A Comparative Study of Aerodynamic Coefficients on Tall Structures using Experimental Studies with International Codes and Standards

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Abstract. This paper illustrates the comparison of aerodynamic forces and coefficients on rectangular tall buildings. The forces and coefficients were obtained using Wind Tunnel Experiment and various international code provisions and standards. Rectangular tall building models selected for the study were made of acrylic sheets with various geometric scales. The models were tested using low-speed wind tunnel for various angles of incidents of wind varying from 0° to 90°. Drag coefficients obtained from experiments were compared with values of mean drag coefficients obtained from codes and practices, (a) IS: 875(Part3): Wind Loads on Buildings and Structures (India, 2015), (b) AS/NZS1170.2:2011, the combined Australia/New Zealand Standard on Wind Actions (Standards Australia,2011); (c) ASCE7–10 (ASCE, 2010); and (d) HKCoP-2019, the Code of Practice on Wind Effects in Hong Kong, (Buildings Department HongKong, 2019). Buildings with the same plan aspect ratio show the same aerodynamic behaviour. Wind tunnel study over-predicts the coefficient values compared to standards and practices. The average coefficient of drag values from codes is in good agreement with wind tunnel data with a deviation of less than 15%. The study also includes an examination of parameters such as pitching moment and its coefficient.

1. Introduction

The era of intelligent buildings has begun with the advancement of smart city concepts worldwide. Tall buildings serve as a solution for population issues and lack of land in most of the major cities. As this scenario increases, the structural concerns related to tall buildings have become more prominent in the areas of research. When the heights of the building were limited, the effect of aerodynamics on them could be approximated. As the height increases, the analysis on aerodynamic parameters needed a change from approximate to accurate predictions. In the initial development stages of analysis, the along wind and across wind responses of skyscrapers were made based on the random process and vibration theory[3]. The codes and standards followed the same during its initial formation years. With the use of wind tunnel experiments for studying the responses of tall structures, there has been a drastic change in the method of evaluation of response towards wind effects [1]. These developments brought revisions in the existing codes and practices. This paper discusses the wind-induced aerodynamic parameters for five selected models from wind tunnel study and compares the along-wind response from the wind tunnel study with various standards and practices. The study involves an investigation of lift, drag and torsional behaviour of selected models in the experimental study.
2. Experimental Study

2.1. Wind Tunnel

The experimental study was conducted in a low-speed wind tunnel at Hindustan Institute of Technology and Science Chennai. The wind tunnel has a test section of 600mm x 600mm and a length of 2m. The parts of the tunnel are: Bell mouthed section, honeycomb, settling chamber, contraction cone, test section, transition, diffuser, fan duct, motor and stand, 2 screens, 8 meshes and 16 mesh stainless steel (Figure 1a). The test section has a proper window for viewing the specimen test section. The fabrication of the tunnel is made by using Teak Wood and waterproofing plywood.

![Figure 1. (a) Components in the wind tunnel, (b) View of wind tunnel in the laboratory, (c) Model mounted over dynamometer in the test section, (d) 3-component instrumentation for reading values.](image)

The model to be tested is mounted over dynamometer (Figure 1c and Figure 4). Wind speed in the tunnel is controlled by varying the RPM. The lift, drag and moment values are displayed in 3-component instrumentation which is connected to a dynamometer.

2.2. Simulation of wind

The accuracy of wind tunnel experiments depends on the characteristics of wind flow inside the tunnel[2]. Here the wind is scaled suitably. The rectangular building models are subjected to simulated flow conditions to a reduced scale with respect to the model. Before the experimental study on five selected models, an experiment is conducted on the scaled down model of Empire State Building (Figure 2) as a validation. Coefficient of drag for Empire State Building being a known value, it was compared with results from the experiment to verify the accuracy of test. The value of the drag coefficient from the experimental study was compared with the actual drag coefficient of structure and found to be the same.

