INTERFERENCE EFFECTS OF MEAN WIND LOADS FOR A GROUP OF HIGH-RISE BUILDINGS WITH UNCONVENTIONAL PLAN SHAPE

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ABSTRACT

High-rise buildings are being constructed in large numbers due to rapid growth of urban population, availability of limited space and huge cost of land in urban areas of developing countries. Generally, these buildings have symmetric/regular plan shapes. In recent years, high-rise buildings with free-style plan shapes are being considered and hence novel/unconventional plan shapes are being adopted in the architectural design. This paper presents a wind tunnel study conducted on a 1:300 scale model of a tall building 101.1 m (in full scale) with unconventional plan shape under isolated condition to evaluate force coefficients. Further, interference effects on the building model in the presence of other interfering building models have also been investigated. Under grouped conditions, significant enhancement of the mean force coefficient values along Y axis is observed for few angles of wind incidence. Further, based on the variation of mean force coefficients, critical angles of wind incidence have been identified as angles of wind incidence normal to faces and diagonal directions for the investigated high-rise buildings by taking into account of the interference effects, which are most important for the evaluation of wind loads on buildings with unconventional plan shapes.

Keywords: Interference effects, High-rise buildings, Unconventional plan shape, Wind effects, Force coefficients

Introduction

In the recent past, high-rise buildings with novel and unconventional plan shapes are being considered in order to have a unique identity among other buildings. Design of such buildings is generally governed by wind/earthquake loads. Wind loads on high-rise buildings depend on many factors viz. terrain conditions, shape along the height, aspect ratio and arrangement of surrounding structures etc. For high-rise buildings with unconventional plan shapes, appropriate wind loading coefficients are not generally available in the codes of practice (viz. IS: 875 (1989)). Further, standard of AIJ-RLB (2004) provides guidelines in commentary for estimating the design wind loads for an identical pair of square tall buildings with aspect ratio of 4. Wind loading due to the presence of other interfering buildings can be reliably ascertained through wind tunnel studies. The importance of wind induced interference effects on tall buildings with regular plan shapes has been studied by many researchers viz. Lam et al. (2011), Gu and Xie (2011), Xie and Gu (2007), Zhang and Gu (2008) and Zhao and Lam (2008) through various techniques, using Boundary Layer Wind Tunnel (BLWT).
Wind effects on high-rise building models with varying plan shapes at different heights under isolated condition have been studied by Tanaka et al. (2012), Gu (2010) and Bandi et al. (2013). Wind tunnel pressure measurement studies on models of tall buildings with irregular plan shapes were conducted in boundary layer flows and reported by Lakshmanan et al. (2004), Harikrishna et al. (2009) and Abraham et al. (2012), among other researchers. In the present study, wind tunnel experiments on a high-rise building model with unconventional plan shape under isolated condition and the influence of various surrounding buildings on the building model under grouped conditions have been conducted. The present study has been conducted in the Boundary Layer Wind Tunnel (BLWT) facility available at CSIR-Structural Engineering Research Centre, Chennai, India. It has a test section of 18 m long and cross-sections of 2.5 m (breadth) x 1.8 m (height).

BLWT Investigations on High-rise Buildings: Fabrication and Instrumentation

A model (scale: 1:300) with a height of 337 mm and plan dimensions of 115 x 111 mm of a high-rise building (Tower A) with unconventional plan shape as shown in Fig. 1 has been fabricated using 3 mm thick acrylic sheet. The fabricated model has been inserted as 4 segments using diaphragms at 4 levels through an aluminium hollow tube with height same as the model. The aluminium hollow tube has been used as load cell by instrumenting with strain gauges at the base to measure bending moments along two orthogonal body fixed axes (X and Y), as shown in Fig. 1a. The model (Fig. 1a) with above instrumentation has been used for isolated condition. In order to study the interference effects due to the presence of various other buildings, other high-rise buildings (Tower B & C) with unconventional plan shapes and H-shaped buildings also have been fabricated (Fig. 1a) by adopting the same scale, as interfering structures. The dimensions of the models of Towers B & C and H-shaped buildings are 320 x 112 x 96 mm and 230/220 x 90 x 50/70 mm. The models of Towers B & C have been instrumented at base to measure bending moments along two orthogonal body fixed axes (X and Y) in order to study the interference effects on these edge buildings also.

Fig. 1a Schematic diagram of high-rise building models with aluminium hollow tube
Simulation of Terrain Characteristics

The high-rise towers are considered to be located in the terrain category 3, as per code [IS: 875 (Part 3) 1987]. Accordingly, profile of mean velocity, profile of turbulence intensity and turbulence spectrum of longitudinal wind velocity corresponding to sub-urban terrain with a length scale of 1:300 have been simulated in the wind tunnel by using a trip board followed by boards of wooden roughness elements, as vortex generators. The results of the simulation in terms of profiles of mean velocity and turbulence intensity, and turbulence spectrum with Karman spectrum given in literature [Simiu and Scanlan (1996)] are shown in Fig. 2. The power law coefficient, ‘\( \alpha \)’ of the mean velocity profile has been experimentally found to be equal to 0.215 and turbulence intensity of 0.18 at roof height.

