DUBAI WIND CODE

Draft Copy

Dubai Municipality

2013

CONTENTS

1. GENERAL

1.1. NOTATION

A = Surface area
b = Width of a structure in the across-wind direction
B^2 = Correlation factor that accounts for the lack of correlation of wind pressures
C_d = Dynamic amplification factor
$C_e(z)$ = Height-dependent surface friction coefficients
C_p = Surface pressure coefficient
$C_{p,1}$ = Surface pressure coefficient for 1.0 m^2 area
$C_{p,10}$ = Surface pressure coefficient for 10.0 m^2 area
$C_q(z)$ = Height-dependent wind pressure coefficient
C_s = Load correlation coefficient
C_t = Topography coefficient
D = Diameter of circular cross-section of a building
d = Width of the structure in the along-wind direction
F = Total wind loads on a building
f = Frequency in *Hz*
$f_L(z,f)$ = Nondimensional normalized frequency
f_o = First natural frequency of a building in *Hz*.
h = Height of the building.
h_0 = Average height of surrounding buildings
h_y = Ficticous increase in ground level to account for surrounding structures
$I_w(z)$ = Height-dependent turbulance intensity
$L(z)$ = Height-dependent turbulance length
$Q(z)$ = Total wind load in a sbuilding at height z
q_b = Basic wind pressure
$q_p(z)$ = Wind pressure for unit area at height z
R^2 = Resonance factor that accounts for dynamic amplification of response
$R_b(\eta_b)$ = Aerodynamic admittance function in horizontal direction
$R_h(\eta_h)$ = Aerodynamic admittance function in vertical direction
$S_L(z,f)$ = Power spectral density function of turbulance
S_t = Strouhal number
V_b = Basic wind speed
$V(z,t)$ = Total wind speed
$|V(z,t)|_{max}$= Maximum total wind sped at height z
V_{cr} = Critical wind speed for vortex shedding
$V_m(z)$ = Height-dependent average wind velocity
$w(z,t)$) = Dynamic component of wind velocity – turbulance.
$\overline{w}_{max}$ = Maximum turbulance velocity
z_o = Surface friction coefficient
z_{min} = Minimum height in which surface friction is constant
z_r = Reference height
δ = Logarithmic decrement corresponding to the first vibration mode
ξ_o = Damping coefficient corresponding to the first vibration mode
ρ = Mass density of air ($\rho = 12.5$ N/m^3)
σ_w = Standard deviation of turbulance

1.2 COVERAGE AND IMPLEMENTATION

This document gives the minimum loads that will be considered when designing structures for wind, including the main structural system, external facade elements, and other components that are exposed to wind.

The development of a structural design code is a long and continuous process that requires consensus from all parties involved. This code is the first step for a comprehensive wind design code for Dubai.

2. GENERAL GUIDELINES FOR WIND LOADS

Wind loads are composed of static and dynamic components. The loads given in this code are the equivalent static wind loads, under which the static deformations of the structure are equal to the sum of static and dynamic deformations induced by wind.

The total wind load on the main load carrying system of the structure is equal to the vectoral sum of the wind loads acting on all surfaces of the structure.

The wind loads on the main structural system, external facade elements, and other non-structural components that are exposed to wind cannot be less than 0.5 kN/m^2.

3. VELOCITY OF WIND

Wind velocity is defined by the following equation:

$$V(z,t) = V_{\mathrm{m}}(z) + w(z,t) \tag{3.1}$$

where

$V(z,t)$: Total wind velocity at height z at time t.

$V_{\mathrm{m}}(z)$: Mean component (i.e., the average) of wind velocity at height z.

$w(z,t)$: Dynamic component of wind velocity (i.e., turbulance) at height z at time t.

3.1. AVERAGE WIND VELOCITY

At a given location, the average wind velocity, $V_m(z)$, at height z is calculated from the following equation :

$$V_m(z) = C_e(z) \cdot C_t \cdot V_b \tag{3.2}$$

where

$V_m(z)$: Average wind velocity at height z.

V_b: Basic wind speed.

$C_e(z)$: Effect of surface roughness at height z.

C_t: Effect of surface topography.

3.1.1. Structure of wind in Dubai

The structure of wind in Dubai is controlled by three different wind phenomena: synoptic winds, Shamal winds, and thunderstorms. The vertical profile of synoptic wind velocities can be modelled by using the standard logarithmic profile model, where the velocity increases monotonically with height and reaches its maximum at the top of the building. Shamal winds, which are the result of desert environment and climate in the region, reach their peak velocity around 200 *m.* The velocity becomes smaller as the altitude gets higher. The thunderstorms typically have their peak velocities around the height of 50 m. The recorded synoptic wind speeds at 10m height are less than those recorded at the same height during thunderstorm events.

Although there are several important studies done on the structure of wind in Dubai, further research is needed to quantify the profiles of Shamal winds and thunderstorms, so that they can be incorporated in design codes.

Studies have shown that for extreme cases the synoptic winds still control the design.
Also, the comparison of velocity profiles in several codes does not suggest any major flaw in extending the log law beyond 200*m* , which is the limit in Eurocode, in light of many other more pressing uncertainties that surface in the quantification of wind velocity profiles.

3.1.2. Basic wind velocity

The basic wind velocity is the value of the 10-min. averaged wind velocities measured at 10-*m* height in an open field that has mean reccurance interval of 50 years (i.e., the annual probability of exceedance = 0.02). The basic wind velocity for Dubai has been estimated to be V_b = 30 *m/s (*108 *km/h)*., the basic wind velocity of 30 *m/s* calculated for averaging time of 10-min. corresponds to a basic wind velocity of 45 *m/s* (160 *km/h*) for averaging time of 3-*sec*. Although studies shows that dominant winds are from the north and the west, in light of all the other uncertainties that are discussed in the next section, the wind directionality is not considered as a factor in the calculation of wind loads.

