

## Theoretical Background

3D Wind Loading

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## Introduction

This document briefly explains the theoretical background along with the scope and limitation of automatic wind load calculation within SCIA Engineer. It does not deal with any user related option of the software for wind load generation. Kindly refer to the help file for the same.

The software module is capable of generating wind loads (actions) on buildings modelled in 3D space using 2D members. It is developed based on the codes of practice and focused on the practical design.

The procedure adopted in this module is that wind loads are obtained from the wind speeds and pressure coefficients for each wind direction.

The basic wind speed is obtained for a particular site where the building is to be constructed. It then refined by many factors like influence of altitude, factor for wind direction, factor for seasons in which the building would stay, type of structure, factor for ground roughness, factor for orography, influence of neighbouring structure, terrain condition, etc.. After these corrections, the wind velocity and air density is used to compute the pressure based on the Bernoulli's equation.

Obtaining the net pressure coefficient involves finding two coefficients; they are external and internal pressure coefficients. External pressure coefficient is based on scaling length derived from building dimensions. There are some gaps in the code of practice to obtain the scaling length. This complex part is most likely successfully implemented in the software module with the help of levelling concepts and corrections based on guidance from the [referance<sup>2</sup>](#).

The net pressure is applied as surface load on 2D members in the normal direction. In calculating the static wind load, the dynamic effects of wind are accounted through factors defined in the code of practice.

The main objective of the module is to deliver the wind loads for building shapes addressed in the code of practice for each wind direction. The scope and limitations of the calculation are discussed in the below chapter.

## Scope

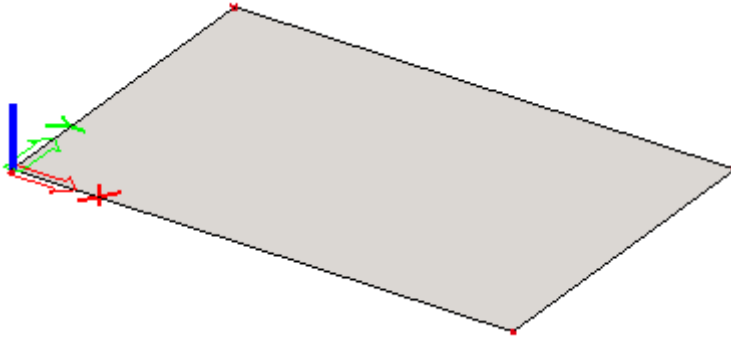
The scope of the module is limited to the following:

1. The calculations work according to the following code of practices:
  - I. EN 1991-1-4: 2005 [reference](#)<sup>3</sup>
    - Default Eurocode parameters (for use with national annex other than UK)
    - UK national annex parameters
  - II. ASCE 7-05 [reference](#)<sup>4</sup>
2. The calculations are applicable for land-based building structures based on pressure coefficients. Other structure like chimney, bridges etc., are out of scope.
3. Only closed buildings are supported, which means all adjacent wall/roof must be connected without gap.
4. Openings defined in 2D member are ignored in scaling length calculation. Openings are dealt by the use of internal pressure coefficients.
5. Frictional (tangential) loads are not considered.
6. The building is assessed using single wind pressure curve. External pressure coefficients are evaluated for four orthogonal wind directions. This is used along with the pressure curve to generate the wind loads.
7. ASCE recommends three procedures for estimating wind loads.
  - Simplified method
  - Analytical method
  - Wind tunnel methodAnalytical procedure – all heights method is available from 2013 version onwards.
8. ASCE has guidance for “main wind force resisting system” and “component and cladding”. The later one is out of current scope.

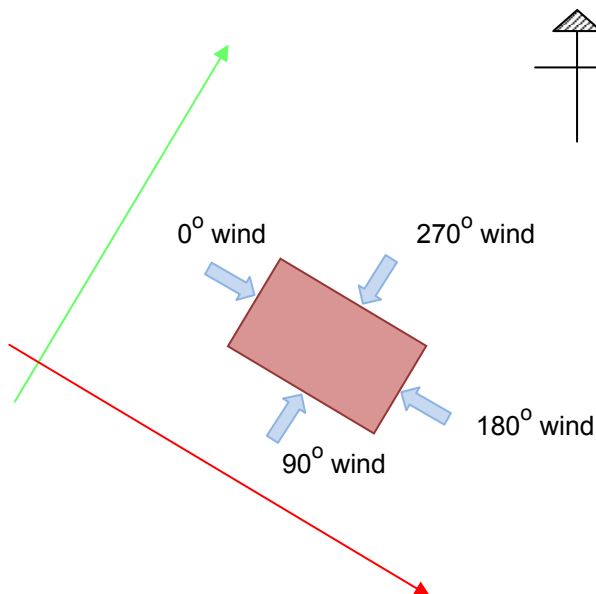
## Terms and definition

**Ground level:** By default the global XY plane in SCIA Engineer denotes the ground / terrain level. If the national code and national annex are EC-EN, user has a choice to offset the ground level by specifying a value of *zmin* in wind data.

Wind load will be applied only to part of the building defined above this ground level.

