simulation of the characteristics of the natural wind inside the tunnel to a reduced scale is the foremost and important step in any wind tunnel experiment. The tall rectangular building model has been tested under simulated boundary layer flow condition corresponding to open terrain. The profiles of mean velocity with the power law coefficient of 0.165 and turbulence intensity profile and spectrum of horizontal wind speed corresponding to an open terrain conditions were simulated to a scale ratio of 1:100. The spectrum of longitudinal fluctuating wind in comparison to the standard von Karman's spectrum is shown in Figure 1.

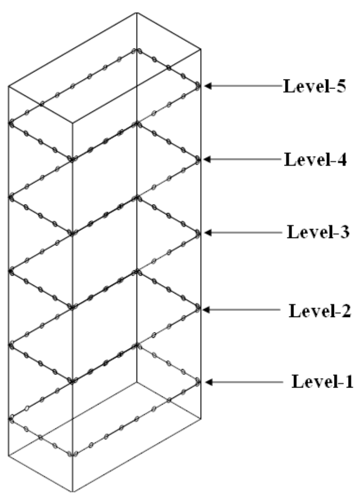
Figure 1: Spectrum of Longitudinal Wind Fluctuations



EXPERIMENTAL SETUP

The experiment was conducted in the Boundary Layer Wind Tunnel (BLWT) facility at CSIR-SERC, Chennai. In wind tunnel study, the model of a building is a geometrically small scale replica of the actual building. In the present study, a rigid model approach has been selected. The dimensions of the rectangular building model with 1:2:7 proportionality has been chosen as 10 cm x 20 cm in plan and 70 cm height. Acrylic material has been used for fabricating the rigid model. A total of 140 pressure taps have been provided along the periphery of the building model at five levels (28 at each level). Figure 2 shows the schematic-isometric view of the rectangular building model with pressure tap locations.

Figure 2: Elevation of the Tall Rectangular Model



The instrumented levels are z/H = 0.1, 0.3, 0.5, 0.7 and 0.9 from the bottom of the building model as shown in Figure 2, corresponding to Levels 1 to 5.

The pressure taps on the model are connected to pressure transducers through PVC tubes with restrictors for the measurement of fluctuating pressures without distortion to the pressure trace. The model has been instrumented with three numbers of Scani-Valve pressure transducers with a sampling frequency of 500 Hz and the characteristic of the tubing is ensured to have flat frequency up to 250 Hz.

TEST RESULTS AND FORCE ESTIMATION

Pressure measurements have been made on the instrumented rectangular building model under open terrain conditions and for angle of wind incidence of 0^0 (Figure 2). The measured pressure data has been processed to evaluate the along-wind load as given below.

Pressure Coefficients

The statistical parameters of the measured pressure time history are evaluated. The mean pressure, $\overline{p}$, of a pressure trace $p(t)$, taken over a period (duration) of time, T, is expressed as:

$$\overline{p} = \frac{1}{T}\int_0^T p(t)dt \quad ...(1)$$

All the pressure coefficients are subsequently deduced with respect to the reference pressure ($\overline{p}_z$) at heights (z/H) of 0.1, 0.3, 0.5, 0.7 and 0.9, for Level 1, Level 2, Level 3, Level 4, and Level 5, respectively. The mean pressure coefficient is calculated as the ratio of mean pressure ($\overline{p}$) to the reference pressure, $\overline{p}_{ref}$. Thus

$$\overline{C}_p = \frac{\overline{p}}{\overline{p}_{ref}} \quad ...(2)$$

where $\overline{p}_{ref} = \overline{p}_z$ (N/m²)

$$\overline{p}_z = \frac{1}{2}\rho\overline{U}_z^{\,2} \quad ...(3)$$

$\overline{U}_z$ = mean velocity at height 'z' of the model (m/s).

Mean velocity is variation along the height of the model and has been considered with a power law coefficient of 0.16.

z = 7 cm, 21 cm, 35 cm, 49 cm, and 63 cm for Levels 1, 2, 3, 4 and 5, respectively. From the analysis of the pressure data, the distribution of mean pressure coefficient along the circumferential of the building model in terms of developed length for 0^0 angle of wind incidence is shown in Figure 3.

