Derivation of wind load

ICON LEGEND
- Design principles
- Applied practice
- Worked example
- Further reading
- Web resources

Introduction

This Technical Guidance Note concerns the derivation of wind load onto structures. It is based on Eurocode 1: Actions on Structures Part 1-4; General Actions – Wind Actions. With this being focused on a load that is sensitive to the environment, the UK Annex to the Eurocode plays a significant part as it makes reference to wind speeds that are unique to the British Isles. It must also be noted that there are a large amount of variations and conditions the designer must be aware of when determining wind loads on structures. It is for this reason that the reader is referred to the code text more often than in other notes in this series.

Design principles

The derivation of wind load requires the design engineer to make judgements on the environment the structure is placed within as well as the material it is clad in. There is also the impact of significant openings in the structure to take into consideration. Eurocode 1-1-4 attempts to address these assumption-based variables by creating a set of coefficients against which a base wind velocity is factored. This is then converted into a pressure that exerts a load onto the structure. This can then be used to design the structure to resist loads due to wind, using the appropriate partial factors.

Coefficients for Wind Velocity

Wind load is based on an assumed velocity. This is referred to as the fundamental basic wind velocity $(v_{b,0})$ within Eurocode 1-1-4, Clause 1.6.1. It is derived from a 10 minute mean wind velocity that has a risk of 1/10 of being exceeded over a period of one year. The height at which this speed occurs is 10m above flat, open countryside and allows for any altitude effects.

In order to arrive at a force due to wind, a series of factors are applied to the fundamental basic wind velocity. These factors are used to determine an air pressure load onto a given structure. The full expression for determining the basic wind velocity (v_b) is:

$$v_b = v_{b,map}\, c_{alt}\, c_{dir}\, c_{season}$$

This is a combination of equations in Clause 4.1 of Eurocode 1-1-4 and NA.1

Each of these factors is defined below:

Location $(v_{b,map})$
The assumed wind velocity is dependent upon the location of the structure in the British Isles. This can be determined by plotting the location of the structure onto Figure NA.1 in the UK National Annex. The value can be interpolated between the contour lines shown in the referenced figure.

Altitude (c_{alt})
The altitude factor (c_{alt}) takes into account the height above ordinance datum the building is being constructed from above ground. Clauses NA. 2a and NA. 2b define how this coefficient is derived:

$c_{alt} = 1+0.001A$, for when 'z' is less than 10m
$c_{alt} = 1+0.001A(10/z)^{0.2}$ for when 'z' is more than 10m

Note that it is acceptable to use the value of c_{alt} where 'z' is less than 10m for all conditions as a conservative assumption. Where:

A is altitude above mean sea level in metres

z is a referenced height based on the type of structure that is being considered. For overall wind pressure it is defined as z_s and can be determined using Figure 6.1 of Eurocode 1-1-4. For pressure on walls of rectangular buildings facing windward, the variable is defined as z_e. It is affected by the geometry of the building, specifically whether it is larger in height than in plan. It can be derived using Figure 7.4 of Eurocode 1-1-4.

Wind Direction (c_{dir}) **and Season** (c_{season})
Wind directional factor (c_{dir}) can be derived from Table NA.1 in the UK National Annex for Eurocode 1-1-4. It is defined based on the clockwise angle from due north the structure is orientated to and the wind direction being considered. It is acceptable to ignore this factor and apply a 1.0 value to it as a conservative estimate. The reader's attention is also drawn to note No. 3 in the previously referenced table that explains the impact this factor has when considering wind loads only from orthogonal directions. In this case the maximum value of (c_{dir}) must be applied for directions that have a bearing of ±45°, normal to the face of the building. The seasonal factor (c_{season}) is only used for temporary structures. It can be determined by using table NA.2 in Clause NA. 2.7 of the UK National Annex.

Coefficients for pressure due to wind

Once the basic wind velocity (v_b) has been determined, the pressure load from it can be deduced. This is described as the peak velocity pressure $(q_p(z))$ and is derived using a set of factors that reflect the effect of roughness of nearby terrain and the structure's proximity to the coast and how far it is located within a town. The full expression to derive the peak velocity pressure is as follows:

$$q_p(z) = c_o(z)\, c_e(z) c_{e,T}\, q_b$$

(Clause NA.2.17, equation NA.3a & 3b)

All of the above variables are defined below:

Topography of Terrain $c_o(z)$
In the Eurocode, surface topography, such as hills and valleys, is referred to as 'orography'. Such features have a significant impact on wind speed, making $c_o(z)$ a very important coefficient. Figure NA.2, Clause NA. 2.9 in the UK National Annex indicates a shaded region where structures that are within it are affected by terrain formations, such as hills and escarpments. It explains how the impact of these features affects the derivation of the wind load. If the structure lies outside the shaded area, the value of $c_o(z)$ is 1.0.

