9th Asia-Pacific Conference on Wind Engineering
Auckland, New Zealand
3-7 December 2017

Investigation of Aerodynamic Forces on High Rise Buildings with Set-Back Modification

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Abstract

In past decades tall buildings have been designed traditionally and with symmetrical shapes like square, rectangular, triangular, circular etc. as these shapes were less prone to the vibrations by seismic loads, but as a result of social and economic need and by the development of peculiar and free style shaped buildings along with the advanced tools and designing methods, new trend is being set by architectures and engineers to display their spirit, inventiveness and design concept while keeping in mind the reduction of wind induced loads which prevails as the height of structure increases as increase in building height raises the concern of wind load. While the efficacy of modifications along the elevation has been widely reported previously by many authors, in present study an effort has been made to investigate the mitigation effect of set-back modification on aerodynamic forces for high rise buildings while keeping the total volume and height of the structure model same as that of reference model (Square). The results show a good amount of reduction in along wind and across wind forces and moments.

Introduction

Progressive development and advancement of new engineering and construction techniques, high grade materials, steel etc., welded connections and light facades (do not impart in strength of structure) has motivated architects and engineers to the construct light tall, super tall and mega buildings [1] but regrettably these advancements in heights have led to increased flexibility, slenderness, lesser damping and low natural frequency [6] and raised concern of wind induced load and response as these are more expected to be in the range of wind gust and moreover vortex shedding is also an important phenomenon whose frequency may reach close to the natural frequency of structure and as a result this may lead to the vibrations in structure, which may be troublesome as serviceability and Survivability issue is concerned [2, 5, 14]. Unlike the physical modifications like mass, stiffness, damping ratio to suppress the wind forces, the aerodynamic modifications along the elevation such as taper and set-back alter the separated shear layer and spread the vortex shedding over a broad range of frequencies and in consequence there is reduction of across wind load on the structures [3, 4, 5, 7, 9, 12]. The Petronas tower, Jin Mao tower and Sear tower are the examples of slight setback for tapering effect which resulted in curtailing of vortex shedding effects. Kim et.al. [8] Studied the effect of tapering for 5%, 10% and 15% tapering ratio through aero-elastic model test. Kim and Kanda [10] investigated the effects of tapering and 2 step set-back (set-back at middle height) on wind forces and observed that overturning moments are reduced largely for setback model rather than taper model with same bottom and top dimensions. Kim and Kanda [12] conducted similar study for the investigation of pressures. Correlation among forces and moments for tapered and setback configurations with eccentricity variations were analysed and addressed by Kim et.al. [11]. So in present work, the pressures, forces and moments of the three step set-back (SB5, SB10, SB15) models having bottom and top dimensions according to the 5%, 10% and 15% tapering ratio (Tapering Ratio=(top width- bottom width)/ height x100%) have been investigated and compared with the reference square model.

Experimental Setup

All the pressure and force measurement tests were carried out in boundary layer wind tunnel at Department of Civil Engineering, Indian Institute of Technology, Roorkee, India. The tunnel is open circuit type with continuous flow of wind at variable speed. The wind tunnel test section is 15 m in length with a cross section of 2 m x 2 m.

The building models for pressure test were made from acrylic sheet and models had 42 pressure points on each face of the model. The length of the venyl tube used for the pressure transmission was kept between 20 cm to 80 cm.

The models for high-frequency force balance tests were made from very thin and light plywood to keep it light and stiff. The wind forces and moments were measured by 5-component load cell by NISSO (LMC-5511-10) and load cell was located at the bottom of the models.

A geometric scale of 1/700 was assumed and correspondingly the model dimensions and height (60cm) were calculated while keeping the volume and height of all models as constant. The details of the models has been shown in the Figure 1.

The velocity at the model height has been used to calculate the dynamic pressure q_H which is used to determine the force and moment coefficients. The details of the velocity profile is shown in the Figure 2.

