Evaluation of Mean Wind Loads on Two Rectangular Building Models

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***Abstract*— Due to faster growth of demand for living space in urban environment, increase in affordability of people and technological development, the constructions of tall buildings become inevitable. Wind induced loads are the major concern for the design of such tall buildings. These buildings can be subjected to wind loads both in along wind and across wind directions. Currently, the code provisions for wind load calculation include pressure coefficients/force coefficients of buildings for wind directions normal to any one face of the building under uniform flow**

We had conducted the wind tunnel experiments on two rectangular building models of plan ratio 1:2 and aspect ratio 1:6 and 1:8 under open terrain condition corresponding to a geometric scale of 1:300, to study the variation of mean force coefficients using High Frequency Force Balance method. In the current work, wide range of ideas from various researchers and theoretical back ground of wind engineering were discussed. In addition the average mean drag coefficients of the present study is compared with IS: 875 (PART 3) - 1987 code values for validation.

I. INTRODUCTION

Buildings are defined as structures utilized by the people as shelter for living, working or storage. Due to the shortage of land to the construct more buildings for both residential and industrial purposes in urban environment resulting in the need of vertical construction. Hence, the construction of tall buildings is being done on a large scale. As the height of the building increases, the effects of wind on the structure also become more critical. The two critical loads which fall on the structure from the nature are seismic loads and wind loads, both these loads are unpredictable. In general, a designer will consider the most critical condition among these two while designing a small residential building, but it is must to consider the wind influence on the building when going to construct a building whose slenderness ratio ($H/\sqrt{A}$) is greater than 1. Due to unpredictable nature of wind, it takes devastating forms in severely affecting the structural integrity, machinery / equipment / and people present inside the structure. So, the study of the wind effects on buildings becomes integral part of building design and planning.

II. WIND CHARACTERISTICS

Near the Earth's surface, the no-slip condition of fluids play an important role in making the wind velocity zero at the ground surface and gradually increasing with height. The region with variation (i.e. increase) of wind velocity with height is called 'atmospheric boundary layer' and is similar in many respects to the turbulent boundary layer flow on a flat plate. The term 'boundary layer' means the region of wind flow affected by friction at the earth's surface, which can extend up to 1 km. Wind was randomly varying with time and distance up to the atmospheric boundary layer.

Wind derives its energy from sun. Solar radiation is strongest at the equator and this produces temperature differences, which in turn produces pressure differences, which creates the so called atmospheric circulations, Additional variations to the atmospheric circulations are caused by seasonal effects (annual march of sun north and south of the equator), geographical effects (uneven distribution of water and land) and rotation of earth (greater speed at equator than near the poles).

Local winds have minimum influence on primary and secondary circulations of wind regardless, they may have high intensity. Thunderstorms caused by heavy precipitation and tornadoes, which are the most powerful winds causing maximum damage, belong in this category.

The properties of wind which are of interest can be grouped as static and dynamic. Static properties of interest are temperature, pressure and density. In a still atmosphere, these changes with altitude and season. But certain averages have been worked out for different regions. The value adopted by International Organization for Standardization and which applies to temperate zones are sea level pressure = 760 mm mercury, sea level temperature = 15˚ C and sea level density = 1.2232 kg/m^3. Although a similar standard for tropics has not been universally established, studies by Indian scientists have indicated that, for India sea level pressure = 758.4 mm of mercury, sea level temperature as 27˚ C and sea level density as 1.073 kg/m^3. However, for case of usage, these have been changed slightly to sea lever pressure = 760 mm of mercury, sea level temperature as 30°C and sea level density as 1.165 kg/m^3. These values are used in aircraft applications. The Bureau of Indian Standards adopted sea level density = 1.2 kg/m^3 as the average for both sea level and interior regions for India, in IS:875 (Part 3) - 1987. No standard pressure and temperature has been specified.

A. Mean wind velocity

The wind velocity at any height (z) above the ground surface fluctuates randomly in space with time.
Thus, wind velocity can be characterized:

$$U(z, t) = \bar{U} + u + v + w$$

where, U (z, t) is the instantaneous wind velocity at height, z with time t, $\bar{U}$ is the mean velocity. u, v and w are the fluctuating components of wind in x, y and z directions respectively.

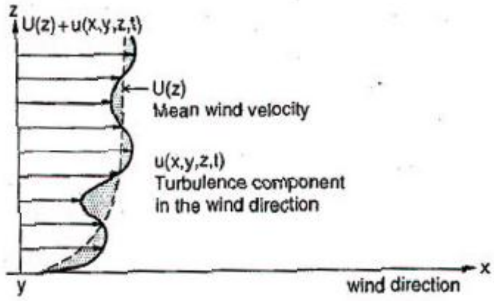

Figure 2.1 – Mean wind velocity

B. Variation of wind velocity with height

The variation of wind velocity with height depends on the roughness in the form of trees, houses, buildings, structures etc., on the ground surface. Depending upon the roughness of the ground surface, the wind velocity increases up to certain height called 'gradient height'. Beyond gradient height, the wind velocity becomes nearly uniform with height and is known as 'gradient wind'.