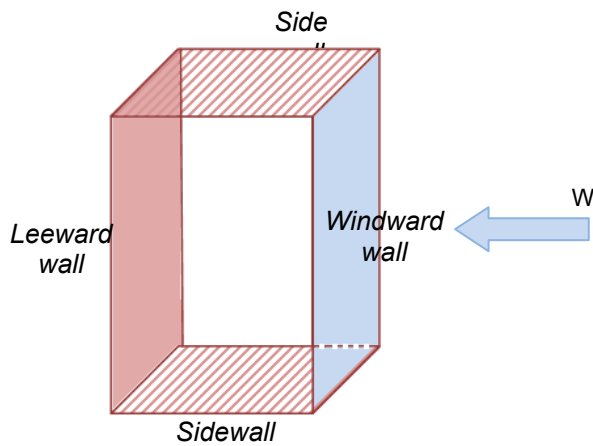
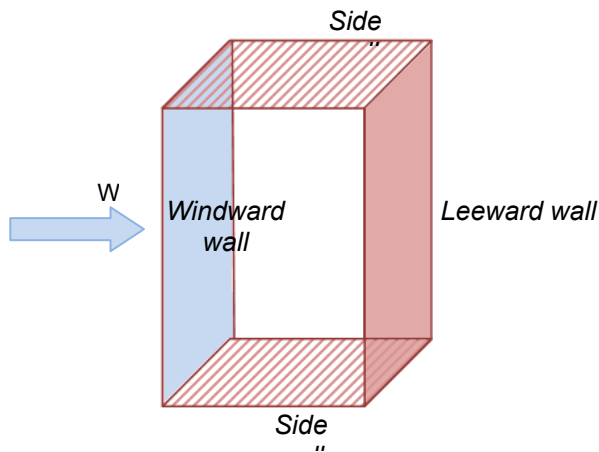


**Wind direction:** Wind direction denotes the orthogonal wind direction to the geographic north is mapped to orthogonal directions as shown below.



Wind direction angle is angle about the Z axis from global X axis vector to wind direction vector. If the wind direction is zero, then wind is blowing along X axis.

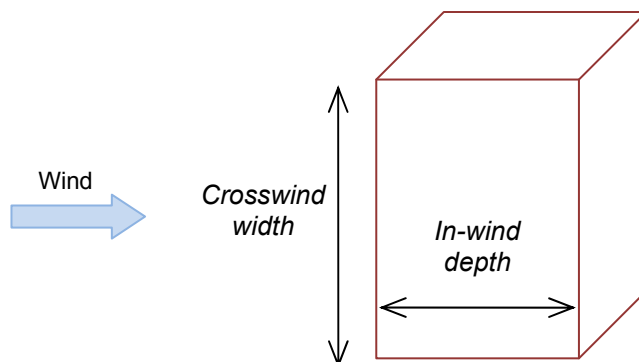
**Windward, Leeward and Sidewall:** Each wall of a building facing the wind is classified as windward, leeward or sidewall. Any change in wind direction requires re-identification of the windward, leeward and sidewall. The following figures show how change in wind flow direction affects the identification of windward, leeward and sidewall faces.



TBC - Explain how we deal with non rectangular faces

**Crosswind width and In-wind depth:** These denote the building dimension across the wind and along the wind and vary for each wind direction. See figure below.

When the plan of the building varies with height crosswind width is computed at each level for scaling length computation. Refer to section 6.1.2.2 for explanation of the same.



**Wall and roof:** 2D element which has an inclination of  $\pm 10$  degrees in the vertical plane is treated as a wall. Otherwise it is taken as roof.

**Roof type:** The roof type (flat or pitched) input by the user will be verified against those computed by the program and error message displayed if required.

The identification of roof type is done by checking the angle between the normal vector of the roof and the global Z-axis (vertical axis). This angle will be greater than zero for pitched roof (a tolerance of  $\pm 5$  deg is allowed).

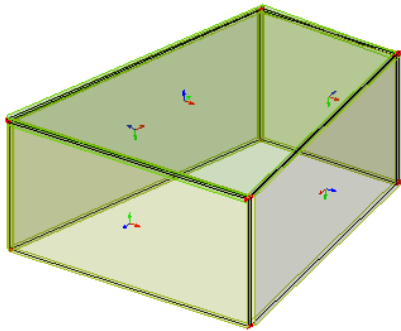


## Do's and don'ts

### Do'S

1. For automatic wind load generation the outer surface of the building should be covered with 2D elements (plate/wall/panel) representing wall and roof. These 2D elements should be assigned wind data by selecting the property '3D wind'.
2. The local axis of the 2D elements should be such that the normal vector is pointing away the building. In the picture below the blue arrows denote the normal vector shown pointing away from the building which is correct.

This is essential in order to get the wind loads in the correct direction. If the normal vector direction is incorrect the 'Swap orientation' property is used to get them right.



3. The model created should be completely closed building. Open buildings will produce error message as they are not handled by the software.
4. The face which has an inclination of more than  $\pm 10$  degree, is considered as roof. Declaring the face as wall will produce an error message.
- 
5. The roof with an angle equal to 5 degree, then consider it as pitched roof. Declaring the roof as 'flat roof' would produce a error message.

### Don'ts

1. Terrain level should not be less than the minimum z of the building.
2. Pitched roof should not be assigned as Flat roof.
3. Do not assign wind data for the face which is present inside the building.

# Wind velocity and pressure

## EN 1991-1-4

TBC -Intro

### Basic wind speed

Basic wind speed,  $V_b$  is determined in accordance to cl.4.2 of EN 1991-1-4.

$$V_b = C_{dir} * C_{season} * C_{prob} * V_{b,0} \text{ (cl.4.1 of EN 1991-1-4)}$$

$C_{dir}$  - Directional factor [cl.4.2(2)P NOTE 2]

$C_{season}$  - Season factor [cl.4.2(2)P NOTE 3]

$C_{prob}$  – Probability factor [cl.4.2(2)P NOTE 4]

$$C_{prob} = [(1 - K * \ln(-\ln(1-p)))/(1 - K * \ln(-\ln(0.98)))]^n \text{ [cl.4.2 of EN 1991-1-4]}$$

$p$  – Probability of annual exceedence in percentage

$K$  – Shape parameter depending on the coefficient of variation of the extreme-value distribution

$n$  - Exponent

$V_{b,0}$  - Fundamental value of the basic wind velocity [cl.4.2(2)P]

$$V_{b,0} = V_{b,map} * C_{alt} \text{ (cl.NA.1 of UK NA to EN 1991-1-4)}$$

$V_{b,map}$  - Fundamental basic wind velocity before altitude correction [eq.NA.1]

$$C_{alt} = 1 + 0.001 * A \text{ for } z \leq 10\text{m [eq.NA.2a]}$$

$$C_{alt} = 1 + 0.001 * A * (10/z)^{0.2} \text{ for } z > 10\text{m [eq.NA.2b]}$$

$C_{alt}$  – Altitude factor [cl.NA.2.5 of UK NA to EN 1991-1-4]

$z$  - Height of the part above ground in m

OR

$z$  - Altitude of the upwind base of the orography feature for significant orography as defined in figure NA.2 in UK NA to EN 1991-1-4

$A$  - Site altitude in m

The fundamental value of the basic wind velocity is the characteristic 10 minutes mean wind velocity, **irrespective of wind direction and time of year**, at 10 m above ground level in open country terrain with low vegetation such as grass and isolated obstacles with separations of at least 20 obstacle heights.

