Wind Effect on Structure

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Abstract— There is a general feeling among engineers that the values of the pressure exerted by the wind commonly used in the design of engineering structures are too high. The experiments on which these values are based were carried out many years ago by relatively inaccurate methods and on models not resembling actual structures. The success of modern wind-tunnel methods in the field of aeronautics suggests their use for the determination of wind pressures on models of structures. Tall and super-tall buildings are going up all over the world, notably in east and south Asia and middle-east. Advances in materials, structural design, and wind engineering ensure that these buildings meet strength and safety requirements. Modern buildings designed such that their lateral drifts under statically applied wind loads are less than some fraction of building height, may vibrate excessively during winds and cause occupant discomfort. This paper presents the effect of wind on structures.

Key words: Wind, Turbulent Flow, Structure

I. INTRODUCTION

Wind has two aspects. The first a beneficial one is that its energy can be utilized to generate power, sail boats and cool down the temperature on a hot day. The other a parasitic one is that it loads any and every object that comes in its way. The latter is the aspect an engineer is concerned with, since the load caused has to be sustained by a structure with the specified safety. All civil and industrial structures above ground have thus to be designed to resist wind loads. This introductory note is concerning the aspect of wind engineering dealing with civil engineering structures.

An important characteristic of the wind is that it is unsteady or fluctuating in Nature; the wind can be considered to consist of a mean and a fluctuating component. The unsteady wind velocity gives rise to pressures on the structure, a mean pressure which varies with height and a localized fluctuating pressure. The unsteady wind pressures transmit fluctuating forces or loads into the structure.

II. LITERATURE STUDY

The greatest probability of damage to structures has been presented by Davenport (1963) to be the case of strong winds with neutral atmospheric conditions. Davenport suggests that structural response to repeated loads of successive gusts is an important factor in the design of tall buildings. Repeated loading may lead to fatigue, failure, foundation settling, excessive deflections causing cracking to building elements, or induced motion that may affect the comfort of the occupants of the structure. A building can be considered to have failed if it becomes unserviceable due to the action of repeated loads or the action of a single large load of great magnitude. It is very important that the fluctuating loads caused by wind on a structure play an important role in the design and analysis of tall buildings, especially structures with large aspect ratios (Reinhold 1977). The primary concern for a structural engineer when studying wind phenomena, around a building, is the mean velocity profile of the wind. Moreover, two aspects of turbulent flows are of interest to the engineer: (a) the state of turbulence of the natural wind approaching a structure, and (b) the local turbulence provoked in the wind by the structure itself. Most structures in civil engineering present bluff forms, in wind engineering studies we focus on the bluff-body aerodynamics aspects of the wind and structure interaction. This has led the industry to further research on the details of flow effects around bluff bodies such as tall buildings. This finally leads to the interest of the engineer in the study of the development of body pressures by the flow acting around a structure (Simiu and Scanlan 1978).

A. *Wind Damaged Structures*

Damage to buildings and other structures by windstorms has been a fact of life for human beings from the time they moved out of cave dwellings to the present day. Trial and error has played an important part in the development of construction techniques and roof shapes for small residential buildings, which have usually suffered the most damage during severe winds. In past centuries, heavy masonry construction, as used for important community buildings such as churches and temples, was seen, by intuition, as the solution to resist wind forces. For other types of construction, windstorm damage was generally seen as an 'act of god', as it is still viewed today by many insurance companies.

The nineteenth century was important as it saw the introduction of steel and reinforced concrete as construction materials, and the beginnings of stress analysis methods for the design of structures. The latter was developed further in the twentieth century, especially in the second half, with the development of computer methods. During the last two centuries, major structural failures due to wind action have occurred periodically, and provoked much interest in wind forces by engineers. Long-span bridges often produced the most spectacular of the failures, with the Brighton Chain Pier, England in 1836, the Tay Bridge, Scotland in 1879, and Tacoma Narrows Bridge, Washington State, U.S.A. in 1940 being the most notable, with the dynamic action of wind playing a major role (Holmes 2007). Other large structures have experienced failures as well for example, the collapse of the Ferry bridge cooling towers in the United Kingdom in 1965, and the permanent deformation of the columns of the Great Plains Life Building in Lubbock, Texas during a tornado in 1970. These events were notable, not only as events in themselves, but also for the part they played as a stimulus to the development of research into wind loading in their respective countries.