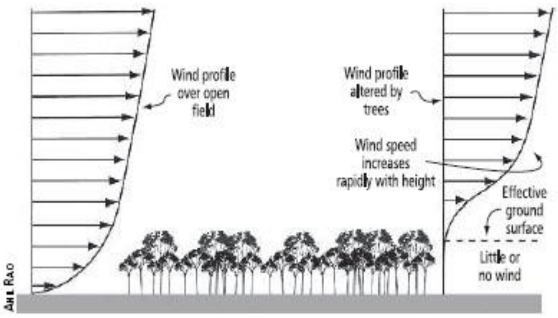

Figure 2.2 – Variation of wind w.r.t height

C. Turbulence intensity

The longitudinal turbulence intensity factor is defined as the ratio of RMS velocity at any height (z) to the corresponding mean wind speed at the same height. The unsteady part of the wind velocity component behaves in a random manner, so by definition the mean of the each turbulence component is zero. The process of turbulence generation is highly complicated. Hence, the measure of the strength of turbulence is defined as the variance or mean square value and its root is called the root mean square or standard deviation of wind velocity. Fig. 1.3 shows the turbulence intensity profile of wind.

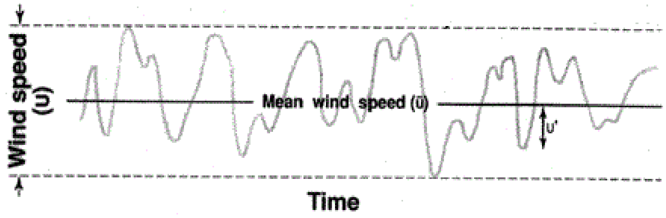

Figure 2.3 – Turbulence intensity

The longitudinal turbulence intensity factor I (i, z) as shown in eq. 1.4 is defined as the ratio of R.M.S velocity at any height (z) to the corresponding mean wind speed at the same height.

Where
I_u (z) = Intensity of the turbulence of the u-component of the wind velocity at height z in the ith of terrain (%).
$\bar{U}$ (z) = Mean wind velocity at height z (m/s).
(z) = R.M.S or standard deviation value of the fluctuating wind velocity (m/s).
Selection of terrain categories shall be made with due regard to the effect of obstructions which constitute the ground surface roughness. Terrain category means the characteristics of the surface irregularities of an area, which arise from natural or constructed features. In IS: 875 (part 3) - 1987, the categories are numbered in increasing order of roughness. Fig.

1.4 represents the various terrain categories.

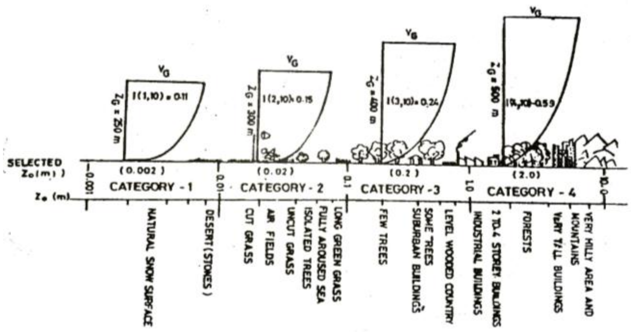

Figure 2.4 – Terrain categories

III. WIND TUNNEL INVESTIGATIONS

There are three different approaches to determine the wind induced behavior of a structure. They are:

1. Wind tunnel experiments on models of structures
2. Full scale tests on prototype structures.
3. Numerical studies on flow around structures.

The first two approaches are the experimental methods for solving several Wind-Engineering problems. Of these three, full scale experiments are time consuming and expensive and generally they are undertaken in a limited number for specific projects. Alternately wind tunnel testing is widely being used for investigating wind effects on models of various buildings and structures. Wind tunnel testing of buildings and structures has been an offshoot of Aeronautical Engineering, in which the flow of wind is duplicated at high altitudes. The wind tunnels for testing airplane models are designed to minimize the effects of turbulence, and as such they do not duplicate atmospheric boundary layer or wind turbulence This is because majority of airplane flight's, except for a brief period of landing and takeoff, flying occur at a height well above the boundary layer. Building activity, on the other hand, occurs precisely within this atmospheric boundary layer, characterized by a gradual retardation of wind speed and high turbulence near the surface of the earth.