For default EN this value is to be input by the user.

For UK national annex, it is calculated as per the expression shown above. A map is provided as an aid to determine these values based on the site location through CADS website <http://wind.cadsglobal.net/>.  $V_{b,map}$  and site altitude can be directly read from the webpage.

Altitude factor for UK national annex is to be calculated and input by the user.

Directional factor is input by the user for both EN default and UK national annex. Since only a single wind pressure curve is used to access the building, it will be appropriate to input the worst wind direction producing maximum value of directional factor. Conservatively default value of 1.0 can be used.

Season factor is input by the user for both EN default and UK national annex. For permanent structures, default value of 1.0 can be used.

Probability factor is calculated by the software based on the probability of annual exceedence, shape factor (K) and exponent (n) inputs. Recommended values of 0.2 and 0.5 are set as defaults for 'K' and 'n'.

## Mean wind velocity (variation with height)

Mean wind velocity is determined in accordance to cl.4.3 of EN 1991-1-4. It is calculated over a range from 0m up to the height of the building.

$$V_m(z) = C_r(z) * C_o(z) * V_b$$

$C_r(z)$  - Roughness factor (cl.4.3.2)

$C_o(z)$  - Orography factor (cl.4.3.3)

Roughness factor for default EN is calculated using the procedure described in cl.4.3.2 of EN 1991-1-4 using the terrain factor ( $k_r$ ), roughness length ( $z_0$ ) and minimum height ( $z_{min}$ ).

Roughness factor for UK national annex is computed based on figure NA.3 and NA.4 using the simplified terrain category, distance upwind to shoreline and distance inside town terrain input by the user.

Terrain category in EN 1991-1-4	Terrain categories in UK NA to EN 1991-1-4
0	Sea
I & II	Country terrain
III & IV	Town terrain

Orography denotes the presence of hills, cliffs etc. Orography factor is input by the user. Default value of 1.0 can be used when the effect of orography is insignificant. See figure NA.2 in UK NA to EN 1991-1-4 for definition of significant orography. Otherwise it should be manually evaluated as recommended in Annex A.3 of EN 1991-1-4: 2005.

Influence of neighboring structures on the mean wind velocity (cl.4.3.4 and A.4) is not considered.

Effect of closely spaced buildings and obstacles (cl.4.3.5 and A.5) is considered in UK national annex only.

## Wind turbulence

Wind turbulence is accounted for in the computation of peak velocity pressure.

For EN default, turbulence intensity is calculated in accordance to cl.4.4

For UK national annex the turbulence factor is calculated using figure NA.6 and figure NA.5 of UK NA to EN 1991-1-4. It is used in the computation of peak velocity pressure when orography is significant and  $z > 50m$ .

## Peak velocity pressure

Peak velocity pressure is determined in accordance to cl.4.5 of EN 1991-1-4. It is calculated over a range of height from 0m up to the height of the building. For UK national annex it is possible to view and edit the calculated values of peak velocity pressure through the library.

For UK national annex, it is evaluated using expression NA.3a and NA.3b depending on the terrain category or using expressions NA.4a and NA.4b when orography is significant.

The exposure factor ( $C_e$ ) and the size factor ( $C_s$ ) used in the calculation of peak velocity pressure is obtained from Figure NA.7, NA.8 and Table NA.3.

## IBC - ASCE/SEI 7-05

### Method 1 – Simplified procedure (section 6.4 of ASCE 7-05)

**\*Simplified procedure is not available with the current version**

This procedure is to be used for buildings which meet conditions set out in cl.6.4.1.1 of ASCE 7-05. No explicit checking will be done by the program for any of those conditions.

In this method user will model the wind surface as a box and specify the value of mean roof height.

The simplified design wind pressure is obtained from figure 6-2. This represents the net pressure (sum of internal and external) for exposure 'B' at height of 30ft and importance factor of 1.0. This value is then adjusted for the actual importance factor, building height and exposure using expression 6-1.

The importance factor for the site is determined based on building and structure categories listed in Table 1-1. The adjustment factor for building height and exposure is determined from figure 6.2 for the mean roof height and calculated exposure category using section 6.5.5.

The simplified design wind pressure is applied to the horizontal and vertical projection of the building surfaces as shown in figure 6.2.

### Method 2 – Analytical procedure (section 6.5 of ASCE 7-05)

The scope and limitation set out in section 6.5.1 and 6.5.2 apply for this method. The design procedure set out in section 6.5.3 is followed. The building is analysed for the four orthogonal wind directions. Design wind pressure is determined based on the method specified by the user. For 'Rigid building of all height' method, expression 6-17 is used and for 'low wise method' expression 6-18 is adopted.

## Dimensions

### Building dimension and orientation

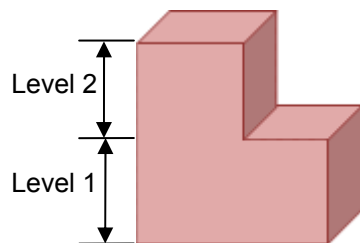
Building height is measured along the z axis from the ground level.

### Scaling length

The following section explains the computation of the scaling length which is used in zoning the side wall for the wind direction being considered.