3.1.3. Surface roughness coefficient

The surface roughness coefficient accounts for the effects of surface roughness in the average wind velocity and its variation with height. It is defined by the following equations :

$$\begin{aligned}
&\text{For } z \geq z_{\min} : \quad C_e(z) = k_r \ln\left(\frac{z}{z_o}\right) \quad \text{with} \quad k_r = 0.23 \cdot (z_o)^{0.07} \\
&\text{For } z < z_{\min} : \quad C_e(z) = C_e(z_{\min})
\end{aligned} \tag{3.3}$$

where

z_0 : Surface friction length in meters.

$z_{\min}$: Minimum friction height in meters where the surface friction is constant.

For five terrain types, the z_o and $z_{\min}$ values are given below, in Table 3.1.

Table 3.1. Surface friction lengths (z_o) ve minimum friction heights ($z_{\min}$)

(*Adopted from Euro Code*)

Terrain No	Terrain type	z_o *(m)*	$z_{\min}$ *(m)*
0	Coastal areas exposed to open sea	0.003	1
I	Lake shores and flat open areas with no obstacles	0.01	1
II	Areas with low vegitaton and isolated obstacles where the average obstacle separation is more than 20 times the average obstacle height.	0.05	2
III	Villages and suburbs, where the average obstacle seperation is less than 20 times the average obstacle height.	0.3	5
IV	City centers and similar areas, where more than %15 of the terrain is covered with structures taller than 15 m.	1.0	10

3.1.4. C_t topography coefficient

For the city of Dubai, the topography coefficient will be taken as

$$C_t = 1 + 0.001\,\Delta \tag{3.4}$$

where Δ is the height of the location in *meters* from the sea level.

3.1.5. Effects of neighbouring structures on average wind velocity

In city centers (Terrain IV in Table 3.1), when calculating wind loads in a tall structures surrounded by shorter structures, the blocking effects of surrounding structures are accounted for by ficticuously increasing the ground level by a specified amount, h_y. The wind loads are calculated by shifting the wind velocity profile vertically by this amount. The rules for determining h_y are given in Eqs. 3.5 and Fig. 3.4

$$
\begin{array}{ll}
\text{If } x \le 2h_o : & h_y = \min\left[0.8h_o,\ 0.6h\right] \\
\text{If } 2h_o < x < 6h_o : & h_y = \min\left[1.2h_o - 0.2x, 0.6h\right] \\
\text{If } x \ge 6h_o : & h_y = 0
\end{array}
\tag{3.5}
$$

where h_0 is the average height of the surrounding structures, h is the height of the building, and x is the distance between the building and surrounding structures. In cases where it is not possible or feasible to determine the average height of the surrounding buildings, it will be assumed that h_o=15 *m.*

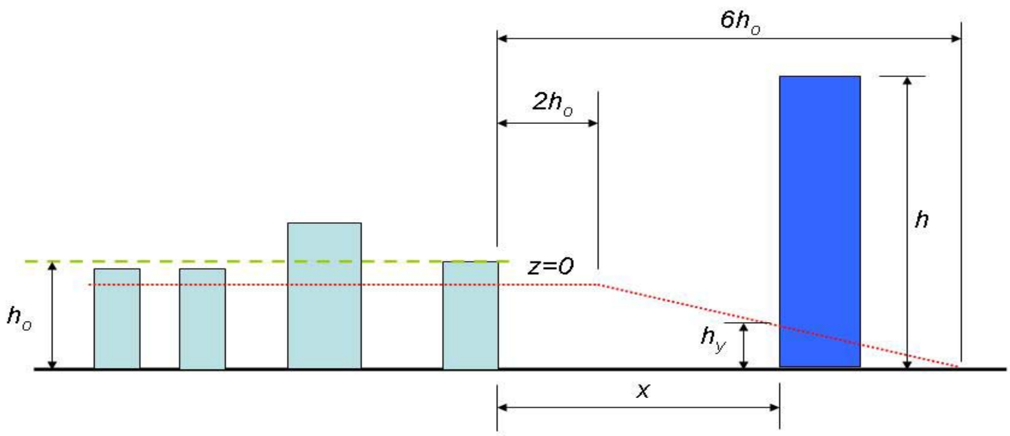

Figure 3.4. Effect of surrounding buildings on the average wind velocity.

3.2. FLUCTUATING WIND VELOCITY (TURBULANCE)

The dynamic component of wind velocity is called the wind turbulance, and is assumed to be a zero-mean Gaussian random variable. It is defined by its standard deviation, σ_w, whose value is defined in terms of the basic wind velocity, V_b, by the following equation

$$\sigma_w = k_r V_b \tag{3.6}$$

where k_r is given in Eq. 3.3. The maximum value of turbulance is assumed to be 3.5 times its standard deviation; that is

$$\bar{w}_{\max} = 3.5\,\sigma_{\mathrm{w}} \tag{3.7}$$

3.2.1. Turbulance intensity

Turbulance intensity, $I_{\mathrm{w}}(z)$, represents the relative amplitude of turbulance with respect to mean wind velocity and varies with height. It is defined by the following equations:

$$\begin{aligned}
&\text{For } \; z_{\min} \le z \le 200\,m: \quad I_{\mathrm{w}}(z) = \frac{\sigma_{\mathrm{w}}}{V_{\mathrm{m}}(z)} = \frac{1}{C_t \ln(z/z_{\mathrm{o}})} \\
&\text{For } \; z \le z_{\min} \;: \quad I_{\mathrm{w}}(z) = I_{\mathrm{w}}(z_{\min}) \\
&\text{For } \; z \ge 200\,m: \quad I_{\mathrm{w}}(z) = I_{\mathrm{w}}(200)
\end{aligned} \tag{3.8}$$

z_{o} and z_{min} values are given in Table 3.1, and for Dubai, C_t =1.