A. BOUNDARY LAYER WIND TUNNEL

Boundary layer is defined as the layer of fluid of certain height in the immediate vicinity of atmospheric boundary surface up to which wind flow is affected by the force due to the friction of the earth's surface where the effects of viscosity are significant. Above the boundary layer, the wind, flows with a constant velocity know as gradient velocity, Vgr and the depth is called boundary layer depth (δ) which is of the order of 500 m, where construction of tall buildings and structures and other man-made activities are carried out. The atmosphere above the boundary layer is called free atmosphere.

In early days, wind tunnels were used for aeronautical studies for the design of aircrafts, where the flow is considered to be uniform throughout the wind tunnel. Boundary layer wind tunnel is a facility to simulate the atmospheric boundary layer under controlled supply of air in laboratory conditions.

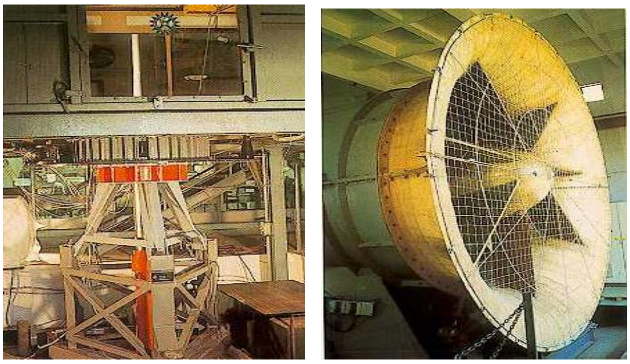

Figure 3.1 - The turntable set-up and the bell mouth entry of BLWT (Boundary layer wind tunnel)

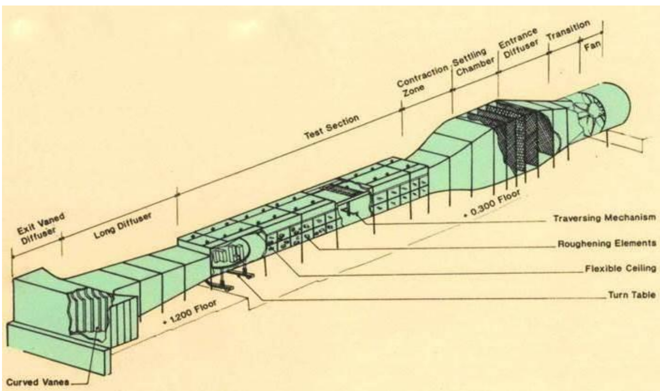

Figure 3.2 - BLWT at CSIR – SERC, Chennai

The test section is provided with glass panels for easy visualization of experiment being carried out. The size of the test section is 18 m x 2.5 m x 2.15 m. Such a long test section is preferred to achieve natural development of equilibrium boundary layer. A flexible ceiling arrangement is provided to achieve zero longitudinal pressure gradients. 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 the wind tunnel. The test section has two turntables one on upstream side and one on downstream side to conduct experiments. The downstream side turn table is to test the models under simulated boundary layer/turbulent conditions and the upstream table is used for studies for models under uniform flow conditions. Fig 3.2 shows the schematic diagram of BLWT facility at CSIR-SERC.

Simulation or modelling of the characteristics of the natural wind in 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. Hi-scan, differential types of pressure sensors are used for pressure measurement studies. 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.

Salient Features of BLWT at CSIR-SERC:

Type of wind tunnel: Open circuit
Fan Type: Blower type axial fan
Max. Power rate of fan: 600 HP
Total length of tunnel: 52 m
Test section dimension: 18 m x 2.5 m x 1.8 m
Wind speed: 0.5 – 55 m/s
Exit velocity: 11 m/s
Turn table diameter: 2.38 m

Simulation of wind characteristics in wind tunnel:

The mean velocity profile and turbulence intensity profile inside the wind tunnel corresponding to an open terrain condition at a geometric scale of 1:300 with a power law of coefficient (α) equals 0.165 were simulated in a BLWT at CSIR-SERC. The turbulence characteristics inside the wind tunnel were simulated by using a set of roughness boards and with the trip board of 30 cm height. The simulated mean velocity profile and turbulence intensity profile inside the wind tunnel are shown in Fig. 3.3.