#### 1.1.1.1 Levels

The software is smart enough to identify the levels internally based on change in plan along the height of the building. For example, see below front elevation of the building which is divided into two levels as the plan of the second level is different from the bottom level.



Front elevation of the building with levels

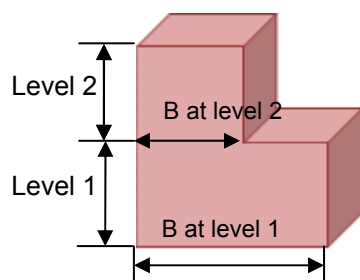
In zoning of side wall of such a building the crosswind breadth (B) is determined at every level and the height is based on the nearest windward face.

The software computes the height of the connected windward faces across the levels for determining the scaling length.

TBC - Show other examples - inclined wall

#### 1.1.1.2 Crosswind breadth

Crosswind breadth (B): It is calculated for each level.



Front elevation of the building showing the crosswind width

### 1.1.1.3 Height of the building

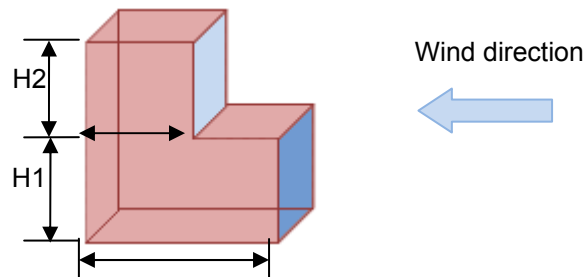
The figure below explains the height used in scaling length calculation. The height,  $h$  is taken as the sum of heights of the walls across levels which are coplanar to the nearest windward wall.

Case 1: Wind from right

In the figure below windward walls are shaded in blue. Windward wall in level 1 is not in the same plane as windward wall in level 2. Hence the height of the individual walls is used in scaling length computation.

For level 1,  $h = H1$  and  $b = B1$

For level 2,  $h = H2$  and  $b = B2$



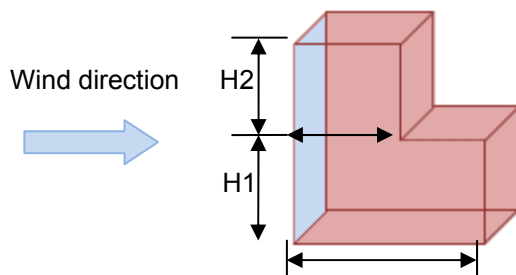
Front elevation of the building showing the windward height

Case 2: Wind from left

For the same building, when wind blows from other end, windward wall in level 1 is connected to and in the same plane as windward wall in level 2. Hence the height of the building for scaling length of both the levels is  $H1+H2$ .

For level 1,  $h = H1+H2$  and  $b = B1$

For level 2,  $h = H2+H2$  and  $b = B2$



### 6.1.4.1.2 EN 1991-1-4

There are no special provisions for re-entrant corner and recessed bay. They are considered as regular buildings.

### Pressure coefficient

TBC - Division of buildings by parts for over all loads

### External pressure coefficients

#### EN 1991-1-4

The building is assessed for four orthogonal wind directions. Each wall is classified as windward, leeward or sidewall for each wind direction as explained in section 3. Scaling

length is computed for each level as explained in section 6.1. Using these external pressure zones and coefficients are computed referring to the appropriate tables and figures from the relevant standard.

EN 1991-1-4 tables are used for default EN and BS 6399-2 tables are used for UK national annex.

### **Cpe,10 Vs Cpe,1**

The area of the wall or roof determines the value to be used. If the area is less than or equal to 1.0 m<sup>2</sup> then Cpe,1 values are used else Cpe,10 values are used.

### **Wall faces (windward, leeward and sidewall)**

The ratio of windward wall height (h) and in-wind depth (D) is used to read the external coefficient value.

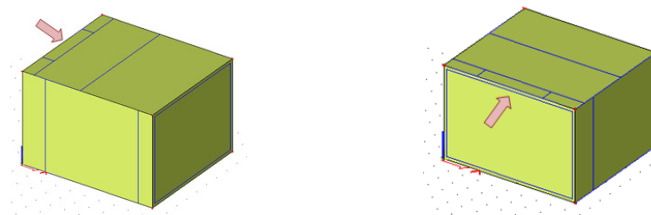
Table 7.1 of EN 1991-1-4 is used when national annex is EN default and table 5 of BS 6399-2 is used for UK national annex.

### **Flat roof**

Flat roof type is assumed to be sharp eaves.

EN default: Cpe values obtained from table 7.2 and the zones are generated in accordance to figure 7.6 of EN 1991-1-4.

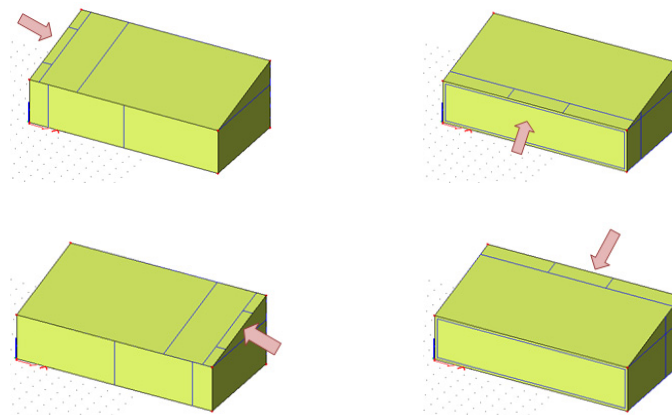
UK national annex: Cpe values are obtained from table 8 and zones generated in accordance to figure 16 of BS 6399-2.



### **Mono pitch roof**

Cpe values obtained from table 7.3a and table 7.3b and the zones are generated in accordance to figure 7.7 of EN 1991-1-4.