3.2.2. Turbulance length

Another parameter that is used to describe the size of the turbulance is the turbulance length, *L(z)*. Turbulance length can be considered as the average wavelength of the air flow in the turbulance, and is expressed by the following equations:

$$\begin{aligned}
&\text{For } \; z \ge z_{\min}: \quad L(z) = 300\left(\frac{z}{200}\right)^{p} \qquad \text{with} \qquad p = 0.67 + 0.05\ln(z_o) \\
&\text{For } \; z < z_{\min}: \quad L(z) = L(z_{\min})
\end{aligned} \tag{3.9}$$

The values of z_o and z_{min} are given in Table 3.1.

3.2.3. Power spectral density function of turbulance

Power spectral density function of turbulance, $S_{\mathrm{L}}(z,f)$, shows the variation of turbulance energy with height and frequency, z and f. It is defined in terms of the nondimensional normalized frequency, $f_{\mathrm{L}}(z,f)$, by the following equation:

$$S_L(z,f) = \frac{6.8\, f_L(z,f)}{\left[1 + 10.2\, f_L(z,f)\right]^{5/3}} \qquad \text{with} \qquad f_L(z,f) = \frac{f\, L(z)}{V_m(z)} \tag{3.10}$$

The variation of $S_L(z,f)$ with $f_L(z,f)$ is shown in Figure 3.5 below.

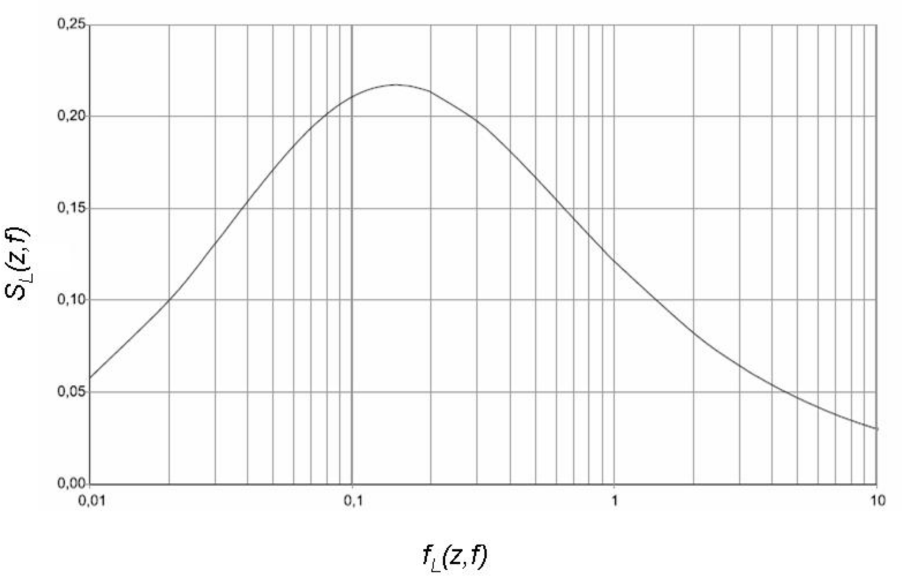

Figure 3.5. Power spectral density function of turbulance.

3.3. MAXIMUM WIND VELOCITY

Using Eqs. 3.1 and 3.7, the expected maximum wind velocity, $|V(z,t)|_{max}$, is calculated as

$$\left|V(z,t)\right|_{\max} = V_m(z) + \overline{w}_{\max} \tag{3.11}$$

4. WIND PRESSURE

4.1. MAXIMUM PRESSURE AT A POINT

Wind pressure is expressed in terms of the density of the air and the square of wind velocity. The wind pressure, $q_p(z)$, for a unit area at elevation z on a plane perpendicular to the main wind flow is calculated by

$$q_{\mathrm{p}}(z)=\frac{1}{2}\cdot\rho\cdot\left[V(z,t)\right]_{\max}^{2} \tag{4.1}$$

where $|V(z,t)|_{\max}$ is the maximum wind velocity at height z, as given by Eq. 3.11, and ρ is the density of the air which can be taken as ρ = 12.5 kg/m^3. By using Eq. 3.11 in Eq. 4.1, and noting that $\bar{w}_{\max} << V_m(z)$, we can approximate the maximum wind pressure by the following equation

$$q_{\mathrm{p}}(z)\approx\frac{1}{2}\rho V_{\mathrm{m}}^{2}(z)+\rho V_{\mathrm{m}}(z)\bar{w}_{\max} \tag{4.2}$$

Using Eqs. 3.7 and 3.8, we can write:

$$q_{\mathrm{p}}(z)\approx\frac{1}{2}\rho V_{\mathrm{m}}^{2}(z)\left[1+7\,I_{\mathrm{w}}(z)\right] \quad \text{or} \quad q_{\mathrm{p}}(z)\approx C_{\mathrm{q}}(z)q_{\mathrm{b}} \tag{4.3}$$

where q_b is the basic wind pressure and $C_q(z)$ is the height-dependent pressure coefficient. Using Eq. 3.2, they are defined as:

$$q_{\mathrm{b}}=\frac{1}{2}\rho V_{\mathrm{b}}^{2} \quad \text{and} \quad C_{\mathrm{q}}(z)=C_{\mathrm{e}}^{2}(z)\cdot C_{\mathrm{t}}^{2}\cdot\left[1+7\,I_{\mathrm{w}}(z)\right] \tag{4.4}$$

For the five terrain types in Table 3.1, the variation of $C_q(z)$ with height is plotted in Fig. 4.1, assuming that C_t=1.