![Figure 2. (a) Model of Empire State Building for calibration of test setup, (b) 3D drawing of model, (c) Model inside test section.](image)
2.3. Models for Experiment
All five models used for the experimental study are made of acrylic sheets of 6mm thick (Figure 3). All models were subjected to wind flow at angles of attack of $0^\circ, 20^\circ, 40^\circ, 75^\circ, 90^\circ$. Details of models are given in table 1.

| Model  | L (mm) | B (mm) | H (mm) | Plan Aspect Ratio $B/D$ | Height Aspect Ratio $H/D$ |
|--------|--------|--------|--------|-------------------------|---------------------------|
| Model 1| 50     | 50     | 300    | 1.0                     | 6.0                       |
| Model 2| 33     | 33     | 300    | 1.0                     | 9.1                       |
| Model 3| 100    | 50     | 150    | 2.0                     | 3.0                       |
| Model 4| 50     | 50     | 150    | 1.0                     | 3.0                       |
| Model 5| 34.5   | 69     | 103.5  | 0.5                     | 1.5                       |

Figure 3. Models in Acrylic (i) Model 1, (ii) Model 2, (iii) Model 3, (iv) Model 4, (v) Model 5.

Figure 4. Models mounted on a dynamometer in the test section.

3. Data Analysis
The measured data from wind tunnel such as lift, drag forces and pitching moment are processed to obtain the coefficients of along wind, across wind and torsional behaviour of each models.
3.1. Along wind response
The measured drag force from the instrument is processed using the following relation to obtain the drag coefficient of the building [2].

\[ C_d = \frac{D}{q_\alpha B'} \]  

(1)

where,
- \( C_d \) : Coefficient of Drag
- \( D \) : Measured Drag Force
- \( q_\alpha \) : Dynamic Pressure \( \left( \frac{1}{2} \rho v^2 \right) \)
- \( B' \) : Projected width normal to wind direction

3.2. Across wind response
The measured lift force from the instrument is processed using the following relation to obtain the lift coefficient of the building [2].

\[ C_L = \frac{L}{q_\alpha D'} \]  

(2)

where,
- \( C_L \) : Coefficient of Lift
- \( L \) : Measured Lift Force
- \( q_\alpha \) : Dynamic Pressure \( \left( \frac{1}{2} \rho v^2 \right) \)
- \( D' \) : Projected width parallel to wind direction

3.3. Torsional behavior
The measured pitching moment from the instrument is processed using the following relation to obtain the pitching moment coefficient of the model [2].

\[ C_M = \frac{M}{q_\alpha B'D'} \]  

(3)

where,
- \( C_M \) : Coefficient of Pitching Moment
- \( M \) : Measured Pitching Moment
- \( q_\alpha \) : Dynamic Pressure \( \left( \frac{1}{2} \rho v^2 \right) \)
- \( B' \) : Projected width normal to wind direction
- \( D' \) : Projected width parallel to wind direction

3.4. Comparison with codes
Four standard design codes were used for the comparison of along wind response calculations of the wind-tunnel data, (a) IS: 875(Part3): Wind Loads on Buildings and Structures (India, 2015), (b) AS/NZS1170.2:2011, the combined Australia/New Zealand Standard on Wind Actions (StandardsAustralia, 2011); (c) ASCE7–10 (ASCE, 2010); and (d) HKCoP-2019, the Code of Practice on Wind Effects in Hong Kong,(Buildings Department HongKong, 2019).

4. Results and Discussions

4.1. Aerodynamic forces and force coefficients
Aerodynamic forces such as lift and drag obtained from the instrumentation of wind tunnel were analysed and the lift and drag coefficients are computed using equations (1) and (2). The Lift and Drag forces are plotted against the angle of attack as shown in figure 5. It can be noted that the along wind forces are more compared to across wind forces. The along wind component tends to increase with the increase in angle of incident wind, whereas the across wind component shows an increase between 0° to 20°. In all five models, the results exhibit that critical angle of attack is between 20° to 40°. From 40° to 90° it has a tendency to reduce. It can also be noted that the L/D ratio has a specific pattern with respect to the angle of attack as the aspect ratio changes (Figure 6). From the graph, it is evident that the buildings with the same plan aspect ratio, i.e. Model 1, 2 and 4 shows same pattern of behaviour. Thus, analysing this will be helpful to optimise the shape of a building in the preliminary design stage.
4.2. Torsional Behavior

From the obtained pitching moment through experiment, the pitching moment coefficient is calculated using equation (3)[2]. The behaviour of moment with respect to angle of incident wind was plotted (Figure 7). Here it can be observed that the coefficient of moment has tendency to increase in the areas where there is a notable increase in lift force and reduces at the areas where lift forces decrease. It can be said that the torsional moment will affect the structure when there is a combined action of along wind and across wind forces.