Wind Tunnel Investigations under Isolated/Grouped Conditions

Initially, model with instrumented aluminium hollow tube has been calibrated by applying known lateral loads using pulley and dead weights to obtain calibration coefficients in two orthogonal axes (X and Y) of models of Towers A, B & C. Typical photographic views of static calibration process on the models of Towers A and B in Y axis is shown in Fig. 3. By using the calibration coefficients, force coefficients in body axes (X and Y) for all the three building models have been computed from the bending moments measured at the base. Strain measurements have been made on the models of Tower A under isolated condition and Towers B & C and H-shaped buildings along with Tower A under grouped condition for 16 angles of wind incidence (\( \theta \)) ranging from 0° to 360° for four different mean velocities of 5.6,
12.0, 14.4 and 16.8 m/s, measured at the top of the model of Tower A. The overall layout of the tested models under grouped condition is shown in Fig. 4.

Fig. 3 Photo views of static calibration along Y axis of the models of Tower A and B

Fig. 4 Photo view of the models tested in BLWT under isolated/grouped conditions

Results and Discussions

The mean force coefficients along body fixed axes (X and Y) have been deduced from the measured base bending moments $M_x$ and $M_y$ (about X and Y axes), as given below:

$$c_{Fx} = \frac{M_y}{\int_0^H \rho V_z^2 B z \, dz}; \quad c_{Fy} = \frac{M_x}{\int_0^H \rho V_z^2 B z \, dz}$$

where,
- $c_{Fx}, c_{Fy}$ = Mean force coefficients along X and Y axes, respectively
- $M_x, M_y$ = Mean bending moments about X and Y axes, respectively
- $V_z = \text{Mean wind velocity at level } z = V_{li} \left(\frac{z}{H}\right)^\alpha$
- $V_{li} = \text{Mean wind velocity at reference height, } 'H'$
- $\alpha = \text{power law coefficient}$
- $B = \text{Reference width } = 111 \text{ mm and 96 mm for Tower A and Towers B & C, respectively.}$

Variation of Mean Force Coefficients ($c_{Fx}$ and $c_{Fy}$) in X and Y Axes

It is to be noted that the variation of mean force coefficients corresponding to Tower A under isolated condition are considered applicable to Towers B and C, since Towers B and C have almost comparable height and plan dimensions as those for Tower A. The variation of mean force coefficients in X and Y axes with angles of wind incidence for Towers A, B and C under isolated/grouped conditions are presented in Fig. 5. From Fig. 5(a) of (i), the values of
mean force coefficients in X and Y axes for Tower A (centre building) under grouped condition are observed to be less in magnitude for most of the angles of wind incidence, when compared to isolated condition except for \( \theta = 120^\circ \) and \( 300^\circ \) for which the values of \( \bar{C}_{Fy} \) are enhanced by 5\% and 9\%, respectively. From Fig. 5(b) & (c) of (i), under grouped condition, the values of \( \bar{C}_{Fx} \) are found to be enhanced by 14\% and 10\% for \( \theta = 90^\circ \) and \( 315^\circ \) for Tower B and by 7\%, 27\%, 22\% and 24\% for \( \theta = 0^\circ, 60^\circ, 135^\circ \) and \( 330^\circ \) for Tower C, respectively, when compared to isolated condition.

From Fig. 5(a) of (ii), the values of \( \bar{C}_{Fx} \) under grouped condition are observed to be more than that for isolated condition, by 10\%, 29\%, 20\%, 12\% and 17\% for angles of wind incidence of \( 120^\circ, 150^\circ, 270^\circ, 300^\circ \) and \( 330^\circ \), respectively. From Fig. 5(b) & (c) of (ii), under grouped condition, the values of \( \bar{C}_{Fy} \) are found to be enhanced by 14\%, 33\%, 14\% and 10\% for \( \theta = 120^\circ, 135^\circ, 270^\circ \) and \( 300^\circ \) for Tower B and for Tower C by 9\%, 21\%, 23\%, 33\% and 27\% for \( \theta = 30^\circ, 45^\circ, 60^\circ, 90^\circ \) and \( 120^\circ \), respectively, and by 15\%, 16\% and 11\% for angles of wind incidence of \( 270^\circ, 300^\circ \) and \( 315^\circ \), respectively, when compared to isolated condition.

![Fig. 5 Comparison of \( \bar{C}_{Fx} \) and \( \bar{C}_{Fy} \) for Towers (a) A, (b) B and (c) C](image-url)
Variation of Mean Drag and Lift Force Coefficients ($\bar{C}_d$ and $\bar{C}_l$)

By resolving the mean forces along and perpendicular to the direction of wind, the mean aerodynamic force drag $\bar{C}_d$ and the mean lift $\bar{C}_l$ coefficients have been evaluated, as given below:

$$\bar{C}_d = \bar{C}_{d_x} \cos \theta + \bar{C}_{d_y} \sin \theta$$
$$\bar{C}_l = \bar{C}_{l_x} \cos \theta + \bar{C}_{l_y} \sin \theta$$

where, $\bar{C}_d$, $\bar{C}_l$ = Mean drag and lift coefficients and $\theta$ = angle of wind incidence