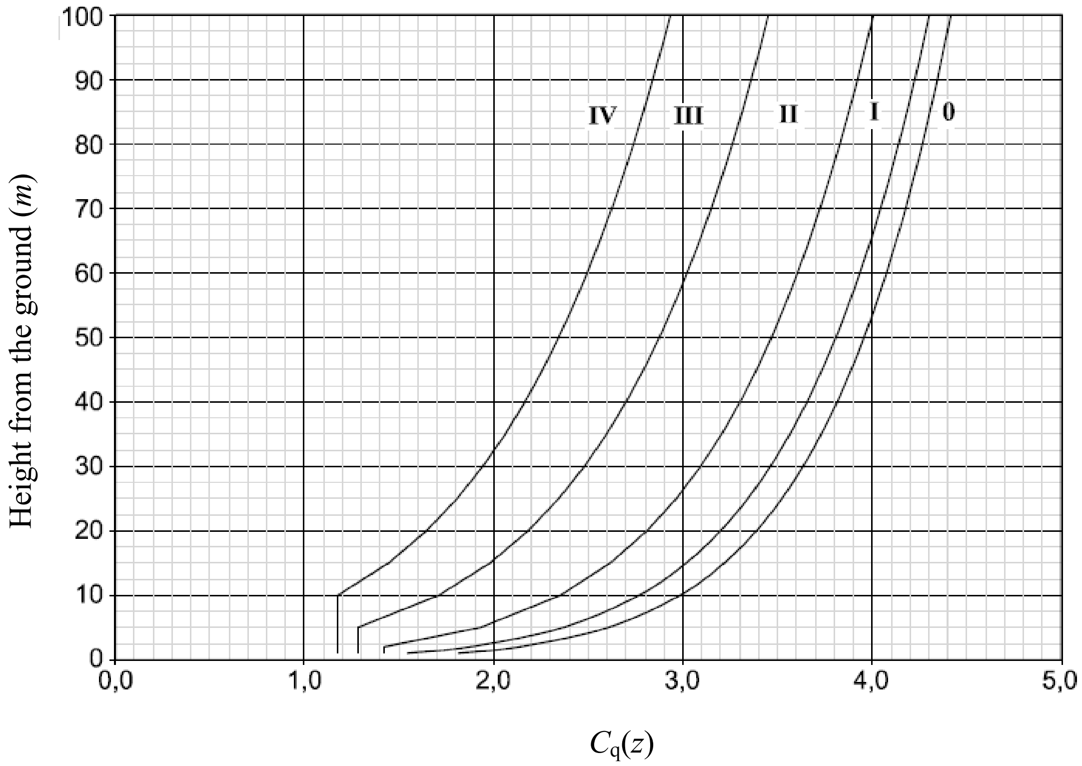

Figure 4.1. Variation of $C_q(z)$ with height for the five terrain types, assuming $C_t = 1$.

4.2. MAXIMUM WIND LOAD ON A SURFACE

The maximum wind load, $Q(z)$, at height z on a surface perpendicular to the main wind flow is calculated by multiplying the maximum wind pressure by the surface area, A, and the surface pressure coefficient, C_p, that is

$$Q(z) = q_p(z) \cdot C_p \cdot A \tag{4.5}$$

The value and the sign of C_p depend on the location of the surface within the structure (i.e., whether it is on the front, back, side, roof, or inside). A positive C_p denotes compression against the surface and a negative C_p denotes suction.

Depending on the size of the surface area, two sets of pressure coefficients are defined: for surface areas 1.0 m^2 or smaller $C_{p,1}$, and for surface areas 10.0 m^2 or larger $C_{p,10}$. The value of C_p for surface areas between 1.0 and 10.0 m^2 is determined by logarithmic interpolation using the following equation

$$C_{p,A} = C_{p,1} - (C_{p,1} - C_{p,10}) \log_{10} A \qquad (1 m^2 \le A \le 10 m^2) \tag{4.6}$$

In general, $C_{p,1}$ is used to calculate wind loads on non-structural components and their connections, whereas $C_{p,10}$ is used to calculate wind loads on the main structural system.

4.3. PRESSURE COEFFICIENTS FOR THE VERTICAL WALLS OF RECTANGULAR BUILDINGS

For buildings with rectangular cross-section, the various wind pressure zones are shown in Fig. 4.2, and the corresponding external pressure coefficients, $C_{pe,1}$ and $C_{pe,10}$, are given in Table 4.2.

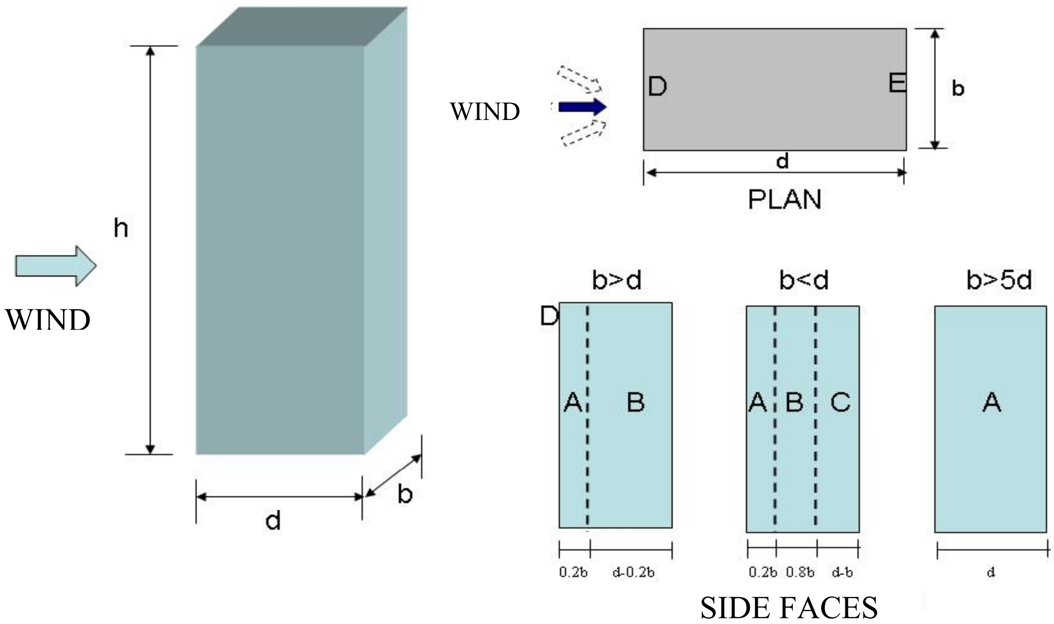

Figure 4.2. Pressure regions for structures with rectangular crossections.