III. ELEMENTARY PRINCIPLES OF WIND ENGINEERING

A. Forces Acting in the Free Atmosphere

Wind is air movement relative to the earth, driven by several different forces, especially pressure differences in the atmosphere, which themselves are produced by differential solar heating of different parts of the earth's surface, and forces generated by the rotation of the earth. The differences in solar radiation between the poles and the equator produce temperature and pressure differences. These, together with the effects of the earth's rotation, set up large-scale circulation systems in the atmosphere, with both horizontal and vertical orientations (Holmes 2007). Severe tropical cyclones such as hurricanes and typhoons generate extremely strong winds over some parts of the tropical oceans and coastal regions both north and south of the equator. For these types of severe storms, the wind is highly turbulent or gusty. The turbulence is produced by eddies or vortices within the air flow, which are generated by frictional interaction at ground level or shearing action between air moving in opposite directions with respect to altitude (Holmes 2007). The two most important forces acting in the free atmosphere, i.e. above the frictional effects of the earth's boundary layer, are the pressure gradient and the Coriolis force.

1) Pressure Gradient & the Coriolis force

Based on the principles of fluid mechanics, at a point in a fluid in which there is a pressure gradient, $\partial p/\partial x$, in a given direction, x, in a Cartesian coordinate system, there is a resulting force per unit mass given by:

Pressure gradient per unit mass

$$= -\left(\frac{1}{\rho_a}\frac{\partial p}{\partial x}\right) \quad 3.1$$

Where, ρ is the density of air and p is the atmospheric pressure. This force acts form a high pressure region to a low-pressure region. The Coriolis force is an apparent force due to the rotation of the earth. It acts to the right of the direction of motion in the northern hemisphere and to the left of the velocity vector in the case of the southern hemisphere; at the equator, the Coriolis force is zero. Within about 5° of the equatorial region, the Coriolis is negligible in magnitude thus explaining why tropical cyclones do not form within this region (Holmes 2007).

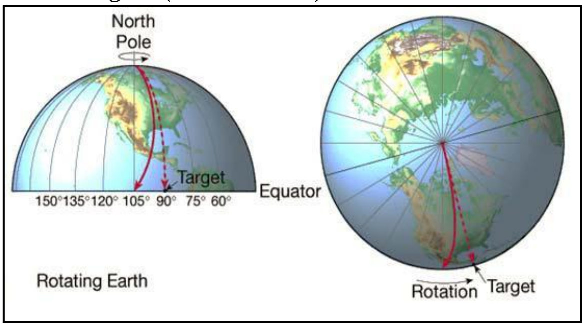

Fig. 1: Coriolis force Results in Wind Being Deflected Owing To the Rotation of the Earth

B. Geotropic Wind, Gradient Wind, & Frictional Effects

Steady flow under equal and opposite values of the pressure gradient and the Coriolis force is known as balanced geotropic flow. Equating the pressure gradient force per unit mass and the Coriolis force per unit mass given by f· U, we obtain:

$$U = -\left(\frac{1}{\rho_a f}\frac{\partial p}{\partial x}\right) \quad 3.2$$

This is the equation for the geotropic wind speed, which is directly proportional to the magnitude of the pressure gradient. In the northern hemisphere the high pressure is to the right of an observer facing the flow direction; in the southern hemisphere, the high pressure is on the left. This results in a counter-clockwise rotation of winds around a low pressure in the northern hemisphere, and a clockwise rotation in the southern half. Rotation about a low-pressure center is known as a cyclone to meteorologists, which usually produces strong winds (Holmes 2007). Near the center of tropical cyclones, the centrifugal force acting on the air particles cannot be neglected due to the significant curvature of the isobars. For flows around a low-pressure center, i.e. cyclone, the centrifugal force acts in the same direction as the Coriolis force and opposite to the pressure gradient force. The equation of motion for a unit mass of air moving at a constant velocity, U, for a cyclone is:

$$\frac{U^2}{r} + |f|U - \frac{1}{\rho_a}\left|\frac{\partial p}{\partial x}\right| = 0 \quad 3.3$$

The quadratic equation represents the gradient wind speed formulation. This equation has two theoretical solutions, but if the pressure gradient is zero then U must also be zero so that the solution, for a cyclone, becomes:

$$U = -\frac{|f|r}{2} + \sqrt{\frac{f^2r^2}{4} + \frac{r}{\rho_a}\frac{\partial p}{\partial x}} \quad 3.4$$

Where, f is the Coriolis parameter (= 2Ω sin λ), λ is the latitude, and r the radius from the storm center. The term under the square root is always positive, therefore the wind speed in a cyclone is only limited by the pressure gradient, and i.e. cyclones are associated with strong winds. As we approach the earth's ground surface, frictional forces gradually play a larger role through the shear between layers of air in the atmospheric boundary layer. The frictional force acts in opposite direction to that of the flow (Holmes 2007).