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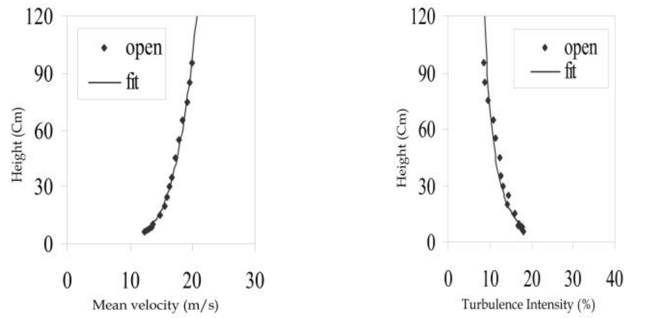


Figure 3.3 - Simulated mean velocity profile and turbulence intensity profile corresponding to open terrain condition

B. HIGH FREQUENCY FORCE BALANCE SYSTEM

In the present investigation, the high-frequency force balance system is to capture the wind-induced forces on the building or structure with a mode-shape which varies linearly over the height. Forces can be evaluated by measuring the dynamic base moments acting on simulated rigid model of the geometry of the building. The high frequency force balance sensor used in this experiment study is ATI Gamma (SI – 130-10) which is shown in Fig. 3.4. The specifications and sensing ranges of the high frequency force balance sensor is given in Table 1 and Table 2, respectively. A model mounted on a high sensitive and stiff force balance measures, its base shear forces and base moments/torques.

The frequency of the model and the balance are to be chosen in such a way, that the range is to be sufficiently high, so that the distortions in the dynamic wind load due to resonance in the frequency range of interest can be avoided. The base moments provide direct measures of the generalized forces associated with the fundamental sway modes of vibration. The measured base torque requires adjustment in order to provide an estimate of the generalized torque, which is the integral of the torque per unit height weighted by the mode shape taken over the height of the building. The loads in the two sway directions and the torque can be combined for dynamic systems which have three-dimensional modes of vibration.

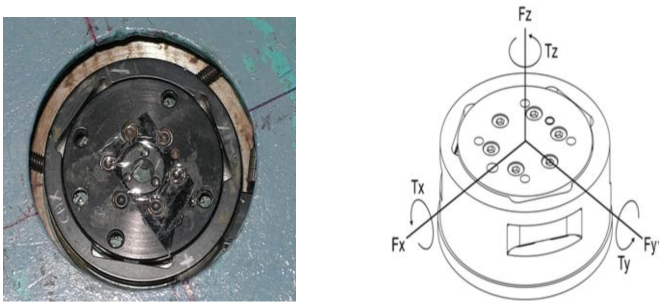


Figure 3.4 - Six axis force balance sensor

Table 1- Physical parameters of six axis Force/Torque sensor

Parameter	Specification
Weight	250 g
Diameter	75.4 mm
Height	33.3 mm

Table 2 Sensing Range of Force/Torque sensor

Force/Torque in axes	Sensing Range
F_x , F_y	130 (± N)
F_z	400 (± N)
T_x , T_y	10 (± Nm)
T_z	10 (± Nm)

C. DETAILS OF FABRICATED MODEL

Two rectangular building models with plan dimensions of 15 cm X 7.5 cm (plan ratio 1:2) corresponding to a geometric scale of 1:300 were chosen for this investigation. The fabricated rectangular building models with thermo-coal material and cladding surfaces were by thin mica sheets. The aspect ratios of 6 and 8 (with respect to smaller dimension, i.e. 7.5 cm) were considered in the present investigation. An aluminum hollow circular pipe of 4.0 cm diameter with 0.2 cm thick was used as a central core to provide the elastic stiffness to the model. The cross-sectional view of a rectangular building model along with its mounting arrangement in six axis force/torque sensor is shown in Fig. 3.5. The heights up to which aluminum pipes was inserted inside the models were as 430, 580 mm for the aspect ratios of 6 and 8, respectively. An adopter plate has been used to fix the rectangular building model along with aluminum core to a six-component force/torque (ATI F/T sensor: Gamma). The orientation of the model for the representation of body axis is shown in Fig. 3.6.

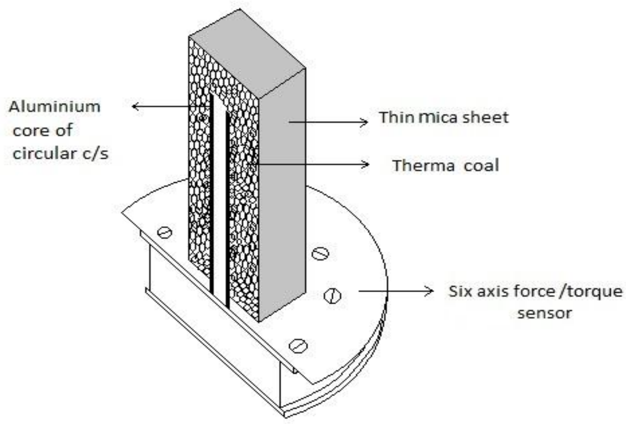


Figure 3.5 - Cross-sectional view of a rectangular building model along with its mounting arrangement in six axis force/torque sensor

