Wind Load Analysis and Design

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Introduction

Wind has two aspects, the first one is beneficial and the other one is problematic one. The beneficial aspects include the generation of wind power, used in sailing in ships in earlier times, etc. The negative aspects include the catastrophic disasters, air drag, etc. One of the negative aspects is the wind load which has been a field of interest in this project and has been discussed throughout.

The civil and industrial structures, which include buildings, towers, dams, etc. always experience some wind loads due to the passing wind currents. Thus, they need to be designed in a way that they are able to resist the wind loads and withstand the wind pressures. In this project, we are mainly focussed on wind patterns across the areas under the political boundaries of India. However, the methods used can be applied to any civil or industrial structures. The area of India is approximately 3.287 million square kilometres and it has a variety of relief features which include plains, plateaus, mountainous areas, and being a peninsular country, it also has coastal areas. And, due to this every area has different wind patterns and the civil structures need to be designed accordingly.

Discussing the hazards due to wind patterns that have been observed over years, the main reasons for them are the population explosion that has led to the increase in number buildings, development of megacities, the types of materials used in construction purposes and the location of the industrial buildings and structures.

Variation of winds is dynamic and varies randomly. At a given area, it has its mean velocity and some fluctuating component. An example plot has been shown in Figure 1.

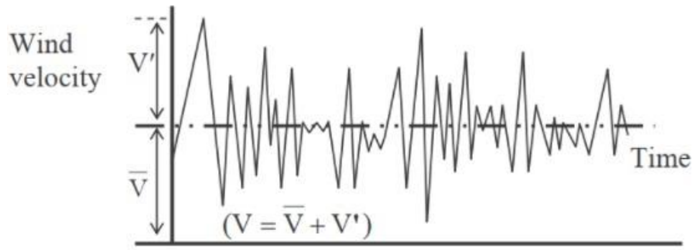

Figure 1 : An example of fluctuating current
(Credits : Handbook on IS 875 Part 3)

The fluctuating component of the wind is responsible for the ‘gustiness’ (a sudden strong rush of wind).

The terrain and topography of a particular region also affects the wind flow of that region. A rough plot of variation of wind speed is depicted in Figure 2.

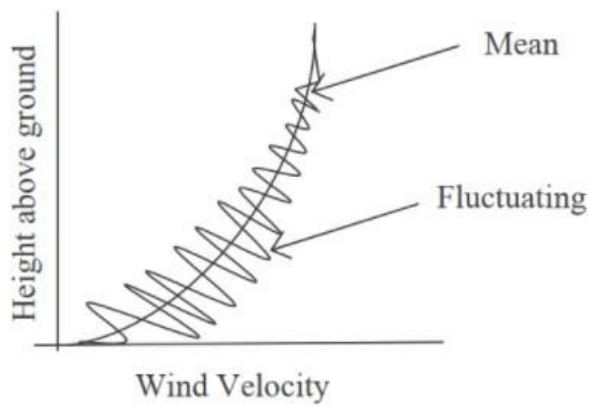

Figure 2 : Variation of wind speed with height

It is always better to represent some phenomena quantitatively. The Reynolds number (Re) can be used to determine the type of flow of wind. It helps predict flow patterns in different fluid flow situations. Low Reynolds number represents the laminar flow of a liquid whereas turbulent flow is represented by a high value of Reynolds number.

The buildings and other civil engineering structures are 3 dimensional bodies and experience varied pressure distributions. Sometimes, the fluctuating component of the wind is so large that it becomes even more than the mean load of the building in cases of extreme pressure and storms. The effect of wind pressure depends on the height of the buildings, for example, tall and slender structures vibrate due to the turbulence inherent in the wind and that generated by the structures themselves due to the separation of the flow of the wind. Besides this, there are two types of responses shown by the wind : along-wind response and across-wind response. Along with the along-wind response, the tall buildings also exhibit across-wind responses. As the buildings become more slender, the across wind behaviour of the buildings becomes more important. Moreover, all the walls and roofs of the buildings don't experience the same pressure, the walls on the windward side, leeward side and on the side of the buildings, all experience different pressures and suction.

The determination of wind loads is conventionally done using theoretical and practical knowledge and sometimes, practical experimentations are also done, if required. Nowadays, with a boom in technology, a useful tool, as a part of computational fluid dynamics, is developing which involves the use of Artificial Neural Networks (ANNs).