The coefficient of pitching moment and variation of pitching moment for model 2 has a mismatch with the other models. This is due to the higher aspect ratio (9.09), i.e. the aspect ratio is more than the preferable aspect ratio of 6.

4.3. Comparison of along wind Response with standards and codes

On comparison of the coefficient of drag from wind tunnel experiments with the four codes and practices namely, (a) IS: 875(Part3): Wind Loads on Buildings and Structures (India, 2015), (b) AS/NZS1170.2:2011, the combined Australia/New Zealand Standard on Wind Actions (StandardsAustralia, 2011); (c) ASCE7–10 (ASCE, 2010); and (d) HKCoP-2019, the Code of Practice on Wind Effects in Hong Kong, (Buildings Department HongKong, 2019), it is clear that the wind tunnel study over predicts the coefficient values compared to standards and practices (shown in table 2, figure 8). Codes and Standards do not consider Ekman effect while analysing solid air interaction whereas in wind tunnel experiments the dynamic nature of wind including all its features are taken into account. Due to this, it is observed that there is a general nature of the variation of coefficient of drag from experimental study compared to the one obtained from Codes and Standards.
Table 2 Comparison of along wind Response with standards and codes.

| Building Model | Plan Aspect Ratio (B/D) | Height Aspect Ratio (H/D) | Effective Drag coefficient (Cd) |
|----------------|-------------------------|---------------------------|---------------------------------|
|                |                         |                           | Wind Tunnel Experiment | IS 875: 2015 | AS/NZS/ASCE7 | Hong Kong Code of Practice 2019 | Average of Codes |
| Model 1        | 1.0                     | 6.0                       | 1.325                     | 1.40          | 1.425        | 1.325                           | 1.4              |
| Model 2        | 1.0                     | 9.1                       | 1.544                     | 1.50          | 1.601        | 1.410                           | 1.5              |
| Model 3        | 2.0                     | 3.0                       | 1.425                     | 1.20          | 1.600        | 1.270                           | 1.4              |
| Model 4        | 1.0                     | 3.0                       | 1.601                     | 1.30          | 1.700        | 1.210                           | 1.4              |
| Model 5        | 0.5                     | 1.5                       | 1.380                     | 1.15          | 1.410        | 1.200                           | 1.3              |

From table 2 it is evident that the average of standard predictions is close to wind tunnel data for drag and the average of coefficient of drag values from codes are in good agreement with wind tunnel data with a deviation less than 15%.

![Comparison of Cd from Experimental Study and Various International Codes](image)

Figure 8. Comparison of Coefficient of Drag from Experimental Study and Various International Codes and practices

5. Conclusions
The study was carried out on five selected models and comparison of results from wind tunnel tests and various codes and standards were made. From the study, the following conclusions have been derived.

- The along wind component has a tendency to increase with the increase in angle of incident wind.
- The across wind component shows an increase between 0° to 20°. In all five models, the results exhibit that the critical angle of attack is between 20° to 40°.
- Buildings with the same plan aspect ratio show the same aerodynamic behavior. Analysing the aspect ratio will be helpful to optimise the shape of a building in the preliminary design stage.
- The model with a higher aspect ratio of 9.1 exhibited variation in behaviour of pitching moment and its coefficient compared to those models which has a lesser aspect ratio. Hence optimising aspect ratio for a project is important during initial stages in design of tall structure.
- On comparison of the coefficient of drag from wind tunnel experiments with codes and practices, it is clear that the wind tunnel study over predicts the coefficient values compared to standards and practices. The average of coefficient of drag values from codes are in good agreement with wind tunnel data with a deviation of less than 15%.
- Codes and standards do not consider Ekman effect while analysing solid air interaction whereas in wind tunnel experiment the dynamic nature of wind including all its features are taken into account. Due to this, it is observed that there is a general nature of the variation of coefficient of drag from experimental study compared to the one obtained from Codes and Standards.
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