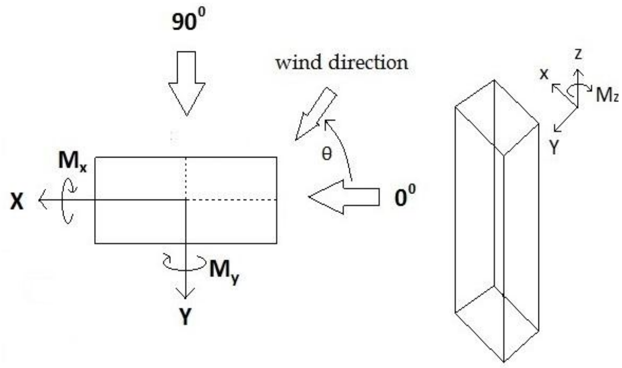
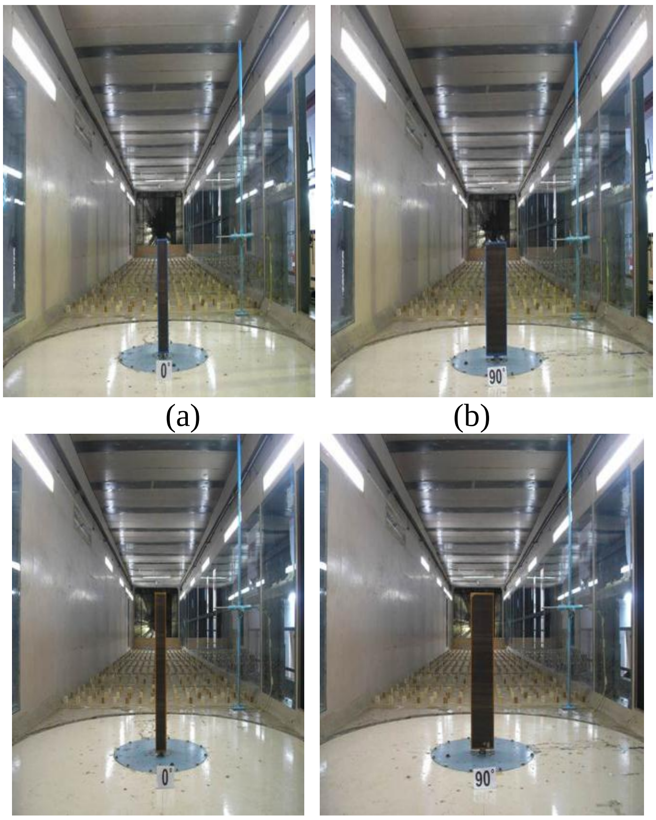


Figure 3.6 - Plan and elevation view of model along with its axes

D. EXPERIMENTAL PROGRAM

The rigid models (2 no's) were mounted on the six axis force/torque sensor in downstream side of wind tunnel for an open terrain category having a power law coefficient equals to 0.165. These models were tested for 8 different angles of wind incidence from 0˚ to 90˚ such as 0˚, 10˚, 20˚, 30˚, 45˚, 60˚, 80˚, 90˚. The orientations of the models in 8 different angles of wind incidence were shown in the Fig. 3.8. For each angle of wind incidence test was conducted for four different wind speeds. Tests were carried in the wind tunnel on the model having an aspect ratio of 6 was tested for four different wind speeds at model height for 8.0 m/s, 10.6 m/s, 13.3 m/s, 15.9 m/s and the model having an aspect ratio of 8 was tested for four different wind speeds at model height for 8.3 m/s, 11.1 m/s, 13.9 m/s, 16.7 m/s and for each wind speed, readings are taken by three trails. Pitot tube was arranged at height of model to collect the velocity readings in wind tunnel. Readings are taken in a sampling rate of 1000Hz in duration of 15sec. For the data acquisition, ATI-DAQ software was used. The typical view of models (aspect ratios 6, 8) at 0˚ and 90˚ are shown in Fig. 3.7 (a, b, c and d).



(c) **(d)**

Figure 3.7 - Typical view of the models a) for h/b=6 at 0˚, b) 90˚, c) for h/b=8 at 0˚ and d) 90˚

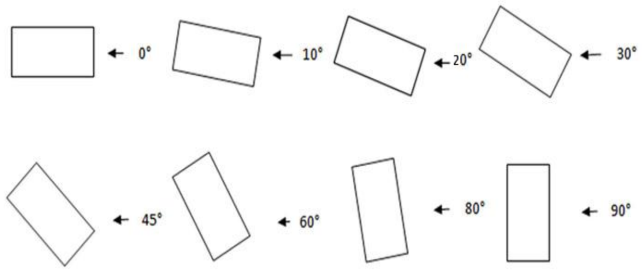


Figure 3.8 - Orientations of the model for different angles of wind incidence

E. PROJECTED WIDTH DIMENSIONS:

For calculation of force/torque coefficients, effective frontal area has to be identified. Effective frontal area was computed by knowing the projected width dimensions. When the tests were conducted on the rectangular building models at 0˚ and 90˚, the effective frontal area was the width of the model but when the model is subjected to various angles of wind incidence ϴ, the projected width is more than the width of the model. Here, the plan view of a model at an angle of incidence ϴ along with its projected width details, forces in body axes, drag and lift force directions are shown in Fig. 3.9.