In this project, in the analytical way of calculating the loads on different buildings and their components (like roofs, walls, columns, etc.), we follow the Indian Standard mentioned in IS 875 Part 3 2015. It provides state of the art information about the different wind patterns across India, the mathematical values of constants for different kinds of buildings under different conditions, ways to calculate the pressure or suction values under different conditions, and other such guidelines which we have to follow.

The formulation of the problems is done in the following way : First, we focus on finding the wind speed and design the wind speed , after we find the wind speed, after finding out the design wind speed , we find the wind pressure at a height and Design wind pressure.

The basic formulas involved are :

$V_z = V_b.k_1.k_2.k_3.k_4$

$P_z = 0.6V_z^2$

$P_d = P_z.K_d.K_a$

$F = C_{pnet}.A_c.P_d$

V_b	Wind speed of a area	K_a	Area averaging factor
V_z	Design wind speed	P_z	Design wind pressure
k_1	Risk Coefficient Factor	P_d	Wind pressure
k_2	Terrain and Height Factor	F	Wind force
k_3	Topography Factor	C_{pnet}	Difference of pressure and suction coefficient
k_4	Importance Factor for cyclonic region	A_{net}	Area on which wind forces/pressures are acting
K_d	Wind directionality Factor		

Table 1.1 : Frequently used variables and coefficients

Problem Formulation

In this section we will have detailed discussion about how the formulation of the problem is done. As discussed roughly at the end of the previous chapter, the basic backbone remains the same.

First of all, for carrying out our calculations, we need to have clarity of how much is the speed of the wind current where the building or any other civil structure of our interest is constructed or going to be constructed. For that, the area of India is divided into six wind zones as per IS 875. So, the zone in which the area, district or city lies needs to be identified.

Zone I	33 metres per second
Zone II	39 metres per second
Zone III	44 metres per second
Zone IV	47 metres per second
Zone V	50 metres per second
Zone VI	55 metres per second

Table 2.1 : Wind speeds according to respective wind zones as per IS 875

Once the zone is identified, and thus the wind speed of the area, now, we need to calculate the design wind speed which is ultimately responsible for the wind load. For that, we need to know different factors that contribute to calculating the same.

These factors are k_1 , k_2 , k_3 and k_4.

The risk coefficient factor (k_1) depends on the life of the structure. The following table (Table 3) contains the values of the factor as per IS 875.

Sl No.	Class of Structure	Mean Probable Design Life of Structure in Years	k_1 Factor for Basic Wind Speed m/s					
			33	39	44	47	50	55
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
i)	All general buildings and structures	50	1.0	1.0	1.0	1.0	1.0	1.0
ii)	Temporary sheds, structures such as those used during construction operations (for example, formwork and false work), structures during construction stages and boundary walls	5	0.82	0.76	0.73	0.71	0.70	0.67
iii)	Buildings and structures presenting a low degree of hazard to life and property in the event of failure, such as isolated towers in wooded areas, farm buildings other than residential buildings	25	0.94	0.92	0.91	0.90	0.90	0.89
iv)	Important buildings and structures such as hospitals communication buildings/towers, power plant structures	100	1.05	1.06	1.07	1.07	1.08	1.08

Table 2.2 : Risk coefficient factor

As the name suggests, the Terrain and Height Factor (k_2) depends on the terrain of the area where the structure is located and the height of the building. Depending on how there are obstructions to wind near our structure, terrains are classified into four categories with category 1 having no or very less obstructions, whereas category 4 having large and closely spaced obstructions.

The following table shows the values of k_2 according to the height of the structure and the terrain category.