TABLE 4.2.
External pressure coefficients for buildings with rectangular crossections
(*adopted from Euro Code*).

	A (side face)		B (side face)		C (side face)		D (front face)		E (rear face)	
h/d	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$
5	– 1.2	– 1.4	– 0.8	– 1.1	– 0.5		+ 0.8	+ 1.0	– 0.7	
1	– 1.2	– 1.4	– 0.8	– 1.1	– 0.5		+ 0.8	+ 1.0	– 0.5	
≤0.25	– 1.2	– 1.4	– 0.8	– 1.1	– 0.5		+ 0.7	+ 1.0	– 0.3	

Note: For intermediate values of *h/d* use interpolation; for *h/d>5,* use the values for *h/d=5.*

4.4. PRESSURE COEFFICIENTS FOR ROOFS AND OTHER STRUCTURES

The pressure coefficients for other structures and components that are not covered here (such as roofs, paraphets, sign boards, etc.) the pressure coefficients will be taken from the Eurocode [1].

5. WIND LOADS ON BUILDINGS

5.1. WIND LOADS ON BUILDINGS WITH RECTANGULAR CROSS-SECTIONS

The total wind loads, F, on a building with rectangular cross-section is calculated from the following equation:

$$F = F_{ex} + F_{in} + F_{fr}$$

with

$$F_{ex} = C_s \cdot C_d \cdot \sum_{\text{surface area}} q_p(z_e)\, C_{pe}\, A_{ex} \qquad (5.1)$$

$$F_{in} = \sum_{\text{surface area}} q_p(z_i)\, C_{pi}\, A_{in}$$

$$F_{fr} = \sum_{\text{surface area}} q_p(z_e)\, C_{fr}\, A_{fr}$$

where

F_{ex} = Forces on external surfaces

F_{in} = Forces on internal surfaces

F_{fr} = Friction forces

C_s = Load correlation coefficient

C_d = Dynamic resonance coefficient

$q_p(z_e)$ = Peak pressure at external height z_e

$q_p(z_i)$ = Peak pressure at internal height z_i

C_{pe} = External pressure coefficient

C_{pi} = Internal pressure coefficient

C_{fr} = Friction coefficient

A_{ex} = External reference surface area

A_{in} = Internal reference surface area

A_{fr} = External surface area parallel to the wind (friction surface area)

The external pressure coefficients for buildings with rectangular cross section are given in Table 4.2. For roofs and all other types of structures they should be taken from Eurocode [1].

The internal pressure coefficients depend on the size and the distribution of the opening in the building envelope. A face of the building should be regarded as dominant when the area of openings at that face is at least twice the area of openings in the remainng faces of the building. External openings, such as doors and windows, which would be dominant when open but is considered to be closed during severe windstorm, should still be investigated as being open as an accidental design situation. Depending on the area of the opening at the dominant face, the internal pressure coefficients are calculated as a fraction of the external pressure coefficients by using the following rules:

If the opening has twice the area of openings in the remaining faces: $C_{pi} = 0.75C_{pe}$

If the opening has at least three times the area of openings in the remaining faces: $C_{pi} = 0.90C_{pe}$

where C_{pe} is the external pressure coefficient at the dominant face. When the openings are located in zones with different external pressure coefficients, an area-weighted average value of C_{pe} should be used.

The friction coefficients for walls, parapets, and roof surfaces are:

C_{fr} =0.01 for smooth surfaces (e.g., steel, smooth concrete)
C_{fr} =0.02 for rough surfaces (e.g., rough concrete, tar boards)
C_{fr} =0.04 for very rough surfaces (e.g., ripples, ribs, folds)

The friction area is the external surfaces parallel to the wind. For vertical walls, the friction area is the total area of walls parallel to the wind. For roofs, the friction area is the roof area located beyond a distance from the upwind eaves equal to the smallest of (*2 x frontal width*) or (*4 x height*).

To calculate the total wind loads in a building, the building is divided into horizontal segments as shown in Fig. 5.1 below. The wind loads for each segment are calculated separately by using the appropriate wind parameters at that height. The height of the segments cannot be bigger than the width of the building in the direction perpendicular to the main wind flow. It is assumed that wind pressures are constant across the width of each segment.

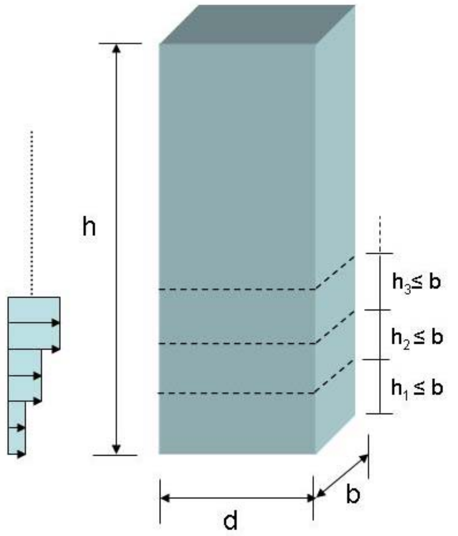

Figure 5.1. Calculation of wind loads along the height of the building.

In Eq. 5.1, the correlation coefficient C_s accounts for the fact that the points on the surface do not experience the maximum wind pressure all at the same time. The resonance coefficient C_d accounts for the increase in the building's displacements due to the turbulance-induced resonance vibrations of the building. They are calculated from the following equations:

$$C_s = \frac{1+7I_w(z_r)\sqrt{B^2}}{1+7I_w(z_r)} \qquad \text{and} \qquad C_d = \frac{1+7I_w(z_r)\sqrt{B^2+R^2}}{1+7I_w(z_r)\sqrt{B^2}} \qquad (5.2a)$$

or

$$C_s C_d = \frac{1+7I_w(z_r)\sqrt{B^2+R^2}}{1+7I_w(z_r)} \qquad (5.2b)$$

In Eqs. 5.2, z_r denotes the reference height in meters, which can be taken as the 60% of the total height (i.e., z_r =0.6h), and $I_w(z_r)$ is the turbulance intensity at the reference height (see Eq. 3.8). B^2 and R^2 are the correlation factor and the resonance factor, respectively. The expressions given by Eq. 5.2 are valid for buildings whose vibrations are dominated by the first mode.