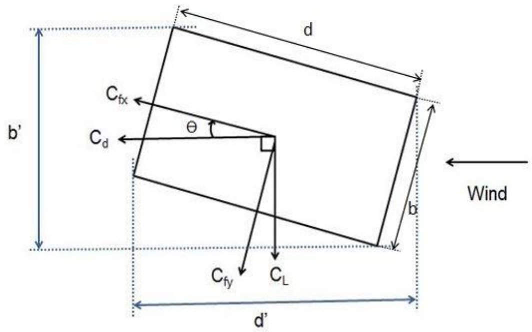


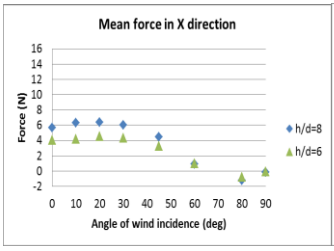
Figure 3.9 - Plan view of a model and direction of forces

Angle of wind incidence	d' (mm)	b' (mm)
0˚	150.000	75.000
10˚	160.745	99.908
20˚	166.605	121.780
30˚	167.404	139.952
45˚	159.099	159.099
60˚	139.952	167.404
80˚	99.908	160.745
90˚	75.000	150.000

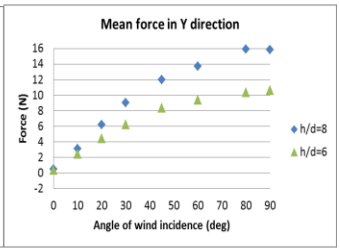
Table 3 – projected width dimensions

IV. EVALUATION OF MEAN FORCE AND TORSION COEFFICIENTS

Six components are taken from the experiment such as forces/torques F_x, F_y, F_z, M_x, M_y, M_z for each model and for each angle at each velocity under each trial. Mean force coefficients in along wind axis and body axis are calculated by using the measured forces/torques from experiment. The force in along wind direction is the drag force and the force in across wind direction is defined as the lift force.



4.1



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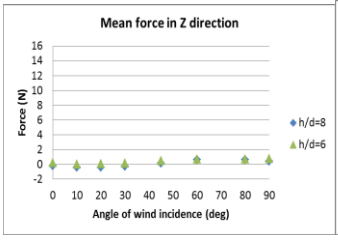

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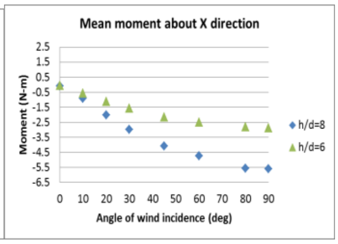

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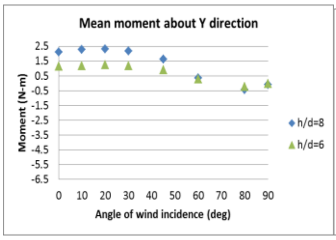

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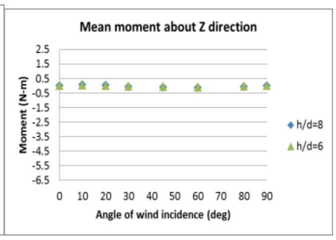
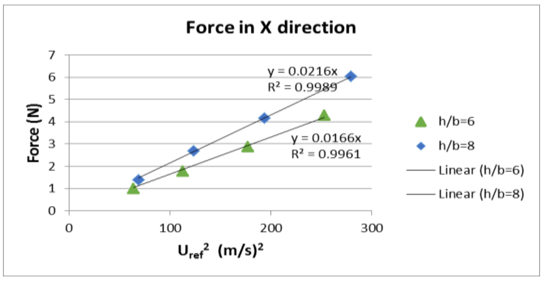


4.6

From Fig. 4.1 – 4.3 and Fig. 4.4 – 4.6, it is seen that the magnitude of mean base forces and torques for model with aspect ratio of h/b = 8 is higher than that for model with aspect ratio of h/b = 6. Further, it is observed that the variation of mean base torque Mx about x axis is having similar trend (but negative) with that the variation of mean base force Fy and the variation of mean base torque My about y axis is having similar trend with that of variation of mean base force Fx.