Sl No.	Height z m	Terrain and Height Multiplier (k_2)			
		Terrain Category 1	Terrain Category 2	Terrain Category 3	Terrain Category 4
(1)	(2)	(3)	(4)	(5)	(6)
i)	10	1.05	1.00	0.91	0.80
ii)	15	1.09	1.05	0.97	0.80
iii)	20	1.12	1.07	1.01	0.80
iv)	30	1.15	1.12	1.06	0.97
v)	50	1.20	1.17	1.12	1.10
vi)	100	1.26	1.24	1.20	1.20
vii)	150	1.30	1.28	1.24	1.24
viii)	200	1.32	1.30	1.27	1.27
ix)	250	1.34	1.32	1.29	1.28
x)	300	1.35	1.34	1.31	1.30
xi)	350	1.35	1.35	1.32	1.31
xii)	400	1.35	1.35	1.34	1.32
xiii)	450	1.35	1.35	1.35	1.33
xiv)	500	1.35	1.35	1.35	1.34

Table 2.3 : Terrain and Height Factor

The Topography factor (k_3) governs the flow of wind and its effects taking into account height, direction and steepness of the slope of the ground. When the slope is greater than 3^o then the effect of topography is significant and the value of k_4 is taken between

1 and 1.36, whereas when the slope is less than 3^o the value 1.00 is taken, since the topographic effects are not so significant.
The value of the Importance factor for the cyclonic region (k_4) is considered according to the recommendations in IS 15498 and are applicable according to the importance of the structure. The following table shows the k_4 values for different structures.

Type of structure	k_4
Structures for post-cyclonic importance for emergency services.	1.30
Industrial Structures	1.15
All other structures	1.00

Table 2.4 : Importance factor for Cyclonic Region

After having the values of k_1 , k_2 , k_3 and k_4, we can calculate the Design wind speed (V_z) using the formula :

$$V_z = V_b.k_1.k_2.k_3.k_4$$

Now that we have found V_z , we can calculate the Design wind pressure (P_d) which can be calculated using the formula :

$$P_z = 0.6V_z^2$$

After calculating P_d we need to calculate the wind pressure (P_z), for that we need the Wind Directionality Factor (K_d) and the Area Averaging Factor (K_a).
For buildings, solid signs, open signs, lattice frameworks and trussed towers (triangular/rectangular), K_d is taken to be 0.9 . For, circular or near-circular structures and for cyclone affected areas, it is taken as 1.0 .
The Area Averaging Factor depends on the tributary area, which is simply the area under the influence of wind load. The following table shows the K_a values for different intervals of areas.

Sl No. (1)	Tributary Area (A) m^2 (2)	Area Averaging Factor (Ka)* (3)
i)	$\leq$10	1.0
ii)	25	0.9
iii)	$\geq$100	0.8

* Linear interpolation for intermediate values of a is permitted.

Table 2.5 : Area Averaging Factor (K_a)

Now that we have K_a and K_d, we can calculate the Wind Pressure (P_d) according to the formula :

$$P_d = P_z.K_d.K_a$$

After calculating P_d, we aim to calculate the forces on different walls and roofs of the structure. For that we need C_{pnet}, which is the difference of external and internal pressure coefficients , C_{pe} and C_{pi} respectively.

C_{pi} depends on degree of permeability of cladding to the flow of air and it may be positive or negative depending on the direction of flow of the wind,

C_{pe} depends on various factors , the ratio of length to breadth of the building, the ratio of height to breadth of the building, the type of wall , whether it is A, B, C or D, the zones in the building E, F, G and H and the angle of incidence of the wind. The table containing the values and these parameters is mentioned in Table 5, Clause 7.3.3.1 and Table 6, Clause 7.3.3.2 of IS 875 Part 3 2015.

Now , after having C_{pe} and C_{pi} , we can calculate C_{pnet} , which is just C_{pe} - C_{pi} .

And now , we can calculate the forces experienced by different walls and roofs of the structure using the formula :

$$\mathbf{F = (C_{pe} - C_{pi}).A_c.P_d = C_{pnet}.A_c.P_d}$$

For high-rise buildings or structures, the value of some constants cannot be taken as common for all heights as they change with height. Moreover, the shape of the structure also matters, The above formulation is the backbone for almost all the problems. However, it may slightly change when the shape of the building is non-rectangular.

In such cases, we need to consider some more factors and constants according to the rules laid down in the Indian Standard Codes.

Results and Discussions

Introduction to this chapter :

Till now, we have discussed the concepts regarding how to find pressures and forces on various walls or roofs of the civil structures due to the load of wind. In this chapter, we are going to implement the concepts discussed in the previous chapter by taking the help of some examples.