The correlation factor, B^2, is calculated from the following equation:

$$B^2 = \frac{1}{1 + 0.9\left[\dfrac{b+h}{L(z_{\mathrm{r}})}\right]^{0.63}} \tag{5.3}$$

where

b : Width of the building in meters in the direction perpendicular to the wind flow.

h : Height of the building in m.

$L(z_r)$: Turbulance length in meters at the reference height of $z_{\mathrm{r}} = 0.6h$ (see Eq. 3.9).

The resonance factor R^2 is calculated from the following equation:

$$R^2 = \frac{\pi^2}{2\delta} \cdot S_{\mathrm{L}}(z_{\mathrm{r}}, f_{\mathrm{o}}) \cdot R_{\mathrm{h}}(\eta_{\mathrm{h}}) \cdot R_{\mathrm{b}}(\eta_{\mathrm{b}}) \tag{5.4}$$

where

δ : Logarithmic decrement of the first-mode vibrations of the building.

f_0 : Frequency of the first mode (in Hz).

$S_L(z_r, f_0)$: Turbulance power spectral density function at z_r, f_0 (see Eq. 3.10).

$R_h(\eta_h)$: Aerodynamic addmitance function in the vertical direction.

$R_h(\eta_h)$: Aerodynamic addmitance function in the horizontal direction.

The logarithmic decrement δ can be calculated in terms of the damping ratio, ξ_0 , for the first mode as

$$\delta = \frac{2\pi\,\xi_{\mathrm{o}}}{\sqrt{1-\xi_{\mathrm{o}}^2}} \approx 2\pi\,\xi_{\mathrm{o}} \tag{5.5}$$

For buildings whose vibrations are dominated by the first mode, the aerodynamic admittance functions $R_h(\eta_h)$ and $R_b(\eta_b)$ can be approximated from the following equations:

$$R_{\mathrm{h}}(\eta_{\mathrm{h}}) = \frac{1}{\eta_{\mathrm{h}}} - \frac{1}{2\eta_{\mathrm{h}}^2}\left(1 - e^{-2\eta_{\mathrm{h}}}\right) \quad ; \quad \eta_{\mathrm{h}} = \frac{4.6\,h}{L(z_{\mathrm{r}})} f_{\mathrm{L}}(z_{\mathrm{r}}, f_{\mathrm{o}}) \; ; \quad \text{and if} \quad \eta_{\mathrm{h}} = 0 \quad R_{\mathrm{h}} = 1$$

$$R_b(\eta_b) = \frac{1}{\eta_b} - \frac{1}{2\eta_b^2}\left(1 - e^{-2\eta_b}\right) \quad ; \quad \eta_b = \frac{4.6\,b}{L(z_{\mathrm{r}})} f_{\mathrm{L}}(z_{\mathrm{r}}, f_{\mathrm{o}}) \; ; \quad \text{and if} \quad \eta_b = 0 \quad R_b = 1 \tag{5.6}$$

where

b : Width of the building in meters in the direction perpendicular to wind flow.
h : Height of the building.
z_r : Reference height ($z_r = 0.6h$).
f_0 : First mode frequency (in Hz).
$f_L(z_r, f_0)$: Normalized frequency at z_r, f_0 (see Eq. 3.10).
$L(z_r)$: Turbulance length at height z_r (see Eq. 3.9).

5.2. WIND LOADS ON BUILDINGS WITH CIRCULAR CROSS-SECTIONS

Wind loads on buildings with circular cross-sections are calculated similar to those with rectangular cross-sections by using Eq. 5.1. The main difference is the pressure coefficient C_p. For circular cross-sections, C_p depends on the Reynolds number, R_e , which is defined as

$$R_e = \frac{D \cdot V_{\max}(h)}{\nu} \tag{5.7}$$

where

D : Diameter of the circular cross-section
$V_{\max}(h)$: Maximum wind speed at the top of the building
$\nu = 15 \cdot 10^{-6} m^2 / s$: kinematic viscocity of the air

However, for most circular buildings and wind storms: $R_e \geq 10^7$.

The pressure coefficient, C_p , is calculated from the following equation

$$C_p = C_{p,0} \cdot \psi_\alpha \tag{5.8}$$

where

$C_{p,0}$: Pressure coefficient without end effects.

ψ_{α}: End-effect factor.

The end-effect factor depends on the angle α, as shown in Fig. 5.2, and is calculated from the following equations:

$$\begin{aligned}
&\text{For } 0^0 \le \alpha \le \alpha_{\min} &:\quad &\psi_{\alpha} = 1 \\
&\text{For } \alpha_{\min} \le \alpha \le \alpha_{A} &:\quad &\psi_{\alpha} = \psi_{A} + (1-\psi_{A}) \cdot \cos\left[\frac{\pi}{2} \cdot \left(\frac{\alpha - \alpha_{\min}}{\alpha_{A} - \alpha_{\min}}\right)\right] \\
&\text{For } \alpha_{A} \le \alpha \le 180^0 &:\quad &\psi_{\alpha} = \psi_{A}
\end{aligned} \tag{5.9}$$

where α_{min} and α_{A} denote the locations of the minimum pressure and the flow separation, repectively. They are given in Table 5.1.

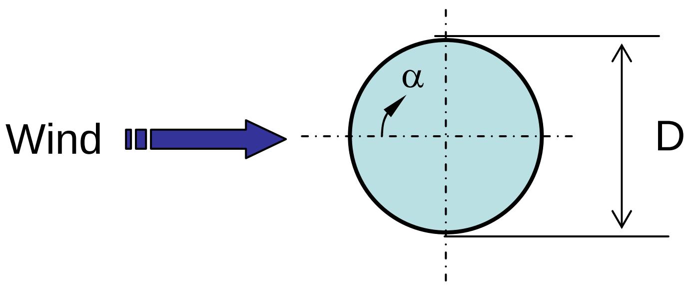

Figure 5.2. Circular cross section subjected to wind.