A. Variations of mean base forces/torques with square of reference velocities:

The variations of mean base forces/torques with square of reference velocities such as for four different wind velocities (8.0 m/s, 10.6 m/s, 13.3 m/s, 15.9 m/s for h/d=6 and 8.3 m/s, 11.1 m/s, 13.9 m/s, 16.7 m/s for h/d = 8) for various angles of wind incidence are to be fitted. The respective force coefficients are calculated by equating the constant terms in mean base shear force and mean base torque equations to the slopes of the fit. For example, the graphs representing the linear fits of mean base forces/torques variations with square of reference velocities for an angle of wind incidence 30˚ are shown in Figures 4.7 – 4.11.



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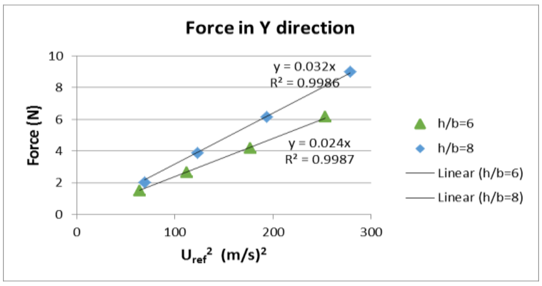

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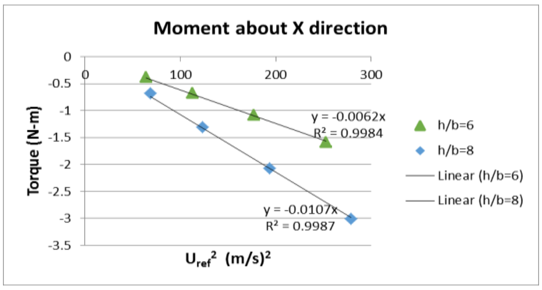

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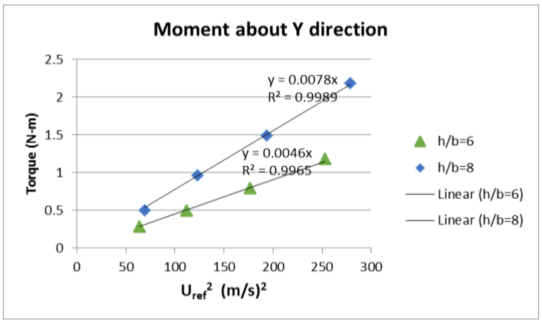

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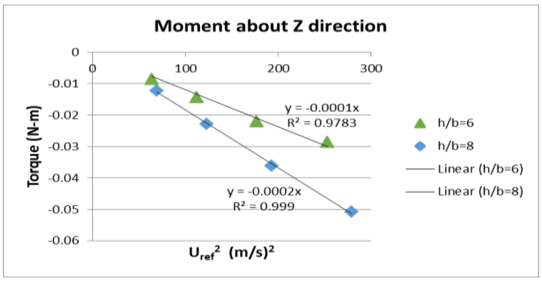

4.11

B. Typical calculation for force coefficients:

Force coefficients in along body X axis and Y axis are calculated by using mean base shear force and mean base torque equations and then average force coefficients are calculated. Force coefficients in along wind and across wind are calculated by using mean base shear force and mean base moment equations and then average drag and lift force coefficients are calculated. Here, the typical force coefficients calculation for the model having an aspect ratio 6 is discussed.

$$C_{fx} = \frac{slope\ of\ F_x}{constant\ term\ in\ F\ expression * b}$$

$$C_{fy} = \frac{slope\ of\ F_y}{constant\ term\ in\ F\ expression * d}$$

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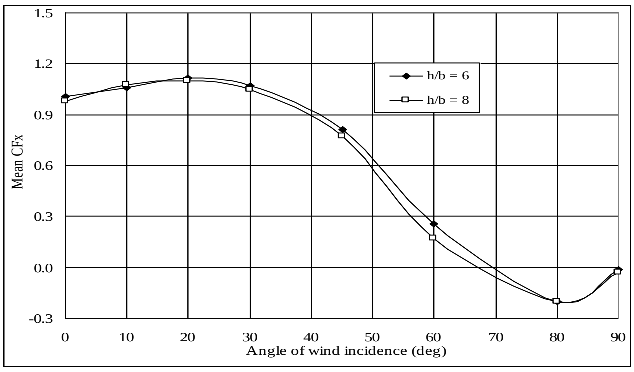
$$C_{mz} = \frac{slope\ of\ M_z}{constant\ term\ in\ M\ expression * b' * d'}$$