C. Atmospheric Boundary Layer

As the earth's surface is approached, the frictional forces play an important role in the balance of forces on the moving air. For larger storms such as extra-tropical depressions, this zone extends up to 500 to 1,000 m height. The region of frictional influence is called the atmospheric boundary layer and it is similar in many respects to the turbulent boundary layer on a flat plate at high wind speeds.

1) Mean Wind Profiles

The ABL characteristics vary with the conditions of the terrain considered. Design standards such as the IS: 875 Part III take into consideration and factor the effect of surrounding structures and terrain in the load conditions of the structure of interest. There are four different types of terrain that will affect shape and thickness of the boundary layer as seen in Figure 9

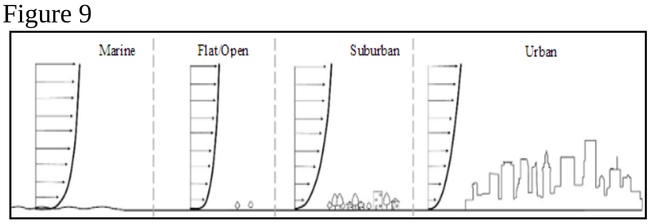

Fig. 2: Wind Profile in Different Boundary Layers

a) The Logarithmic Law

In strong wind conditions, the most accurate mathematical expression is the logarithmic law for wind profiles. The logarithmic law was originally derived for the turbulent boundary layer on a flat plate by Prandtl; however it has been found to be valid in an unmodified form in strong wind conditions in the atmospheric boundary layer near the surface (Holmes 2002). The logarithmic law describes the variation with height and surface roughness of strong mean speeds with averaging times of 10-min to 1-hr in straight winds. After mathematical derivation, its expression may be written as:

$$\vec{V}(z) = \overrightarrow{V_{Zref}} \frac{\ln\frac{Z}{Z_0}}{\ln\frac{Z_{ref}}{Z_0}} \quad 3.5$$

Where, $\vec{V}(z)$ and $\overrightarrow{V_{Zref}}$ is the mean wind speeds at elevation Z and Z_{ref} respectively, and Z_{ref} is a reference elevation, and Z_0 is an empirical measure of the surface roughness called roughness length. Another measure of terrain roughness is the surface drag coefficient, C_{sd} which a non-dimensional surface shear stress is defined as:

$$C_{sd} = \left\{\frac{k}{\ln\frac{33}{z_0}}\right\}^2 \quad 3.6$$

Where, k is known as von Karman's constant, and has been found experimentally to have a value of ≈ 0.4. This value is typically based by the mean wind speed measured at a height Z_{ref} of 10 m (32.8 ft.). Table 1 (Simiu 2011) gives the appropriate value of roughness length and surface drag coefficient, for various types of terrain types adapted from IS: 875 Part III.

On a final note, the logarithmic law has some mathematical constraints which may cause problems: first, the logarithms of negative numbers to not exist, and secondly, it is less easy to integrate. To avoid some of these problems, wind engineers have often preferred the use of the power law.

b) The Power Law

The power law has no theoretical basis but is easily integrated over height a convenient property when wishing to determine bending moments at the base of a tall structure. To relate the mean wind speed at any height z with that at 10 m (32.8 ft.) the power law can be represented as:

$$V_{(Z)} = V_{Z_{ref}} \left(\frac{Z}{Z_{ref}}\right)^{1/\alpha} \quad 3.7$$

The exponent α will change with terrain roughness, with height range, and upon averaging time. The power law applied to 3 sec. gusty wind profiles has the same form as Equation 3.7.

Figure 10 shows a matching of the two laws for a height range of 100 m using the previous equations where the average height in the range over which matching is required (i.e. 50 m). It is clear that the two are relatively close, and the power law can be adequately used for engineering purposes (Holmes 2007).