Proximity to Shoreline $c_e(z)$
Higher wind speeds are typically found near coastal areas. It is therefore important to allow for this when determining the wind pressure that is being applied to a structure. Figure NA.7 in the UK National Annex is used to determine the value of $c_e(z)$ which is the factor that is applied to the peak velocity wind pressure.

In order to use Figure NA.7 the displacement height (h_{dis}) must be known; this is dependent on the height of neighbouring buildings. Figure A.5 in Annex A.5 of Eurocode 1-1-4 describes how the displacement height is derived. Note that in the absence of accurate data regarding the heights of nearby structures, it is acceptable to assume a value of 3m for the (h_{dis}) variable in a town environment. When a structure is in the countryside, the value of (h_{dis}) is 0.

Structures Within Towns Exposure Modifier $(c_{e,T})$
Where buildings are located with a town, an exposure correction factor is applied $(c_{e,T})$.

The further the structure is from the edge of the town the more enclosed it becomes. This reduces the wind speed around the building and thus there is a corresponding drop in the applied pressure. Figure NA.8 in the UK National Annex is used to determine this factor. This figure is a chart that plots the displacement height (h_{dis}) subtracted from the height of the application of wind pressure force (z) is being considered.

Pressure due to Wind (q_b)
The base value of pressure due to wind (q_b) is defined in Eurocode 1-1-4, equation 4.10, which reads as follows:

$$q_b = 0.5\, p v_b^2$$

Where p is the density of air, and is defined as 1.226 kg/m³ in clause NA.2.18. It is therefore possible to reduce this equation to:

$$q_b = 0.613\, v_b^2$$

Determining Wind Action

Once the peak velocity pressure $(q_p(z))$ has been calculated, the wind load (or variable static action as they are classified in Eurocode 1-1-4) can be determined. This varies depending on what part of the structure is being assessed for wind loading.

The following coefficients are used to determine the magnitude of wind loads on sections of a building. They are reliant upon where in the structure of the wind loads are being assessed.

External Pressure Coefficient (C_{pe})
There are two forms of the external pressure coefficient (C_{pe}). $(C_{pe,1})$ applies to wind load onto discrete portions of the structure. Typically this is used for the design of cladding elements and is limited to an area no greater than 1m². Coefficient $(C_{pe,10})$ concerns larger portions of the structure and is defined in Clause 7.2.1 of Eurocode 1-1-4.

Table NA.4 in the UK Annex provides the values of these pressure coefficients. These are based on zones within vertical walls of a building that are defined in Figure 7.5 of Eurocode 1-1-4.

For elements of the roof structure to the building, the reader is referred to table NA.5 for flat roofs, NA.6a & NA.6b for mono-pitch roofs, NA.7a & NA.7b for duo-pitched roofs and NA.8 for hipped roofs. For the definition of the areas of the roof being considered by these tables, please see figures 7.6, 7.7, 7.8 & 7.9 in Eurocode 1-1-4.

Lack of Correlation Between Wind Pressures
There is normally a lack of correlation between wind pressures onto walls that are exposed to windward or leeward winds, compared with those that are within the prevailing wind. To address this, Eurocode 1-1-4 clause 7.2.2(3) provides a factor that is applied to the wind forces to certain vertical walls. This factor only applies to walls that are within the windward and leeward wind areas and not those within the prevailing wind area. In addition, the building's h/d aspect ratio must be less than 1 before the factor can be applied. Provided all of these conditions are met, all forces on vertical faces within windward and leeward wind exposed faces (e.g. areas D & E shown in Figures 1 and 2) can be multiplied by a factor of 0.85.

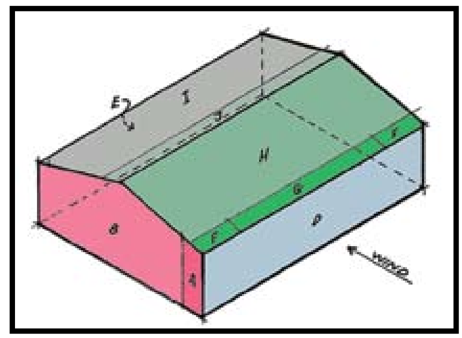


Figure 1 External pressure coefficients zones for a warehouse building with duo-pitched roof