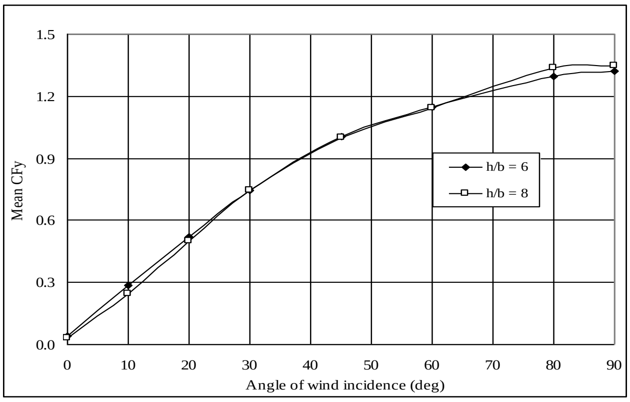
C. Mean Drag and Lift forces coefficients:

Mean Drag coefficients are calculated by using mean base force and mean base torques as follows.

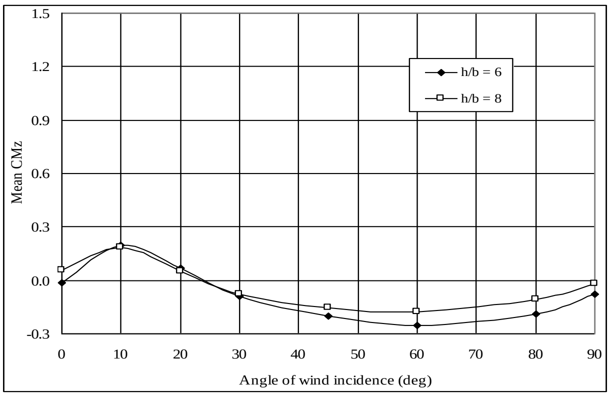
1. Variation of mean force coefficient (CFx)



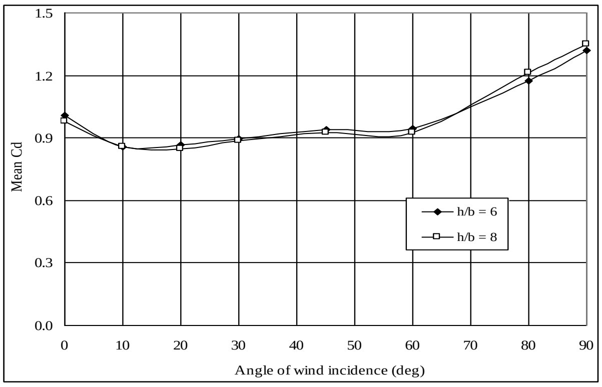
2. Variation of mean force coefficient (CFy)



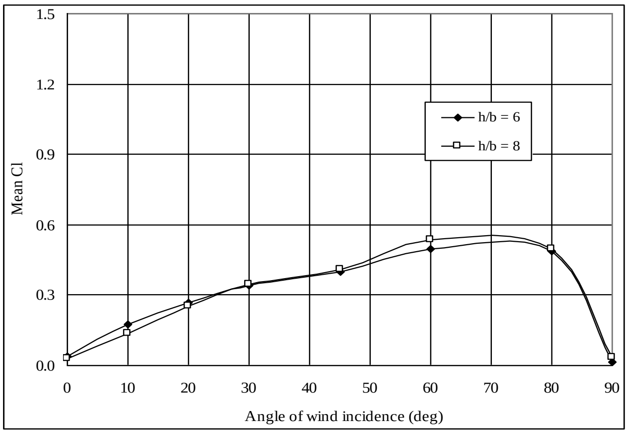
3. Variation of mean torque coefficient (C_{mz})



4. Variation of mean drag coefficient (Cd) in along the wind direction



5. Variation of mean lift coefficient (Cl) in across wind direction



V. CONCLUSIONS

Force measurements on tall building models with h/b=6 & 8 was carried out for 8 different angles of wind incidence and for 4 different mean wind velocities under open terrain conditions using six axes force/torque sensor in BLWT.

1. In general, the measured mean base forces/torques or moments for model with h/b = 8 is higher than the model with h/b = 6.
2. The percentage difference of measured velocities at reference heights between the models are observed to be within 5% and the percentage difference of turbulence intensities are observed to be 8%. The evaluated values of mean Cf_x & Cf_y are found to be same for both models.
3. The percentage difference of evaluated values of C_d between the models is observed to be up to 3%.
4. The percentage difference of evaluated values of C_l between the models is observed to be 2 – 7 %.
5. For θ=0º, the percentage difference between the evaluated values of mean force coefficients and IS 875 are found to be 18%and 28% respectively. For θ=90º, the percentage difference between the evaluated values of mean force coefficients and IS 875 are found to be within 5%. It is found that the values given in IS 875 are found to be conservative for the models considered in the present study.

VI. REFERENCES

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