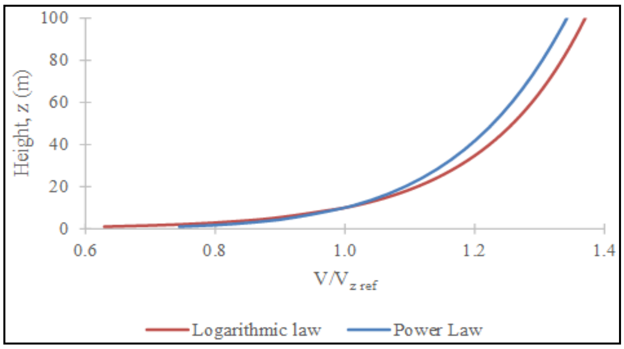

Fig. 3: Comparison of the Logarithmic and Power Law for mean Velocity Profile for z 0= 0.02 m and α = 0.128

2) *Turbulence*

The general level of turbulence or 'gustiness' in the wind speed, such as that it can be measured by its standard deviation, or root-mean-square. First we subtract out the steady or mean component, and then quantify the resulting deviations. Since both positive and negative deviations can occur, we first square the deviations before averaging them, and finally take the square root to give a quantity with the units of wind speed. Mathematically, the formula for standard deviation can be expressed as:

$$\sigma_u = \left\{\frac{1}{T}\int_0^T [U_{(t)} - \bar{U}]^2 dt\right\}^{1/2} \quad 3.8$$

Where, $U_{(t)}$ is the total velocity component in the direction of the mean wind equal to $(\bar{U} + u(t))$, where u(t) is the 'longitudinal turbulence component (i.e. in the mean wind direction). Other component of turbulence in the lateral horizontal direction is denoted by v (t) and the vertical directions by w (t) are quantified by their standard deviations σ_v and $\sigma_w$respectively.

a) Turbulence Intensities

The ratio of the standard deviation of each fluctuating component to the mean value is known as the turbulence intensity (TI) of that component. Figure 11 illustrates a typical time dependent measurement of wind velocities measured in the atmospheric boundary layer. The velocity in the figure is decomposed into a steady mean value with a fluctuating component (Versteegand Malalasekera 2007).

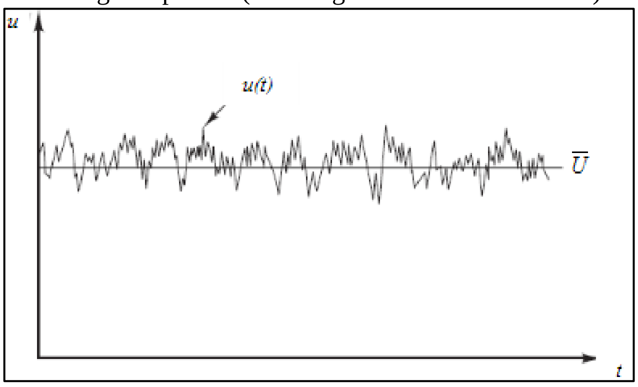

Fig. 4: Typical Point Velocity Measurements in Turbulent Flow

Therefore the equation for turbulence intensity can be represented as:

$$TI_u = \frac{\sigma_u}{\bar{U}} \text{(longitudinal)};\ TI_v = \frac{\sigma_v}{\bar{V}} \text{(lateral)};\ TI_w = \frac{\sigma_w}{\bar{W}} \text{(vertical)} \quad 3.9$$

It has been measured that near the ground by winds produced by large depression systems the standard deviation of the longitudinal wind is approximately equal to $2.5u_*$, where u_* is the friction velocity. Alternatively, the turbulence intensity TI_u can be expressed as the following equation:

$$TI_u = \frac{2u_*}{\left(u_*/_{0.4}\right)\ln\left(z/_{z_0}\right)} = \frac{1}{\ln\left(\frac{z}{z_0}\right)} \qquad 3.10$$

For a rural terrain with a roughness length (z_0) of 0.04 m the various longitudinal turbulence intensities for increasing height above ground is demonstrated in Figure 12, thus it can be concluded that the turbulence intensity above ground decreases as the height increases.

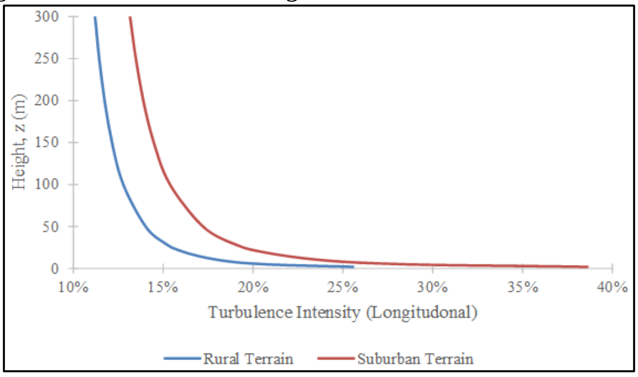

Fig. 5: Longitudinal Turbulence Intensity for Rural Terrain (z_0= 0.04 m) and Suburban Terrain (z_0= 0.15 m)