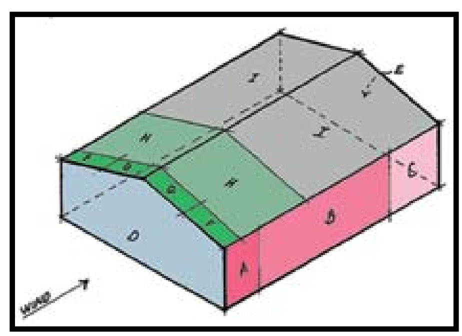


Figure 2 External pressure coefficients zones for a warehouse building with duo-pitched roof when gable end is facing the primary wind direction

Internal Pressure Coefficient (Cpi)
The internal pressure coefficient (C_{pi}) is sensitive to openings within the walls of the structure being considered for wind loads. Clause 7.2.9 of Eurocode 1-1-4 explains how the coefficient is derived by assessing the openings within the envelope to the structure. If there are openings on opposing sides of the structure that are greater than 30% of each surface area, then the structure should be treated as a canopy. It is at that point that clauses 7.3 and 7.4 of Eurocode 1-1-4 have to be followed.

Some structures have a face with a dominant opening. The term 'dominant' is defined as one face of a building having a single large opening. This opening can be equated to be the sum of smaller apertures within a face that equates to an area that is twice that of all other openings in the structure.

The value of the internal pressure should be taken as a proportion of the external pressure coefficient (C_{pe}) when a dominant face is present in the structure. If the openings in the dominant face are twice that of all other openings in the other faces of the structure, then the value of (C_{pi}) is 0.75_{pe}. When the number of openings is three times that of the remaining faces, the value of (C_{pi}) is $0.9C_{pe}$.

Where dominant faces are not present in a structure, Figure 7.13 of Eurocode 1-1-4 should be used in conjunction with table NA.9 that lists typical values of permeability. If there is a lack of any certainty regarding the structure's envelope, then the value of (C_{pi}) should be taken as either +0.2 or -0.3, whichever provides the more onerous result. For more details on this see Clause 7.2.9(6) of Eurocode 1-1-4.

To determine the wind loads both (C_{pi}) and (C_{pe}) are summed and applied to the peak velocity pressure $q_p\,(z)$ that is defined above, thus:

$$q_p\,(z)\,(C_{pe} - C_{pi})$$

This only applies to a section of the cladding to a structure and not the structure as a whole.

The Structural Factor $c_s c_d$
The final coefficients that are applied to the peak velocity pressure $q_p\,(z)$ to determine the action due to wind are the size and dynamic factors. This is known as the Structural Factor $(c_s c_d)$ and can be determined by using either clause 6.2 (1) in Eurocode 1-1-4 or clause NA.2.20 in the UK National Annex. The latter clause separates the size and dynamic components of the structural factor, as it requires the use of table NA.3 and Figure NA.9 to derive the value of c_s. It is acceptable to assume a value of 1.0 for the structural factor.

Net Pressure Coefficient
As well as considering discrete elements of the structure for wind loads, the National Annex allows for the generation of overall wind loads. These are derived using clause NA 2.27. There is a chart within this clause from which the net pressure coefficient can be read and $q_p\,(z)$ can be multiplied by.

Partial Factors

Partial factors for wind loads depend largely on how they are combined with other loads. If they are being considered in isolation, then the partial factor is 1.5 Q_k. If however, they are being considered in combination with other loads, then the ψ_0 combination factor must be applied to the base partial factor for the wind load. Thus:

$$1.35\,G_k + 1.5\,Q_{k,1} + (0.5_{\psi_0})\,1.5\,Q_{k,2}$$

Where $Q_{k,2}$ is the partial factor for the wind load and ψ_0 is the variable action factor when wind is combined with other loads. Note that the numbers stated adjacent to the factors in the above expression are their values.

Applied practice

The applicable codes of practice for the derivation of wind loads are as follows:

BS EN 1991-1-4 Eurocode 1: Actions on Structures – Part 1-4: General Actions – Wind actions

BS EN 1991-1-4 UK National Annex to Eurocode 1: Actions on Structures – Part 1-4: General Actions – Wind actions

PD 6688-1-4:2009 Background information to the National Annex to BS EN 1991-1-4 and additional guidance

Worked example

A 30m x 60m x 12m high at eaves, 15m at apex warehouse is to be constructed, 35 km south of Preston. Figure 3 shows the site layout and highlights the location of the building being considered (green):