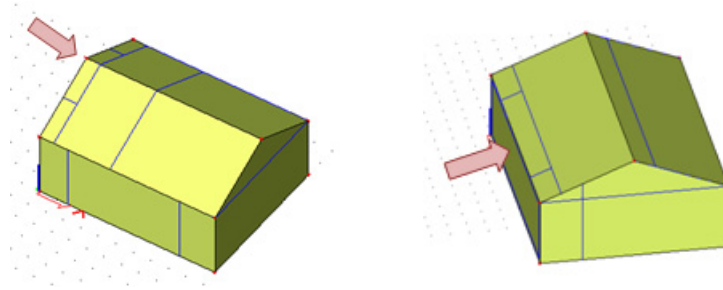
UK national annex: Cpe values are obtained from table 9 and zones generated in accordance to figure 19 of BS 6399-2.



## Duo pitch roof

Cpe values are obtained from Table 7.4a, Table 7.4b and the zones generated in accordance to figure 7.8 of EN 1991-1-4.

UK national annex: Cpe values are obtained from table 10 and zones generated in accordance to figure 20 of BS 6399-2.

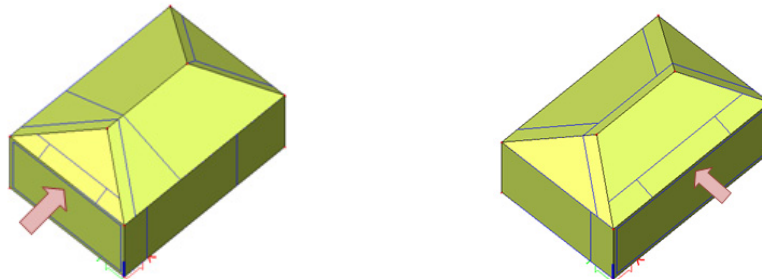


## Hipped roof

Cpe values are obtained from Table 7.5 and the zones generated in accordance to figure 7.9 of EN 1991-1-4.

UK national annex: Cpe values are obtained from table 11 and zones generated in accordance to figure 21 of BS 6399-2.

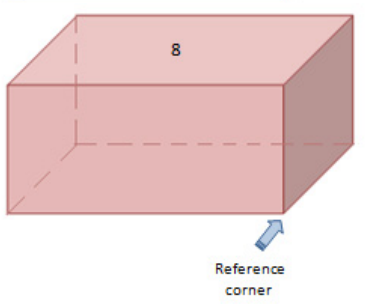
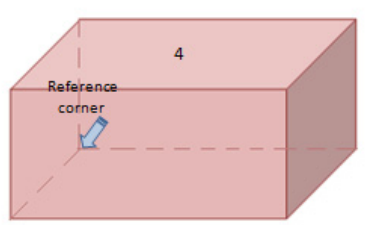
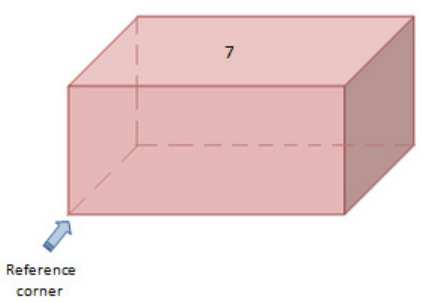
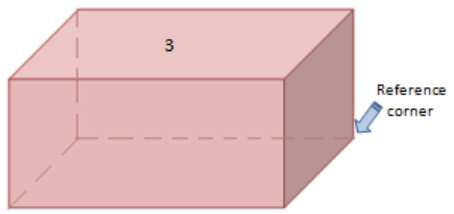
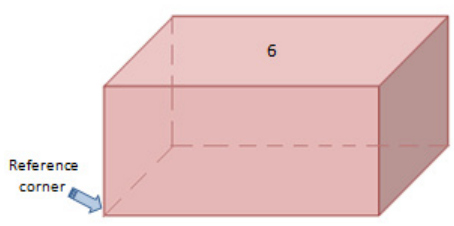
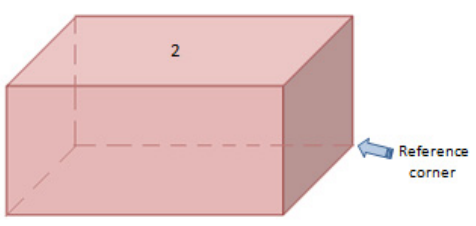
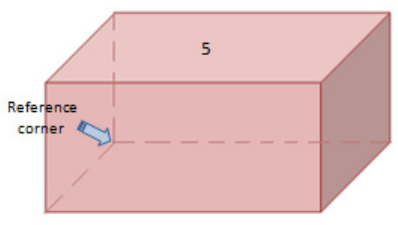
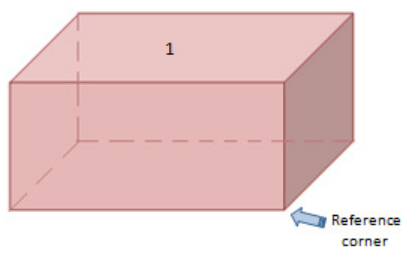
Other roof types are out of scope of this calculation.



## IBC - ASCE 7-05

Simplified procedure directly gives the net pressure values from figure 6-2 which is adjusted for the actual importance factor, building height and exposure. In this method, the program by default will generate 8 load cases, four wind directions times two reference corners. If the roof angle is between 25 to 45 degrees, further 8 load cases will be created for 'Load case 2' value in figure 6-2. This is illustrated in the below picture. The blue arrows mark the wind direction and the reference corner with respect to which the external pressure zones will be created.





In case of analytical procedure, the external pressure coefficients are read from fig 6-6 or 6-8 for 'rigid buildings of all height' and fig 6-10 for 'low-rise building'.

Similar to the simplified procedure, this method can generate maximum of 32 wind load cases. 16 basic load cases and 16 torsional load cases considering 4 wind directions, 2 reference corners, 2 load cases for roof angle between 25 to 45 degrees.