Figure 3: Mean Pressure Distribution for 0^0 Wind Angle

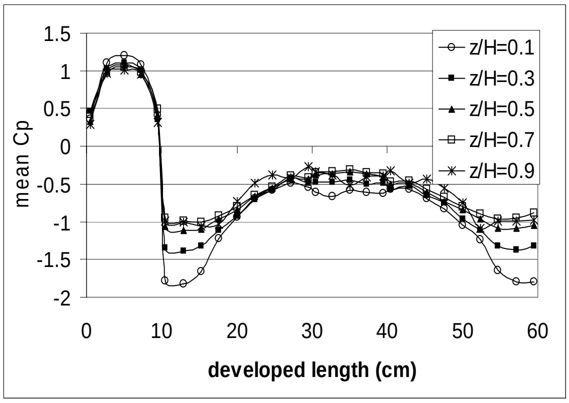
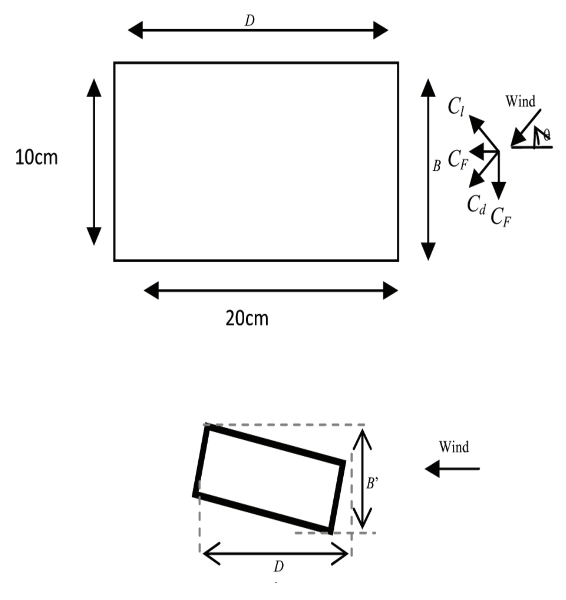


Figure 4: Orientation of Various Axes and Reference Widths



FORCE COEFFICIENT AND ESTIMATION OF WIND LOAD

With reference to a fixed set of body axes (X and Y), orientations for forces F_x, F_y, along with drag and lift directions corresponding to angle of wind incidence are defined in Figure 4. Forces per unit height F_x and F_y along the X-axis and Y-axis (body fixed axes), respectively are computed by integrating the measured pressures along with respective tributary widths.

By resolving F_x and F_y in the direction of wind and perpendicular to the direction of wind, the drag force F_d and the lift force F_l are evaluated.

The mean force coefficients in X, Y directions and the mean coefficients of drag and lift are obtained at each level as given below:

$$\bar{C}_{Fx} = \frac{\bar{F}_x}{W_{ref} B \bar{p}_{ref}} \; ; \quad \bar{C}_{Fy} = \frac{\bar{F}_y}{W_{ref} \bar{p}_{ref}} \; ;$$

$$\bar{C}_d = \frac{\bar{F}_d}{W_{ref} \bar{p}_{ref}} \; ; \quad \bar{C}_l = \frac{\bar{F}_L}{W_{ref} \bar{p}_{ref}} \quad (4)$$

where $\bar{F}_x, \bar{F}_y$ = mean force along X and Y axes, respectively

$\bar{F}_d, \; \bar{F}_l$ = mean drag and lift force, respectively

$\bar{C}_{Fx}, \bar{C}_{Fy}$ = mean force coefficient along X and Y axes, respectively

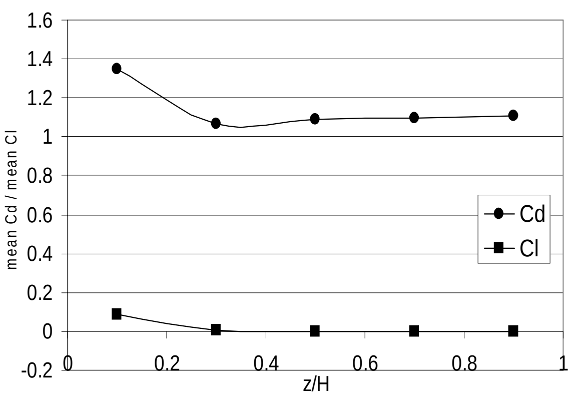
$\bar{C}_d, \; \bar{C}_l$ = mean coefficient of drag and lift, respectively