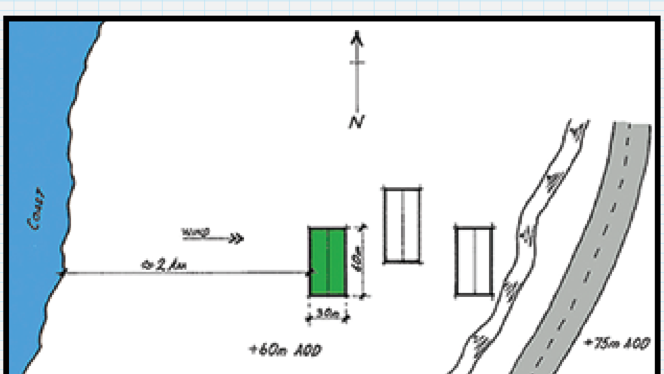


Figure 3 – **Worked example site plan**

Determine the wind loads on all faces of the building due to wind blowing from the west.

First the fundamental basic wind velocity is calculated:

$$V_{b,0} = V_{b,map}\; C_{alt}\; C_{dir}\; C_{season}$$

$V_{b,map} = 23\,m/s$ (FIGURE NA.1)

$C_{alt} \Rightarrow h < b$ (FIGURE 7.4) $\therefore z_e = 12m$

$\therefore C_{alt} = 1 + 0.001 \times 60m \times \left(\frac{10}{12m}\right)^{0.2} = 1.06$

$C_{dir} \Rightarrow$ WIND DIRECTION IS WITHIN 45° OF NORMAL TO FACE $\therefore C_{dir} = 1.0$ (TABLE NA.1)

$C_{season} \Rightarrow$ NOT RELEVANT AS STRUCTURE IS PERMANENT

$$\therefore V_{b,0} = 23\,m/s \times 1.06 \times 1.0 = \underline{24.4\,m/s}$$

Worked example continued...

Then the peak velocity pressure is calculated:

$q_p(z) = C_e(z)\, C_{e,T}\, q_b$

$C_e(z) = 2.75$ (FIGURE NA.7)

$C_{e,T} \Rightarrow H_{dis} = 12m$, STRUCTURE IS OUTSIDE OF TOWN

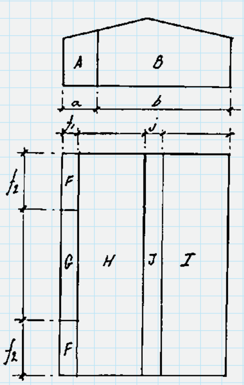
$C_{e,T} = 1.0$ (FIGURE NA.8)

$q_b = 0.613 \times (24.4\,m/s)^2 = 365\,N/m^2 = 0.37\,kN/m^2$

$\therefore q_p(z) = 2.75 \times 1.0 \times 0.37\,kN/m^2 = 1.02\,kN/m^2$

Now that the base wind load has been determined, the areas over which each differing coefficient for external pressures is applied are defined for the structure:

COEFFICIENT OF EXTERNAL PRESSURES FOR AREAS OF THE FAÇADE $> 1.0m^2 = C_{pe,10}$
AREAS OF VARYING VALUES OF $C_{pe,10}$ ARE DEFINED AS FOLLOWS:
IN WINDWARD DIRECTION:



USING FIGURE 7.5, THE AREAS DIFFERING VALUES OF $C_{pe,10}$ ARE:

$e = 2 \times h = 2 \times 15m = 30m$

$\therefore a = \frac{30m}{5} = 6m$

$b = 30m - 6m = 24m$

USING FIGURE 7.8, THE AREAS ON THE DUO PITCHED ROOF WITH DIFFERING VALUES OF $C_{pe,10}$ ARE:

$f_1 = \frac{30m}{10} = 3m$

$f_2 = \frac{30m}{4} = 7.5m$

$j = \frac{30m}{10} = 3m$

$C_{pe,10}$ MAGNITUDES AS FOLLOWS:

FROM TABLE NA.4: $\frac{h}{d} = \frac{15m}{30m} = 0.5$

$\therefore A = -1.2,\ B = -0.8,\ D = +0.75\ \&\ E = -0.4$

FOR THE ROOF, THE VALUES OF $C_{pe,10}$ ARE:
ROOF PITCH = 11.3°, REFERRING TO TABLE NA.7a

$\therefore F = -1.5$ OR $+0.1$, $G = -1.0$ OR $+0.1$, $H = -0.5$ OR $+0.1$, $I = -0.5$ OR -0.5 & $J = -1.1$ OR -1.1

The internal pressure coefficient is then determined, by checking for the presence of a dominant opening in any face of the building. It has been assumed that the openings are not blocked in this calculation:

DETERMINE PRESENCE OF DOMINANT FACE:

AREA OF DOORWAY AT GABLE END OF BUILDING $\Rightarrow 20m \times 4m = 80m^2$

OPENINGS IN ALL OTHER FACES $= 2m \times 4m \times 4N^o \times 2N^o$ WALLS $= 64m^2$

CHECK FOR DOMINANT FACE: $\frac{80m^2}{64m^2} < 2$ $\therefore$ NO DOMINANT FACE/OPENING

$\therefore C_{pi} = +0.2$ OR -0.3

The last factors to be determined concern the structural form and lack of wind pressure correlation to vertical surfaces.