In order to allow the load combination for 'All height' method (figure 6-9)

## Manual correction

Manual corrections of these zone geometry and coefficients are possible as detailed in Scia Engineer help.

## Internal pressure coefficients

Internal pressure coefficients are directly input by the user. Two values (pressure and suction) can be specified for each wind direction.

	Direction	+CPE, +CPI	+CPE, -CPI	-CPE, +CPI	-CPE, -CPI	+CPI	-CPI
1	0	☒	☒	☒	☒	0.20	-0.30
2	90	☒	☒	☒	☒	0.20	-0.30
3	180	☒	☒	☒	☒	0.20	-0.30
4	270	☒	☒	☒	☒	0.20	-0.30

Calculation method: Standard

Include torsional load case

OK Cancel

## Net pressure

### EN 1991-1-4

Applied wind load (F) is based on the net pressure which is calculated using expressions 5.1, 5.2, 5.5 and 5.6 of EN 1991-1-4: 2005

$$F = qp * (CsCd * Cpe - Cpi)$$

Where,

F is the net pressure representing the applied wind load in kN/m<sup>2</sup>

qp is the peak velocity pressure

Cpe is the external pressure coefficient

Cpi is the internal pressure coefficient

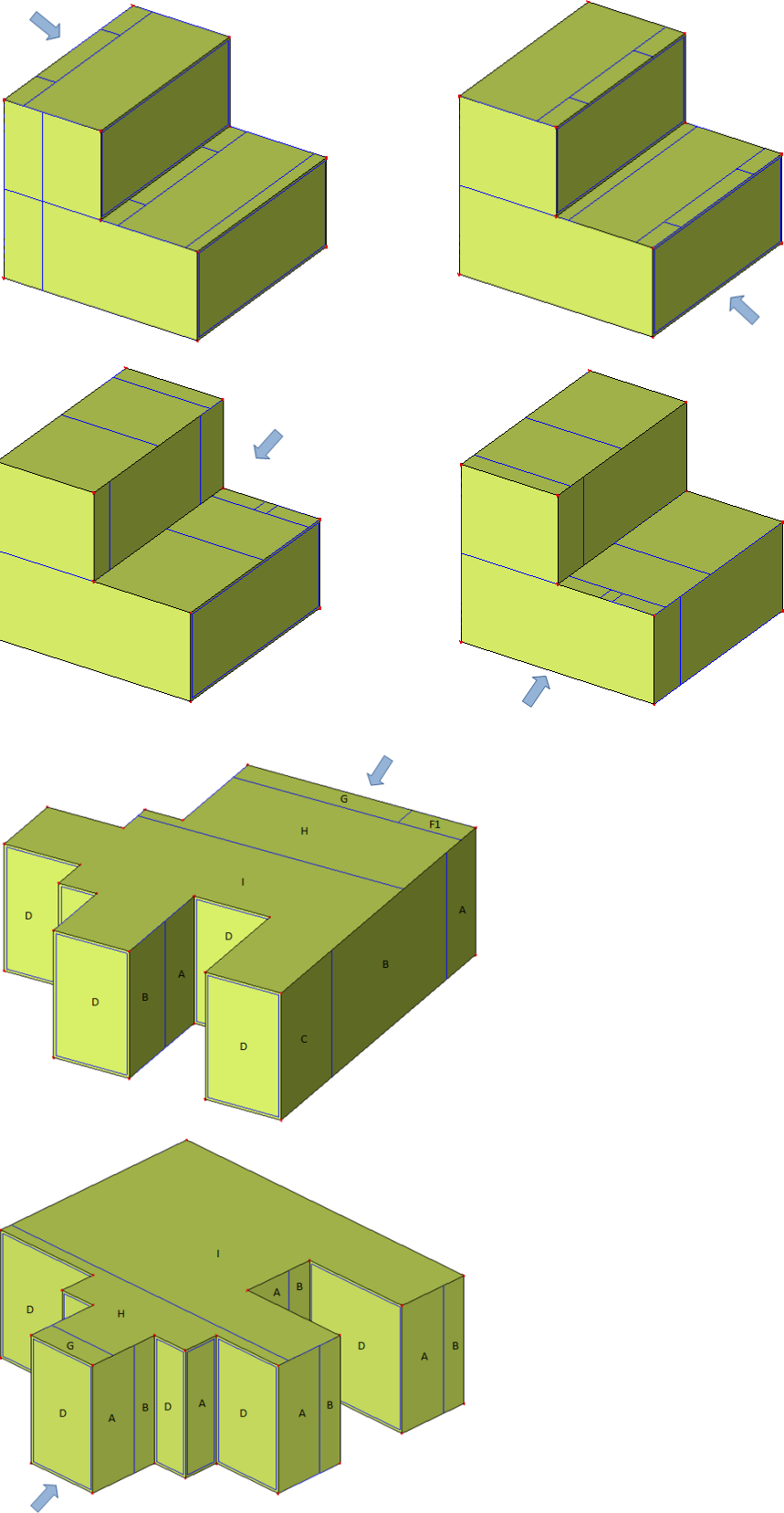
CsCd is the structural factor assumed to be 1.0