The lateral and vertical turbulence components are generally lower than the corresponding longitudinal value. For well-developed boundary layer winds, simple relationships between standard deviation and the friction velocity u_* have been developed. For well-developed boundary layer winds, simple relationships between standard deviation and the friction velocity u_* have been developed. Therefore, the standard deviation for the lateral velocity, v, is approximately equal to $2.20u_*$, and the vertical, w, component is given by approximately $1.35u_*$, The equivalent turbulent intensity equations for $TI_v$and TI_w can be shown to be:

$$TI_V \cong \frac{0.88}{\ln\left(\frac{z}{z_0}\right)};\ TI_V \cong \frac{0.55}{\ln\left(\frac{z}{z_0}\right)} \qquad 3.11$$

The intensity of turbulence at height $\bar{z}$ is defined as:

$$I_{\bar{z}} = c\left(\frac{33}{\bar{z}}\right)^{1/6} \text{ or } I_{\bar{z}} = c\left(\frac{10}{\bar{z}}\right)^{1/6} \qquad 3.12$$

Where, $\bar{z}$ is the equivalent height of the structure at 0.6th and not less thanz_{min}. The equation on the left represents imperial units, and on the right the international system.

b) Integral Turbulent Length Scale

The velocity fluctuations in a flow passing a point may be considered to be caused by an overall eddy consisting of a superposition of component eddies transported by the mean wind. Each component eddy is viewed as causing, at that point, a periodic fluctuation with frequencyf. Integral turbulence length scales are measures of the spatial extents of the overall turbulent eddy. The integral turbulence scale Lu is an indicator of the extent to which an overall eddy is associated with the longitudinal wind speed fluctuation u will engulf a structure in the along-wind direction, and will thus affect at the same time both its windward and leeward sides. If Lu is large in relation to the along-wind dimension of the structure, the gust will engulf both sides. The scales Lv and Lw are measures of the lateral and vertical spatial extent of the fluctuating longitudinal component u of the wind speed. Mathematically the integral turbulent length Lu is defined as follows:

$$L^*_u = \frac{1}{u^2}\int_0^\infty R_{u_1u_2}(x)dx \qquad 3.13$$

In which $u_1 = u(x_1, y_1, z_1, t), u_2 = u(x_1 + x, y_1, z_1, t)$, and the denominator is the variance of the longitudinal velocity fluctuations, a statistic that for a given elevation z is the same throughout the flow. The integrand is the cross covariance of the signals u_1 andu_2. The integral length is a measure of the average eddy size (Simiu 2011). Measurements show that Lu increases with height above ground and as the terrain roughness decreases.

The length scale at height z is defined as:

$$L_{\bar{z}} = \ell\left(\frac{33}{\bar{z}}\right)^{\bar{\epsilon}} \text{ or } L_{\bar{z}} = \ell\left(\frac{10}{\bar{z}}\right)^{\bar{\epsilon}} \qquad 3.14$$

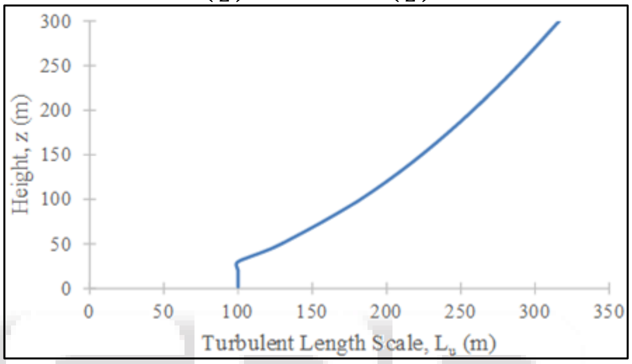

Fig. 6: Variation of turbulent length scale as height increases

IV. Conclusion

Wind is the main problem in design of high rise buildings and skyscrapers. Each high-rise project is unique and depends on the many conditions which influence the choices made in the design of a tall building. Example of such conditions are the wind climate. Vortex shedding can play the cause of disaster but with proper analysis and tools such as wind tunnel test it can be avoided. Innovative structural systems for the next generation of sustainable, ultra-high tall buildings and mega-structures should be developed. There is a need for creating a comprehensive database of structural systems for tall buildings throughout the globe. With the development of increasingly taller buildings using lighter members, serviceability issues like lateral sway, floor vibration, and occupant comfort need to be given more attention by researchers.

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