Implementation :

Let us first begin with a simple problem,

Example 1 : Wind Pressure and Forces on a Rectangular Clad Building : Flat Roof

Problem Statement :

Calculate wind pressures and design forces on walls and roof of a rectangular building having plan dimensions 10m x 50m and height 5m, as shown in Figure 3.1. The building is situated in Mohali (Chandigarh) in an upcoming Institutional complex on a fairly level topography. Walls of the building have 20 openings of 1.5m x 1.5m size. The building has a flat roof supported on load bearing walls.

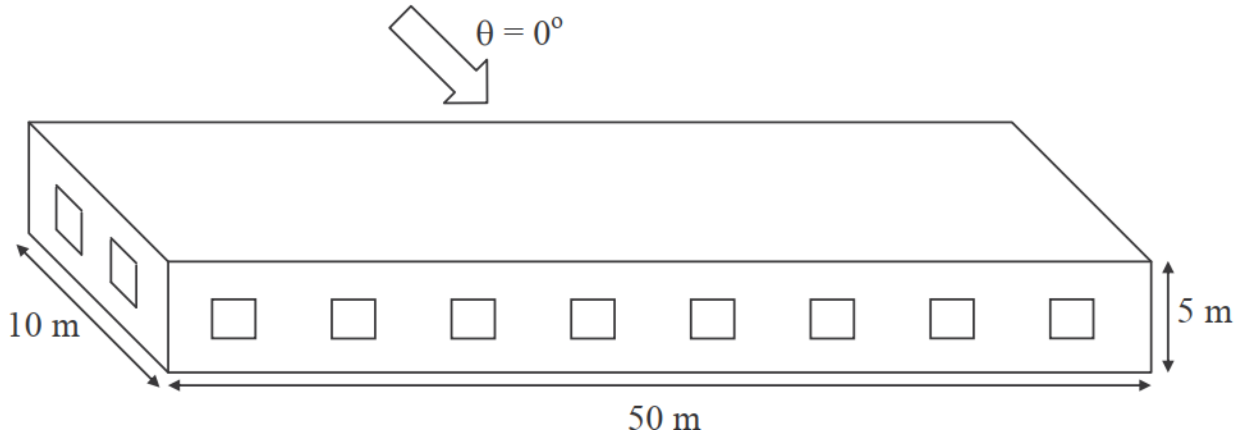

Figure 3.1

Solution :

First, we need to find out the speed of the wind in our area of interest, that is Mohali. As per IS 875, Mohali lies in Zone IV. So, according to Table 2.1, the areas in Zone IV experience wind speed of 47m/s. Also, the building lies in the Topographic category 4.

Now, we will focus on calculating the design wind speed. For that, we need to find the different factors k_1 , k_2 , k_3 and k_4 as discussed earlier in chapter 2.
First focusing on k_1, the Risk coefficient factor. Since the building is an institutional complex, it comes under the category of "All general buildings and structures" and thus, for all wind zones, the value of k_1 will be equal to 1.
The building lies in category 4 topographic zone and the height of the building is 5m. So, according to table 2.3, we will consider the value of Terrain and Height factor, k_2, equal to 1.
Now, since we are considering θ as 0^o , the value of k_3, the topographic factor, will be equal to 1.
Since Mohali is located in Punjab, the place where there are no chances of cyclone since it is very far from coastal areas, the value of k_4, Importance factor for cyclonic areas, will be equal to 1.

Now, we are ready to find out the Design wind speed, which is responsible for the load on the building.
Using the formula :

$$\mathbf{V_z = V_b.k_1.k_2.k_3.k_4}$$

$$V_z = (47)(1)(1)(1)(1) = 47 \text{ m/s}$$

Now, we can find out the design pressure :

$\mathbf{P_z = 0.6V_z^2}$

$P_z = 0.6(47)^2 = 1325.4\ N/m^2 = 1.3254\ kN/m^2$

Now that we have the design wind pressure, we need to find out the wind pressure. For that , we need the Area averaging factor (K_a) and the Wind Directionality factor (K_d).

According to IS 875 Part-3 2015, for buildings, solid signs, open signs, lattice frameworks and trussed towers (triangular/rectangular), K_d is taken to be 0.9 .

To find K_a, we need to know the tributary area for each wall and the roof.

Tributary area of short walls : 10 x 5 = 50 m^2
Tributary area of long walls : 50 x 5 = 250 m^2
Tributary area of roof : 50 x 10 = 500 m^2

From Table 2.5, after doing the linear interpolation, which is permissible according to the IS 875 Part-3 2015, we get the value of K_a equal to 0.867 for short wall and 0.8 for long wall and roof.