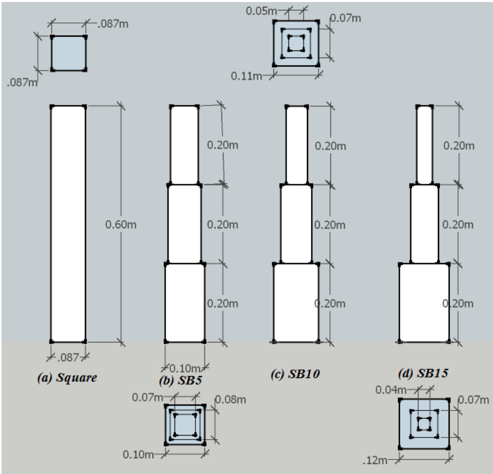


Figure 1: Model Dimensions

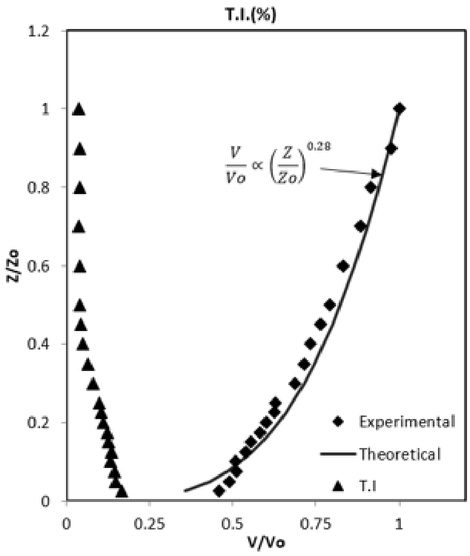


Figure 2: Velocity and Turbulence profiles of incident flow

Figure 3 given below, shows the definition of coordinate system, forces and moments. Where angle α is the wind incidence angle.

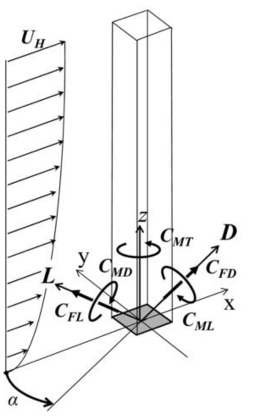


Figure 3: Definition of Forces and coordinate system

Experimental Results and Discussion

Pressure Test:

Wind pressure coefficients were calculated using the following formula:

$$Cp_i = \frac{Pi - Po}{\left(\frac{1}{2}\rho U_H^2\right)}$$

Where Pi is the mean pressure at the point located on the surface of the model, ρ is the density of air and U_H is the reference velocity at the height of the building model.

Figure 4 shows the contours of mean coefficient of pressure on windward, leeward and side face respectively for square and setback models for 0^0 angle of incidence.

From the contour levels it can be seen that the maximum mean pressure coefficient on windward face for square, SB5 and SB10 is 0.9 and it decreases to 0.8 for SB15 model. On the windward face one stagnation point appears for square model however more than one stagnation points can be observed for setback models. For leeward faces the square model shows less variation in the values while other three height modified models show large difference in all the three steps of setback, this is likely to arise due to the impediment of the downwash/downdraft by the increasing cross-sectional shape along the downward direction. [12]