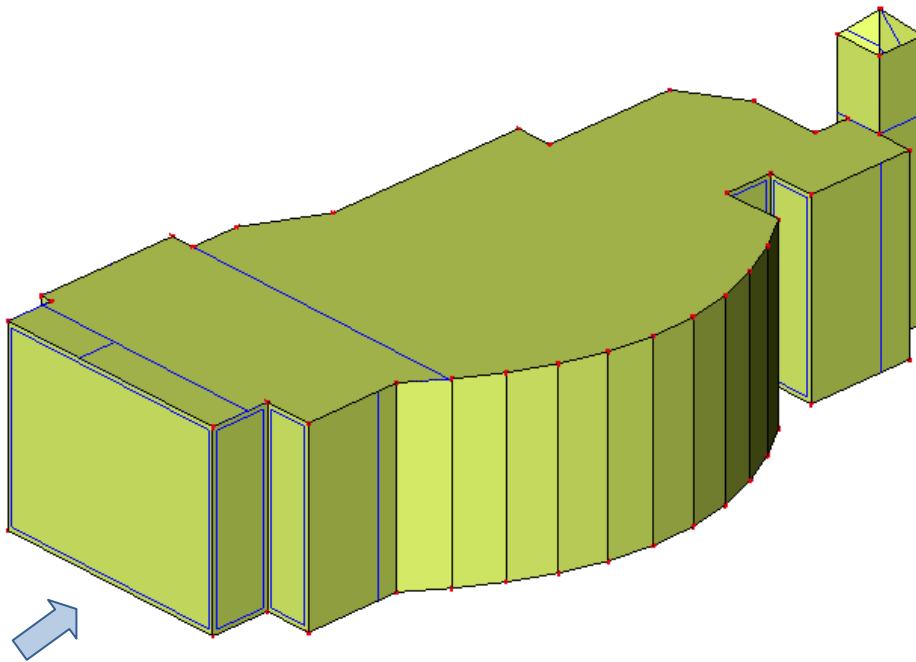
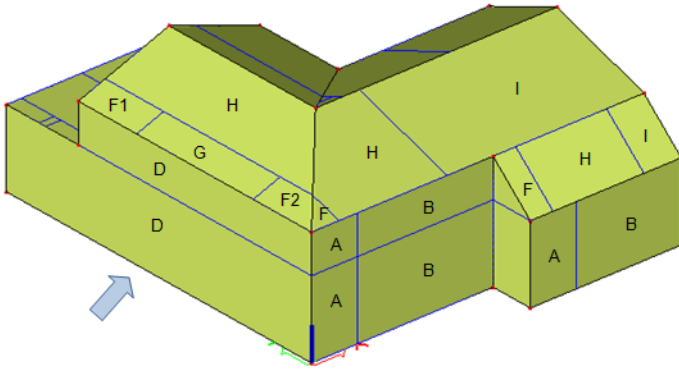
Uniform velocity pressure is assumed over each horizontal strip in accordance to figure 7.4 of EN 1991-1-4 based on the reference height. If a wall is in between the boundary of two strips then upper bound value is used.

### **IBC - ASCE/SEI 7-05**

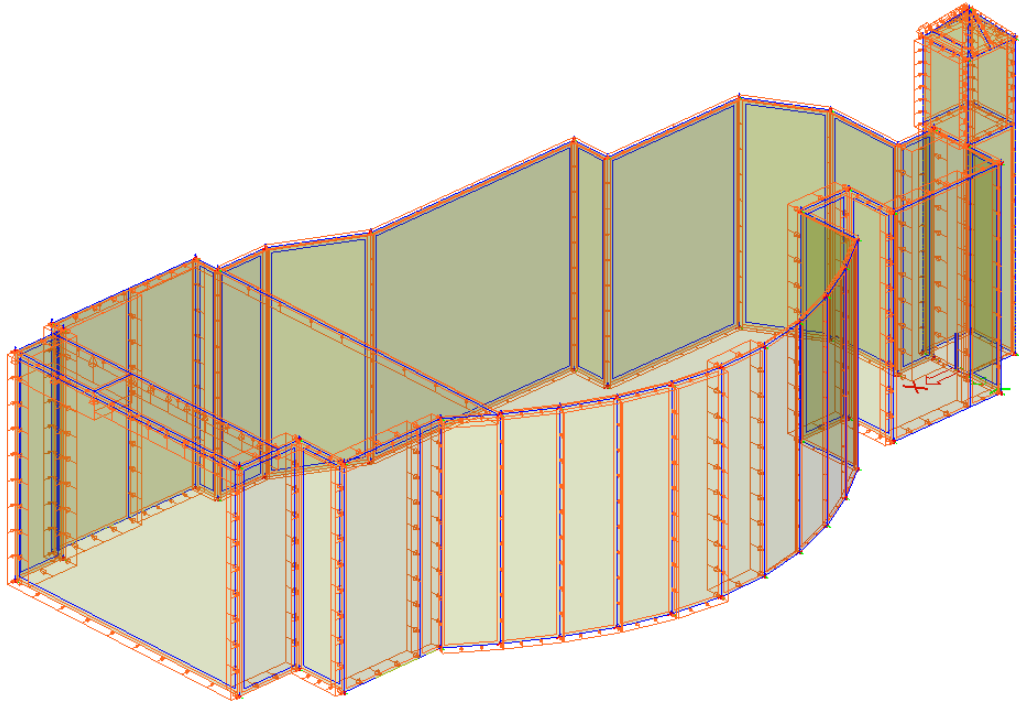
The design wind pressure calculated from figure 6-6, 6-8 or 6-10 is applied as wind load on the structure.