STRUCTURAL FACTOR $C_s C_d = 1.0$, BUILDING IS 15m HIGH

$\frac{h}{d}$ RATIO $= \frac{15m}{30m} = 0.5 < 1.0$ $\therefore$ 0.85 FACTOR APPLIED TO WINDWARD FACING VERTICAL SURFACE IE FACE 'D'.

The net wind pressure coefficient is determined based on clause NA 2.27:

OVERALL WIND LOAD COEFFICIENT : 0.95 (CLAUSE NA.2.27)

Now that all factors have been defined, the characteristic wind load can be determined for the structure, thus:

AREA 'A' $= 1.02 \times (-1.2 - 0.2) \times 1.0 = -1.4\,kN/m^2$

AREA 'B' $= 1.02 \times (-0.8 - 0.2) \times 1.0 = -0.9\,kN/m^2$

AREA 'D' $= 1.02 \times (0.75 - (-0.3)) \times 1.0 \times 0.85 = 0.9\,kN/m^2$

AREA 'E' $= 1.02 \times (-0.4 - 0.2) \times 1.0 \times 0.85 = -0.5\,kN/m^2$

AREA 'F' $= 1.02 \times (-1.5 - 0.2) \times 1.0 = -1.7\,kN/m^2$

AREA 'G' $= 1.02 \times (-1.0 - 0.2) \times 1.0 = -1.2\,kN/m^2$

AREA 'H' $= 1.02 \times (-0.5 - 0.2) \times 1.0 = -0.7\,kN/m^2$

AREA 'I' $= 1.02 \times (-0.5 - 0.2) \times 1.0 = -0.7\,kN/m^2$

AREA 'J' $= 1.02 \times (-1.1 - 0.2) \times 1.0 = -1.3\,kN/m^2$

OVERALL NET WIND PRESSURE $= 1.02\,kN/m^2 \times 0.95 = \underline{1.0\,kN/m^2}$

Glossary and further reading

Action – An applied load, due to either a direct application or as a consequence of an indirect effect such as thermal expansion of the structure.

Characteristic load – A base load that has not had any partial factors applied to it.

Partial factor – A factor that is applied to characteristic loads when carrying out design of structures and the elements they are constructed from.

Variable action – A load that is not static, such as wind pressure.

National Annex – A part of the Eurocode that has been written specifically for a particular region.

Further Reading

Manual for the design of building structures to Eurocode 1 and Basis of Structural Design – Institution of Structural Engineers – April 2010

Web resources

For more information on this subject, please visit the Institution's website: **http://www.istructe.org/resources-centre/library**

The Institution of Structural Engineers

StructuralAwards2012

www.structuralawards.org

NOW OPEN FOR ENTRIES

Submit your project now for the structural engineering and construction industry's premier awards. With 11 categories to choose from covering all types of structure, there's one for your project.

Visit www.structuralawards.org for more information.

Deadline for entries is THURSDAY 19 APRIL 2012.

The Institution of Structural Engineers

A GOOD STRUCTURAL ENGINEER HAS VALUE WAY BEYOND HIS COST TO HIS CLIENT.

How can that simple message be relayed with the pressures on everyone looking at the bottom line rather than what is included within that?

To enter the Kenneth Severn Award, please submit a paper titled "Cost vs Value" of no more than 4 sides of A4 including images to **louise.clifton@istructe.org** by Friday 30 March 2012. Points will be awarded for originality, the value of the paper to the structural engineering profession and clarity of presentation.

The winning paper will be:

- Published in The Structural Engineer (subject to appropriate review)
- The author will receive a prize of £500
- The author will receive the Kenneth Severn Diploma

Entrants for the Kenneth Severn Award must be 28 years of age or under on 1 January 2012. Entry is NOT restricted to membership of the Institution.

For more information visit: **www.istructe.org**

Please ensure that you include the following details with your entry: full name, date of birth, address, name of employer/university, daytime telephone number.

Registered with the Charity Commission for England and Wales No. 233392 and in Scotland No. SC038263