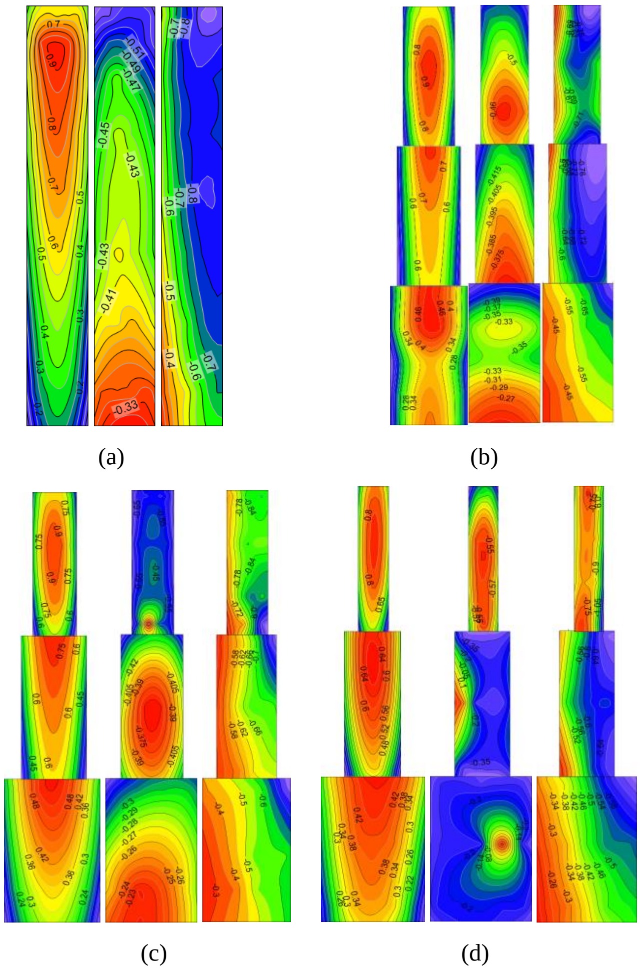


Figure 4: Pressure Contours (a) Model Square, (b) Model SB5, (c) Model SB10, (d) Model SB15

Force Balance Test

The wind forces and moments were calculated using the following formulas:

$$\bar{C}_{F_x} = \frac{\bar{F}_x}{0.5\rho {U_H}^2}$$

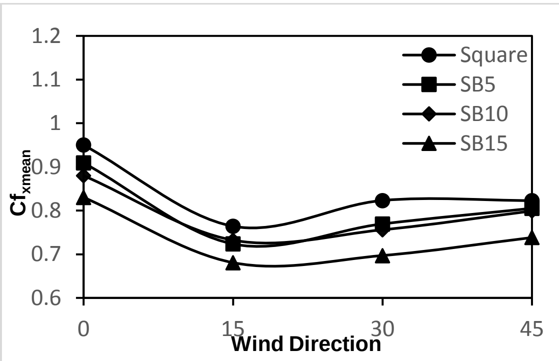
$$\bar{C}_{F_y} = \frac{\bar{F}_y}{0.5\rho {U_H}^2}$$

$$\bar{C}_{M_x} = \frac{\bar{M}_x}{q_H B H^2}$$

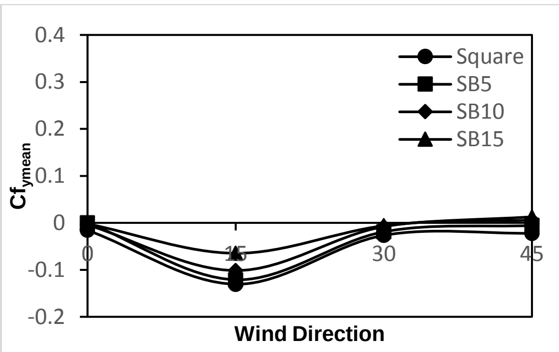
$$\bar{C}_{M_y} = \frac{\bar{M}_y}{q_H B H^2}$$

Where $\bar{F}_x$is the mean wind force in x direction, $\bar{F}_y$is the mean wind force in y direction, $\bar{M}_x$is the mean overturning moment about x direction, $\bar{M}_y$is the mean overturning moment about y direction, $U_H$is the mean velocity at the building top, B is the side length of the building model and H is the height of the building model.