The variation of $\bar{C}_d$ and $\bar{C}_l$ corresponding to base of the models of Towers A, B & C for isolated/grouped conditions are shown in Fig. 6. From Fig. 6(a) of (i), the values of $\bar{C}_d$ are observed to be mostly shielded (i.e. less in magnitude) except for angles of wind incidence of 120°, 270°, 300° and 330°, for which $\bar{C}_d$ values are observed to be more than the isolated condition values by about 9%, 20%, 12% and 6% for Tower A under grouped condition. From Fig. 6(b) & (c) of (i), under grouped condition, the values of $\bar{C}_d$ are observed to be more than the isolated condition for angles of wind incidence of 120°, 135°, 150°, 270° and 300° by about 8%, 10%, 11%, 14% and 19% for Tower B and by about 7%, 10%, 24%, 33%, 5%, 15%, 6% and 35% for angles of wind incidence of 0°, 45°, 60°, 90°, 135°, 270°, 315° and 330° for Tower C.

From Fig. 6(a)-(c) of (ii), for Towers A, B and C, the values of $\bar{C}_l$ are observed to be significantly affected due to interference effect for individual angles of wind incidence. For Tower A, the maximum positive value of $\bar{C}_l$ among the grouped condition is observed to be 0.40 for $\theta = 240^\circ$. Similarly, the minimum negative value of $\bar{C}_l$ is observed to be -0.42 for $\theta = 150^\circ$. The maximum positive and minimum negative values of $\bar{C}_l$ are observed to be 0.31 for $\theta = 270^\circ$ and -0.64 for $\theta = 180^\circ$ for Tower B. For Tower C, these values are observed to be 0.79 for $\theta = 240^\circ$ and -0.45 for $\theta = 330^\circ$. 
Variation of Mean Resultant Force Coefficients ($\overline{C_{Fr}}$)

The values of $\overline{C_{Fr}}$ have been computed using $\overline{C_{Fx}}$ and $\overline{C_{Fy}}$, as given below:

$$\overline{C_{Fr}} = \sqrt{\overline{C_{Fx}^2 + C_{Fy}^2}}$$  \hspace{1cm} (3)

The variation of $\overline{C_{Fr}}$ corresponding to base level of the models of Towers A, B & C for isolated/grouped conditions is shown in Fig. 7. From Fig. 7, it is observed that the variation of $\overline{C_{Fr}}$ are seem to be similar to the variation corresponding to $\overline{C_d}$.

Identification of Critical Angles of Wind Incidence

As mentioned earlier, for high-rise buildings with unconventional plan shapes, appropriate wind loading coefficients are not generally available in the codes of practice (viz. 315
Identification of critical angles of wind incidence is most important for the evaluation of wind loads on high-rise buildings, especially buildings with irregular/unconventional plans and further, such buildings are under grouped condition. Based on the present study, the variations of $C_{Fx}$ and $C_{Fy}$ with angles of wind incidence for grouped condition for Towers A, B and C have quite different trends in comparison to those for isolated condition. Whereas, the variations of $F_{Fx}$ and $F_{Fy}$ with angles of wind incidence for grouped condition have trends similar to those for isolated condition due to all faces being parallel to either X or Y axes. Hence, even though the present study is case specific, critical angles of wind incidence have been identified for Towers A, B and C (Tables 1 and 2) for the evaluation of wind loads based on the variation of $F_{Fx}$ and $F_{Fy}$. It can be seen from the Tables 1 and 2 that the critical angles of wind incidence are found to be angles of wind incidence normal to all four faces and skewed/diagonal with respect to either X or Y axis.

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<th>0 &amp; 180</th>
<th>90 &amp; 270</th>
<th>120 &amp; 300</th>
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<th>45 &amp; 135</th>
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Summary and Conclusions

Wind tunnel studies on a model (scale: 1:300) of high-rise building with unconventional plan shape have been carried out under isolated condition to evaluate mean force coefficients (along body fixed axes) by using strain measurements for 16 angles of wind incidence ranging from $0^\circ$ to $360^\circ$ for four different mean velocities of 5.6, 12.0, 14.4 and 16.8 m/s under simulated suburban terrain. Further, interference effects due to the presence of surrounding building models also have been investigated. Based on the present study, the evaluated mean force coefficients obtained under grouped condition are observed to be enhanced by about 10% to 33% in comparison with the values obtained under isolated condition for specific angles of wind incidence. This increase in mean force coefficients need to be considered for the estimation of design wind loads on the centre and the edge high-rise buildings in order to account for the interference effects of neighboring high-rise buildings. Further, based on the variation of mean force coefficients, critical angles of wind incidence have been identified as $0^\circ$, $90^\circ$, $180^\circ$, $270^\circ$ (angles of wind incidence normal to faces) and also at angles $45^\circ$ and $135^\circ$ (skewed/diagonal angles of wind incidence) for the investigated high-rise buildings by taking into account of the interference effects, which are most important for the evaluation of wind loads on buildings with unconventional plan shapes.
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References