Now we can find the wind pressure (P_d) using the formula :

$\mathbf{P_d = P_z.K_d.K_a}$

$P_d = (1.3254)(0.9)(0.867) = 1.034\ kN/m^2$ for short wall

$P_d = (1.3254)(0.9)(0.8) = 0.954\ kN/m^2$ for long wall and roof

Now that we have the pressure on different walls and the roof, we can find the forces acting on them.
For that we need C_{pnet}, which is the difference of external and internal pressure coefficients , C_{pe} and C_{pi} respectively.
For C_{pi} we need to find out the permeability of the cladding to the flow of wind.

Area of all the walls : 5x(2x10 + 2x50) = 600 m^2
Area of all the openings : 20 x 1.5 x 1.5 = 45 m^2
Percentage opening area : 7.5% , which is between 5 and 20%, so the building is of medium permeability.

According to section 7.3.2.2 of IS 875 Part-3 2015, for buildings with medium openings between 5 and 20% of the wall area, shall be examined with internal pressure coefficient +0.5 and and later with -0.5 and the analysis which produces greater distress of the member shall be opted. So, from here we get $C_{pi} = \pm 0.5$.
Now, we need to find the External pressure coefficient.
The h/w ratio for the building is 0.5. According to Table 6 of IS 875 Part-3 2015, for buildings with roof angle 0^o, the pressure coefficients are tabulated below.

Portion of Roof	Wind Incidence Angle	
	0º	90º
E	-0.8	-0.8
F	-0.8	-0.4
G	-0.4	-0.8
H	-0.4	-0.4

Table 3.1 : External Pressure Coefficients for roof

The E, F, G and H portions of the building are assumed according to the diagram below.

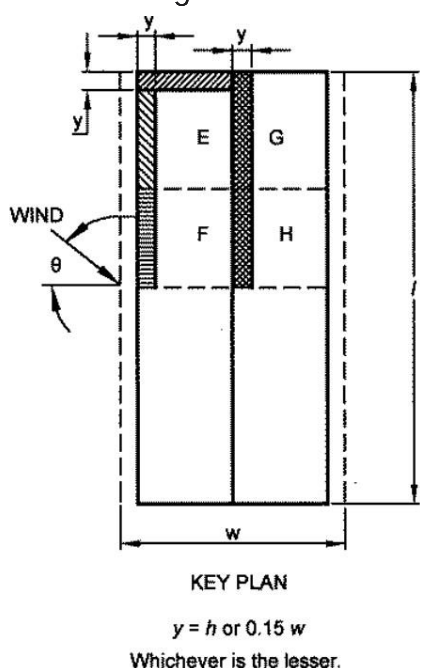

Figure 3.2

We need to make combinations for E, F, G and H zones separately to deal with cases like the addition of negative external pressure to positive internal pressure.

From the dimensions of the building, we know that we have the h/w ratio as 0.5 and l/w ratio as 5 for the building. Now, we can find the value of C_{pe} for different walls.

Wall	Wind Incidence Angle	
	0º	**90º**
A	+0.7	-0.5
B	-0.25	-0.5
C	-0.6	+0.7
D	-0.6	-0.1

Table 3.2 : External Pressure Coefficients for walls

The A, B, C and D walls of the building are assumed according to the diagram below.

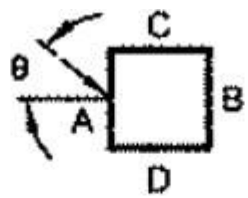

Figure 3.3

Now, we have C_{pe} and C_{pi} , we can find C_{pnet}, which is just the difference between the two.