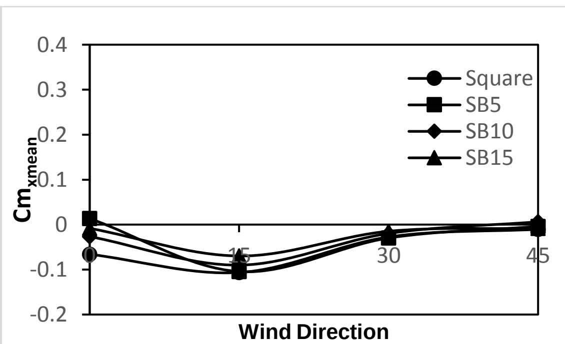
Mean Wind Forces:



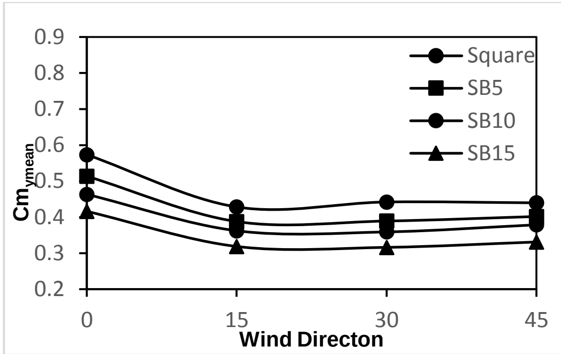
(a)



(b)



(c)



(d)

Figure 5: Variation of mean coefficients with wind directions (a) Mean coefficient of drag in x direction (b) Mean coefficient of force in y direction (c) Mean overturning moment coefficient about x direction (d) Mean overturning moment coefficient about y direction

From Figure 9(a) it is evident that among all the models the square models has the highest mean values of C_{fxmean} for all the wind incidence angles having highest value at 0^0 and it decreases with the increase in wind incidence angle, the magnitude of C_{fx} decreases as the modification i.e. the difference between the top bottom and top dimension of the setback increases. A same pattern is followed by the variation of Cm_{ymean} with wind incidence angle.

Figure 9(b) shows the comparison of mean Cf_{ymean} among four models and the absolute value decrease for all the modified model as compared to square model, for angle 15^0 Cf_{ymean} the absolute value of models reaches to its maximum. The Cm_{xmean} values follow the same pattern as of Cf_{ymean} (Figure 9(c)). In Figure 9(d) variation of Cm_{ymean} with wind direction has been shown and qualitatively it follows Cf_{xmean}.

θ	**Coeff.**	**Square**	**SB-5**	**SB-10**	**SB-15**
	Cf_{xmean}	0.95	0.90	0.8	0.83
	Cf_{ymean}	-0.001	0.00	-0.004	-0.002
	Cm_{xmean}	-0.06	0.01	-0.02	-0.008
	Cm_{ymean}	0.57	0.51	0.46	.42
	Cf_{xmean}	0.76	0.72	0.73	0.68
	Cf_{ymean}	-0.13	-0.12	-0.10	-0.06
	Cm_{xmean}	-0.11	-0.10	-0.09	-0.06
	Cm_{ymean}	0.43	0.38	0.36	0.31
	Cf_{xmean}	0.82	0.76	0.75	0.69
	Cf_{ymean}	-0.03	-0.02	-0.008	-0.006
	Cm_{xmean}	-0.03	-0.02	-0.02	-0.02
	Cm_{ymean}	0.44	0.38	0.36	0.35
	Cf_{xmean}	0.82	0.81	0.79	0.73
	Cf_{ymean}	-0.02	-0.005	0.006	0.00
	Cm_{xmean}	-0.01	-0.003	0.006	-0.008
	Cm_{ymean}	0.44	0.40	0.37	0.33

Table 1. Coefficients of forces and moments for different wind incidence angles

Conclusions

The pressure test and force balance tests are conducted and the results are analysed for square and set-back models under boundary layer flow. The conclusions are follows:

- The difference in mean pressure values on the windward faces is not large, on all the models it varies in between the range of 0.2-0.9, however differences on leeward faces are due to the geometrical characteristics of the modified models which results in the reduction of drag forces.

-The force balance test shows quite good results for height modified model as compared to the square model. The geometric modification along the height results in the good amount of reduction in mean along wind and across wind forces. It is clearly seen by modification of cross section along the elevation through setback configuration, reduced mean overturning moments in along and across wind directions were achieved.

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