Table 5.1. Parameters of pressure distribution around circular cylinders.

α_{min}	$C_{p0,min}$	α_{A}	$C_{p0,A}$
75	-1.5	105	-0.8

5.3. ESTIMATION OF THE FREQUENCY AND DAMPING OF BUILDINGS

The frequency and damping of the building are the two key parameters required to calculate wind loads. Typically, the computer models of buildings provide the natural frequencies. However, during the preliminary design stages, there is a need to know the frequency and damping of the building to complete the design and develop the computer model. The latest ASCE Standard, ASCE 7-05, provides some empirical equations and guidelines to predict the frequency and damping for preliminary design [8].

6. CALCULATION OF MAXIMUM ACCELERATIONS

Wind design is based on maximum displacements, which are calculated by applying the forces discussed above as static loads to the structure. In some cases, maximum accelerations are also needed for the design of the structure (e.g., to check the possibility of human discomfort in tall, flexible buildings). This requires a more detailed dynamic analysis. Since dynamic wind loads are defined statistically (i.e., in terms of the power spectral density function of gust), the analysis requires the application of the Random Vibration Theory.
There are approximate methods that can also be used to estimate accelerations from the gust loading factor approach presented in this document (e.g., Refs. 9 and 10). A full dynamic analysis for wind loads should be made under the guidance of an expert who are familiar with the theory and practice. A dynamic wind tunnel test can be a substitute for any dynamic analysis.

7. ACROSS-WIND RESPONSE OF BUILDINGS

When wind pass through tall and flexible buildings, vortices develop on the sides and the back of the building as schematically shown in Fig. 7.1 below. Since the development of vortices on side faces alternate (i.e., they develop first on one side and then the other side), the direction of vortex-shedding forces also alternate, creating vibrations in the direction perpendicular to the main wind flow. If the frequency of vortex shedding forces is close to one of the natural frequencies of the structure, the amplitudes of vortex-induced oscillations can reach to values that are much larger than those of the oscillations in the along-wind direction. The wind speed at which the maximum cross-wind response occurs is known as the critical wind speed, V_{cr} .

Both narrow-band and broad-band responses can develp due to vortex shedding. At small amplitudes, the response is broad-band . When the oscillations become large, the vortex-shedding frequency locks in to the nearest natural frequency of the structure, creating constant-amplitude and narrow-band (i.e., almost sinusoidal) oscillations over a range of wind speeds. Sometimes, a combination of both forms of response occurs. The oscillations change from being small and random to being sinusoidal and large over irregular time periods.

Galloping is another flow phenomenon that can cause across-wind vibrations and often occurs coincidently with vortex shedding. Galloping is the self-excited vibrations due the motion of the structure in the wind, and developes above a critical value of wind velocity. It is basically a structural instability phenomenon that can initiate in low turbulance levels and at frequencies lower than that of vortex shedding.

The size and the shape of the structural section are critical factors influencing the vortex shedding and galloping. Structural sections that have significant afterbodies after the separation points of vortices, and no flow reattachment are particularly susceptible.

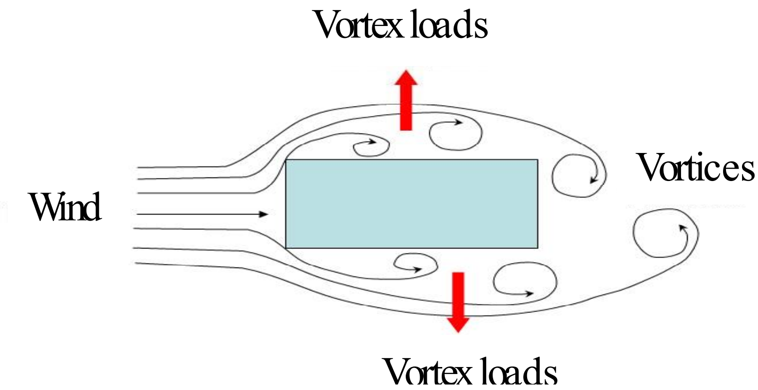

Figure 7.1. Development of vortex shedding forces.

Vortex induced vibratons of the building can be neglected if the following conditions are satisfied:

$$\begin{aligned} & h / b_{\min} < 6 \\ & V_{\mathrm{cr}} > 1.25 V_{\mathrm{m}}(h) \end{aligned} \tag{7.1}$$

where

h : Height of the building.

$b_{\min}$: The smallest width of the building in the across-wind direction.

$V_m(h)$: Average wind velocity at the top of the building m / s.

V_{cr} : Critical wind velocityin m / s.

The critical wind velocity, V_{cr}, is defined by the following equation:

$$V_{\mathrm{cr}} = \frac{b\, f_{\mathrm{oy}}}{S_{\mathrm{t}}} \tag{7.2}$$

where

b : Width of the building in the across-wind direction.

f_{0y} : Natural frequency of the building in the across-wind direction (in *Hz*).

S_t : The Strouhal number.

For buildings with circular cross-sections, the Strouhal number is 0.18. For buildings with sharp-edged rectangular cross-sections the Strouhal number varies as a function of depth/width ratio, *d/b*, and is given in Table 7.1 below. Stouhal numbers corresponding to the intermediate values of *d/b* can be found by linear interpolation.

TABLE 7.1. Variation of Strouhal number in rectangular cross-sections as a function of *d/b*.

d/b	1	2	3	3.5	5	10
S_t	0.12	0.06	0.06	0.15	0.11	0.09

For non-circular cross-sections, a step-by-step analytical procedure to determine the possibility of vortex shedding is provided in ESDU 90036 [11]. The analysis is based on the assumptions that for many sharp-edged structures the separation points of the flow around the structure are fixed over the whole range of flow conditions and Reynolds numbers. If the analysis predicts a predominantly narrow-band type response, the structural design should be considered unsatisfactory. If the analysis predicts a predominantly broad-band type response, the structural design should still be checked for fatigue and serviceability.