C_{pnet} for walls A or B :

= 0.7-(-0.5) = +1.2 pressure

= -0.5-(+0.5) = -1.0 suction

C_{pnet} for walls C or D :

= 0.7-(-0.5) = +1.2 pressure

= -0.6-(+0.5) = -1.1 suction

Design wind pressures for long walls : **$F = C_{pnet}.A_c.P_d$**

= 1.2 x 1 x 1 x 0.954 = 1.1448 kN/m^2 Pressure

= -1.0 x 1 x 1 x 0.954 = -0.954 kN/m^2 Suction

Design wind pressures for short walls : **$F = C_{pnet}.A_c.P_d$**

= 1.2 x 1 x 1 x 1.034 = 1.2408 kN/m^2 Pressure

= -1.1 x 1 x 1 x 1.034 = -1.1374 kN/m^2 Suction

Design wind pressures for roof : **$F = C_{pnet}.A_c.P_d$**

= 0.1 x 1 x 1 x 0.954 = -0.0954 kN/m^2 Pressure

$$= -1.3 \times 1 \times 1 \times 0.954 = 1.2402 \text{ kN/m}^2 \quad \text{Suction}$$

This ends our first example. In this example, the steps are implemented according to the problem formulation method discussed in chapter 2.

Let us now discuss a slightly different and complex problem, which involves pitched roofs and is located in a coastal area.

Example 2 : Wind Pressure and Forces on a Rectangular Clad Building : Pitched Roof and is located in a Coastal area.

Problem Statement : *Calculate wind pressures and design forces on walls and roof of a rectangular clad building with pitched roof having plan dimensions 10m x 50m and height 5m, as shown in Figure 3.4. The building is situated in Visakhapatnam, Andhra Pradesh near the sea-coast in an industrial area 500m inside open land on a fairly level topography. Walls of the building have 20 openings of 1.5m x 1.5m size. The roof is of GC sheeting and the roof angle α = 15° . Also calculate the local wind pressure on the roof and the wall cladding. The columns and trusses are at 5m c/c, longitudinally , purlins are at 1.4m c/c and columns at Gable ends are at 5m c/c.*

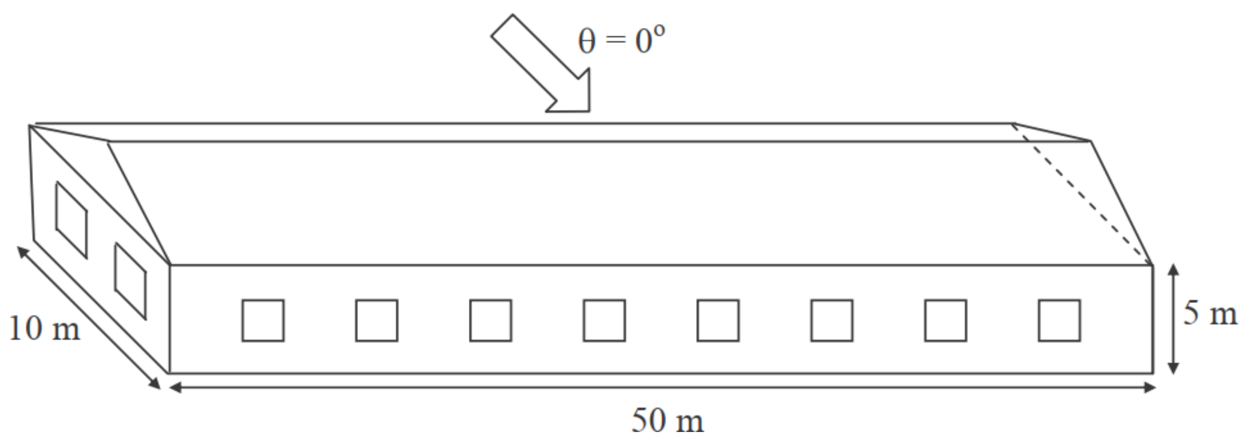

Figure 3.4

<u>Solution :</u>

Visakhapatnam lies in zone V , so the wind speed there is 50 m/s.

Risk coefficient factor (k_1) : 1.00
The building lies in category 5 topographic zone and the height of the building is 5m. So, according to table 2.3, we will consider the value of Terrain and Height factor, k_2, equal to 1.05.
Topography factor (k_3) : 1.00
Importance factor for cyclonic regions (k_4) : 1.15 (Industrial structure , ref : Table 2.4)

Design Wind speed : $\mathbf{V_z = V_b.k_1.k_2.k_3.k_4}$

V_z = (50)(1)(1.05)(1)(1.15) = 60.375 m/s

Wind pressure : $\mathbf{P_z = 0.6V_z^2}$

$P_z = 0.6(60.375)^2 = 2187\ N/m^2 = 2.187\ kN/m^2$

Now we need to find the Area averaging factor and the wind directionality factor to find the wind pressure.