W_{ref} = reference width = B

$\bar{p}_{ref}$ = reference pressure = $\bar{p}_z$

Variation of mean C_d and C_l with different levels is shown in Figure 5. The values of C_d varied from 1.35 to 1.10 along the height of the model due to variation in velocity and the mean C_l is almost zero due to the symmetry of the cross-section for 0^0 angle of wind incidence. To account for the dynamic effects due to along-wind loads or drag loads, it is necessary that dynamic analysis using the gust factor method based on the first sway mode frequency as recommended in IS: 875 (Part 3) 1987 is performed. Typical calculation procedures for the evaluation of forces F_x and F_y are described below:

Figure 5: Mean Drag and Lift Coefficients for 0⁰ Wind Angle



Calculation Of Forces F_X and F_Y Based on Gust Factor Method

F_x = G (B' segment height) $\bar{p}_z$

F_y = G $\bar{C}_{Fy}$ (B' segment height)

B = reference width

G = gust factor (from clause 8.3 of IS: 875

$\bar{C}_{Fx}$ and $\bar{C}_{Fy}$ = mean force coefficients as obtained from experimental measurements

$\bar{p}_z$ = hourly mean design pressure = 0.6

$\bar{V}_z$ = hourly mean wind speed at height 'z'

$= k_1 \; \bar{k}_2 \; k_3 \; V_b$

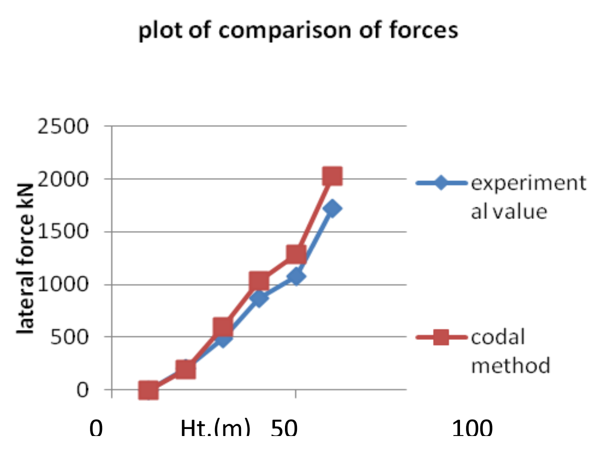
$\bar{k}_2$ = hourly mean wind speed factor at the mid height of the segment (from Table 33 of IS: 875)

k_1 = risk coefficient (from Table 1 of IS: 875)

k_3 = topography factor =1.0 for flat topography (from Appendix C of IS: 875)

V_b = basic wind speed (from Figure 1 of IS: 875).

Figure 6: Comparison of Experimental Values of Forces with Codal Values



CONCLUSION

The present study has been conducted to examine the significance of boundary layer wind tunnel experiments in the design of tall buildings. From all the values obtained on pressure coefficients, the maximum values corresponding to zero degree angle of attack is used for the estimation of design forces, for simplicity in comparison. The Codal procedure as per IS 875: Part 3-1987 has been used to find out the along-wind forces to examine the wind load variation compared to that of a boundary layer wind tunnel results.

- Pressure coefficients are observed to be more for z/H = 0.1 (Level 1) than those for other levels due to edge effect near ground surface (Figure 3).
- The variation of pressure coefficients accounts for better and safer design of structural elements compared to the values given in IS: 875 - Part 3.
- Figure 5 shows variation of C_d along the height of the building model. IS: 875 (Part 3) 1987 provides mean C_d values in the form of force coefficients in Figure 4 of the code and also in the form of pressure coefficients on the windward and leeward faces of the building in Table 4 of the code. However, the values of mean C_d in the code are obtained from wind tunnel experiments conducted under uniform flow conditions.
- It is observed that along-wind force based on wind tunnel experiment is in good comparison with that of the values obtained from the Codal procedure.

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