External pressure zones generated for few buildings shapes





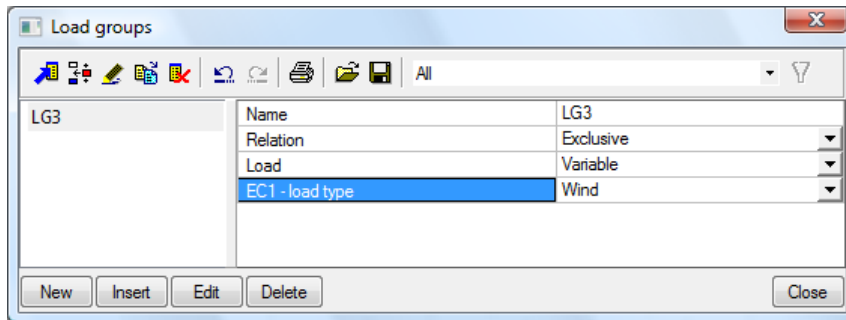
Zones on a complex building model



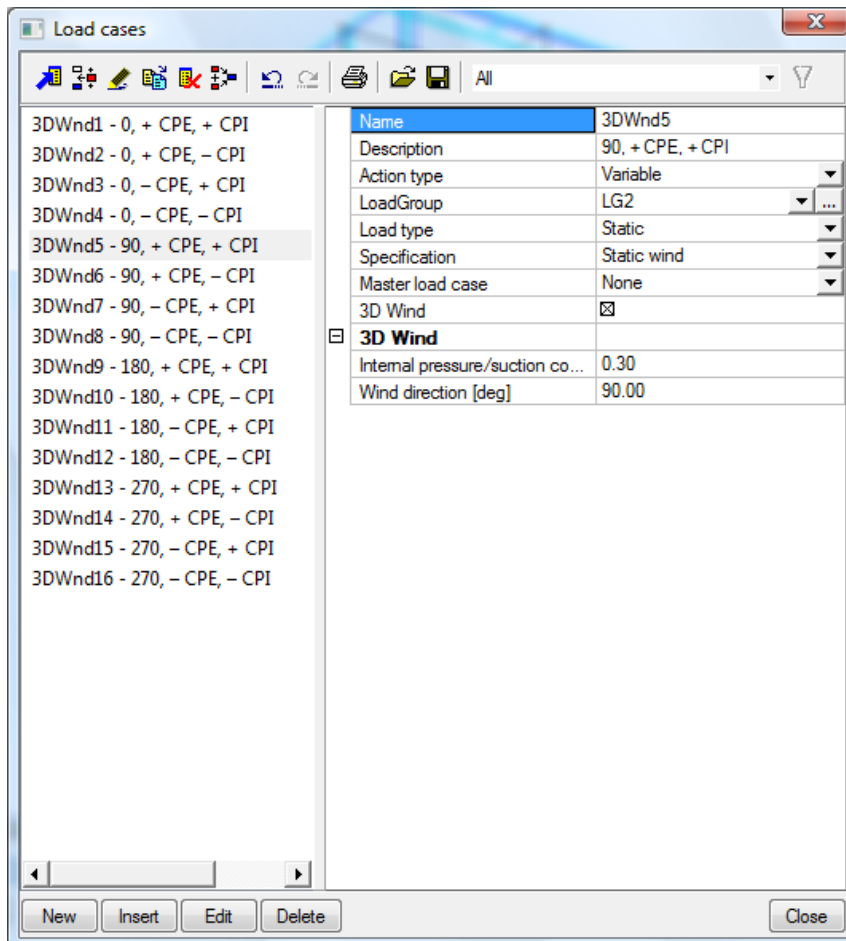
Generated wind loads on the building after analysis

## Actions and combinations

The load group and load cases for wind load are automatically generated by the program. This can be used for automatic code based load combination generation without modification.



16 load cases are generated by default, catering for 4 wind directions, positive and negative external and internal pressure coefficient combinations.



In the implementation of IBC code there are few limitations in the creation of torsional load cases.


For analytical procedure: rigid buildings of all heights, out of the torsional load cases specified in figure 6-9 only CASE 1 is supported. Four load cases will be generated for CASE 1, one per wind direction. CASE 3 has to be manually created by the user by combining the CASE 1 load cases in a combination. CASE 2 and CASE 4 are not supported.

For analytical procedure: low rise, torsional load cases are specified in figure 6-10. One torsional load case is created per wind direction.



## Warning and Error messages

This section of the document explains the messages built in the program to ensure the wind load calculations proceed satisfactorily.

S.No.	Message	Explanation
1.	CADS WLE is not installed. Please install 3D Wind Generator Setup from Add-on	This error occurs when the 3D wind loading module is not installed.  To install wind loading module:  Close Scia Engineer  Right click on the Scia Engineer installation from Control panel and select Change  A dialog would pop-up with few options. Choose 'Modify' and click Next  In the next page select CADs Wind Load Engine under the Add-ons  This will install the module for wind load generation
2.	Specify 3D wind in member/panel properties for wind load generation	This error occurs when there are no 2D members/panels with wind data.  For the wind loading to work the structure has to be surrounded by wall and roof elements. This can be done by wrapping the structure with 2D members or Panels with the property '3D wind' selected in the properties dialog.  
3.	Type of the 2D member(s) S5, S6 ... incorrect	The error will occur when the user specifies a vertical member as a roof or a horizontal/inclined member as a wall. See terms and definitions: <a href="#">wall and roof</a>  This error should rarely occur as the program sets the correct defaults when creating wind data.
4.	The structure is open near the 2D member(s) S6, S5, ... Current version supports only closed buildings.	This might happen if the user is trying to model an open structure like canopy OR due to an error in modelling a closed building.  Hence if you are not modelling an open building, check for the modelling errors which could be one of combination of the following:  1. 2D member/panels representing the wall/roof may not be input in a part of the model producing a closed space.  2. Wind data may not be defined for one or more 2D member/panels.
5.	Terrain level is equal to or greater than the building height	These errors occur when the input terrain level is invalid.
6.	Terrain level is less than the building base	
7.	Flat roof declared as pitched roof for 2D member(s) S7, .....	These are error messages about the declared roof type. The program checks the input roof type with that expected by the code based on the geometry. See terms and definitions: <a href="#">roof type</a>
8.	Pitched roof declared as flat roof for 2D member(s) S8, ...	

## References

1. BS 6399-2:1997 –Loading for buildings – Part 2: Code of practice for wind loads
2. Wind loading a practical guide to BS 6399-2 Wind loads on buildings – Nicholas J. Cook.
3. EN 1991-1-4:2005 Eurocode 1:Actions on structures – Part 1-4: General actions – Wind actions
4. ASCE STANDARD ASCE/SEI 7-05 – Minimum Design Loads For Buildings and other Structures
5. Guide to the use of the wind load provisions of ASCE 7-02 – Kishor C. Mehta and James M. Delahay
6. Designers guide to EN 1991-1-4 Eurocode 1: Actions on structures, general actions, Part 1-4: wind actions