According to IS 875 Part-3 2015, for buildings, solid signs, open signs, lattice frameworks and trussed towers (triangular/rectangular), K_d is taken to be 0.9 .

Now, to find K_a, we will find the tributary areas of the walls, roofs, columns, trusses and purlins.

Tributary area of long walls	:	50 x 5	= 250 m^2	⇒ K_a = 0.8
Tributary area for roof	:	50 x 10	= 500 m^2	⇒ K_a = 0.8
Tributary area for columns	:	5 x 5	= 25 m^2	⇒ K_a = 0.9
Tributary area for trusses	:	2 x 5.176 x 5	= 51.76 m^2	⇒ K_a = 0.864
Tributary area for purlins	:	1.4 x 5	= 7 m^2	⇒ K_a = 1.00

Tributary area of short walls for design of wind braces in plan :

10 x 5 + 0.5 x 10 x 1.34 = 56.7 m^2 ⇒ K_a = 0.858

Design Wind pressure : $\mathbf{P_d = P_z.K_d.K_a}$

P_d = (2.187)(0.9)(0.858) = 1.689 kN/m^2 for short wall

P_d = (2.187)(0.9)(0.8) = 1.574 kN/m^2 for long wall and roof

Area of all the walls : 5x(2x10 + 2x50) + 2 x 0.5 x 1.34 x 10 = 613.4 m^2
Area of all the openings : 20 x 1.5 x 1.5 = 45 m^2
Percentage opening area : 7.336% , which is between 5 and 20%, so the building is of medium permeability.

According to section 7.3.2.2 of IS 875 Part-3 2015, for buildings with medium openings between 5 and 20% of the wall area, shall be examined with internal pressure coefficient +0.5 and and later with -0.5 and the analysis which produces greater distress of the member shall be opted. So, from here we get $C_{pi} = \pm 0.5$.

Now, we need to find the External pressure coefficient (C_{pe}).
The h/w ratio for the building is 0.5. According to Table 6 of IS 875 Part-3 2015, for buildings with roof angle 15^o, the pressure coefficients are tabulated below.

Portion of Roof	Wind Incidence Angle	
	0^o	90^o
E	-0.8	-0.75
F	-0.8	-0.6
G	-0.4	-0.75
H	-0.4	-0.6

Table 3.3 : External Pressure Coefficients for roof

We need to make combinations for E, F, G and H zones separately.

From the dimensions of the building, we know that we have the h/w ratio as 0.5 and l/w ratio as 5 for the building. Now, we can find the value of C_{pe} for different walls.

Wall	Wind Incidence Angle	
	0^o	90^o
A	+0.7	-0.5
B	-0.25	-0.5
C	-0.6	+0.7
D	-0.6	-0.1

Table 3.4 : External Pressure Coefficients for walls

C_{pnet} for walls A or B :

= 0.7-(-0.5) = +1.2 pressure

= -0.5-(+0.5) = -1.0 suction

C_{pnet} for walls C or D :

= 0.7-(-0.5) = +1.2 pressure

= -0.6-(+0.5) = -1.1 suction

Local pressure coefficients for the design claddings and fasteners :

For this, we will refer to Table 6 of IS 875 Part 3 for roof angle = 15^o

Local C_{pe} for eaves portion in mid zone : NA
Local C_{pe} for eaves portion in end zone : NA
Local C_{pe} for ridge portion : -1.2
Local C_{pe} for gable edges : -1.2
Local C_{pe} for corners of walls : -0.6

From here we can notice that the maximum local C_{pnet} for roof at the edges and the ridge = -1.2-(+0.5) = -1.7
Similarly, for wall edges = -0.6-(+0.5) = -1.1

But, for local pressure coefficients, we will take K_a = 1 and thus

$$P_d = 1.735 \times 0.9 = 1.5777 \text{ kN/m}^2$$

At the zone of local coefficients (0.15 x 10 = 1.5m) , that are ridges, eaves and gable ends and wall wall corners (0.25 x 10 = 2.5m), the cladding and fasteners shall be checked for increased force.

Force due to frictional drag :

Here, this acts in the longitudinal direction of the building along the wind.
Since, in this case, h < b, the first equation will be used and $C_f^{'}$ = 0.02. And since the area of walls is more than $100m^2$, K_a=0.8 will be used.