Similar analytical procedures are given for the vortex-induced response of circular and polygonal sections in ESDU 96030 [12], and for the galloping response in ESDU 91010 [13].

Another alternative to investigate across-wind response, as well as torsional response, is to use the electronic database assisted system as recommended in the ASCE Standard 7-05 [8]. The database can be accesed through Internet at http://aerodata.ce.nd.edu/interface/interface.html and consists of high-frequency base balance measurements of seven rectangular building models with depth-to-width ratios from 1/3 to 3, three height-to-width ratios for each model, and two incoming flow types representing an open and an urban environment. Using this interactive web site, users can select the geometry and the dimensions of the model building, and the flow condition, and automatically obtain the dynamic load spectra for along-wind, across-wind, and torsional directions. The web site includes documentation, analysis procedure, and examples. The web site is not intended to replace the wind tunnel testing, but provides useful tools for preliminary design.

Any analytical study should be done under the supervision of a consultant who is familiar with the theory.

If the predicted reponse values due to vortex shedding exceed the design or serviceability limits, some preventive measures can be taken to reduce them, although they are often difficult and too expensive to implement, particularly for tall buildings. They include increasing the natural frequency of the structure by increasing stiffness, increasing the damping by using additional dampers, and reducing the across-wind forces by changing the cross-sectional shape of the building, such as rounding the corners of a sharp-edged rectangular.

The study of across-wind vibrations of any building with unusual geometry and height requires wind tunnel testing.

8. WAKE BUFFETING

The buildings whose height-to-width ratio is four or greater, and located on the leeward side (i.e., back) of a similar size building may experience additional vibrations due to the turbulance generated by the presence of the building in front. This is known as *Wake Buffeting.* Wake buffeting can be neglected if any one of the following two conditions is satisfied:

(a) The distance between the two buildings is 25 times or more of the across-wind width of the building in front.

(b) The natural frequency of the subject building is greater than 1.0 *Hz*.

Otherwise, wake buffeting should be accounted for in the design. This usually requires wind tunnel tests.

9. WIND TUNNEL TESTS

Wind tunnel tests are required for structures that are not regular and/or likely to have unusual wind response characteristics. They include

1. Structures that are spatially irregular and very tall.
2. Structures that are very flexible with natural frequencies below 1.0 Hz.
3. Structures that are susceptible to vortex shedding, galloping, or wake buffeting.
4. Structures that are susceptible to wind-induced human discomfort.
5. Structures whose wind response requires a more accurate estimation of response and/or curtain wall pressures.

Wind tunnels tests can be used as an alternative to the numerical procedures presented above.

A wind tunnel test should satisfy the following conditions:

1. The variation of average wind velocity with height should be matched.
2. Macro- and micro-length scales of turbulance should be matched.
3. The effects of Reynolds number on pressures and forces should be minimized.

4. Longitudinal pressure gradient in the tunnel should be accounted for.
5. The structure, and the geometry of the topography and the surrounding structures should be properly modeled.
6. The projected area of the test stucture and the surroundings should be less than 8% of the tunnel cross-sectional area.
7. Appropriate sensors should be used to measure the desired response parameters.

More on wind tunnel tests can be found in Ref. [14]

REFERENCES

[1] *Eurocode 1: Action on structures*, prEN 1991-1-4.6:2002.

[2] Membery, D.A (1983). Low-Level winds during the Gulf Shamal, *Weather* Vol 38: pp18-24

[3] Aurelius, L., Buttgereit, V., Cammelli, S. and Davids, A. (2007). A detailed review of site-specific wind speeds for tall building design in Dubai, *Proceedings,* The 8th UK Conference on Wind Engineering, University of Surrey, 14-16 July 2007.

[4] Aurelius, L, Buttgereit, V, Cammelli, S, and Zanina, M. (2007). The impact of Shamal winds on tall building design in the Gulf Region, *Proceedings*, Int. Conf. on Tall Buildings – Architectural and Structural Advances, Abu Dhabi, UAE.

[5] Zhou, Y., Kijewski, T. and Kareem, A. (2002). Along-Wind Load Effects on Tall Buildings: Comparative Study of Major International Codes and Standards, *Journal of Structural Engineering*, ASCE, June 2002.

[6] Zhou, Y., and Kareem, A. (2002), Definition of Wind Profiles in ASCE 7, Technical Note, *Journal of Structural Engineering*, ASCE, Vol.128, No.8, pp.1082-1086.

[7] 2. Durst, C.S. (1960). Wind speeds over short periods of time , *Meteor. Mag.,* 89, 181-187.

[8] ASCE (2005*). Minimum Design Loads for Buildings and Other Structures*, ASCE Standard, ASCE/SEI 7-05.

[9] Zhou, Y., Kijewski, T. and Kareem, A. (2003), Aerodynamic Loads on Tall Buildings: Interactive Database, *Journal of Structural Engineering*, ASCE, Vol.129, No.3, pp. 394-404.v

[10] Kwon, Dae-Kun, Kijewski-Correa, T. and Kareem, A. (2008), e-Analysis of High-Rise Buildings Subjected to Wind Loads, *Journal of Structural Engineering*, ASCE, 133 (7), 1139-1153

[11] ESDU 90036 (1990). *Structures of non-circular cross section: Dynamic response due to vortex shedding,* HIS ESDU International, London.

[12] ESDU 96030 (1996). *Response of structures to vortex shedding: Structures of circular or polygonal section,* HIS ESDU International, London

[13] ESDU 91010 (1993). *Response of structures to galloping excitation: Background and approximate estimation,* HIS ESDU International, London.

[14] ASCE (1999). Wind Tunnel Model Studies of Buildings and Structures, *Manuals and Reports on Engineering Practice*, No. 67, American Society of Civil Engineers, New York.