NCSEA
National Council of Structural Engineers Associations

STRUCTURAL ENGINEERING SUMMIT

WIND ENGINEERING COMMITTEE

EXAMPLE PROBLEMS: TORNADO LOADS ON SCHOOLS AND HOSPITALS

Tornado Loads – Schools

OVERVIEW

This example demonstrates tornado load determination using ASCE 7-22 Chapter 32. The example building is a 1-story Elementary school located in Evansville, Indiana with the following criteria:

Building use: Elementary School with greater than 250 occupants
Building plan dimensions: See Figure 1
Building Height: One story with 16' mean roof height, and an attached Gym with 25' roof height
The project site is loaded in suburban terrain with farm field around, representing exposure C conditions.
The site ground elevation is 379 feet above mean sea level.

Chapter 26 Wind load Paramenters:
Basic Wind speed:113 mph (Risk Category III)
Exposcure C
Topographic factor, K_{zt} = 1.0
Building is ridgid, G= 0.85
Building is enclosed, GCpi= +0.18, -0.18

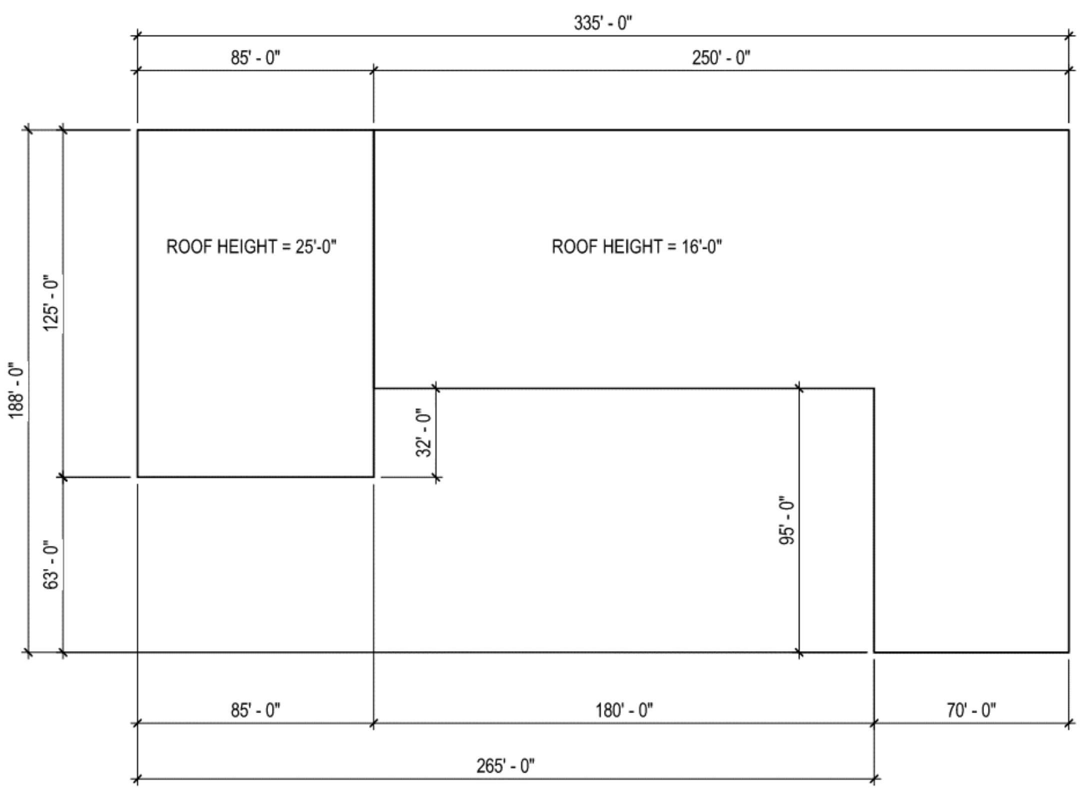


Figure 1: Building plan dimensions

DETERMINE WHETHER DESIGN FOR TORNADO LOADS IS REQUIRED

ASCE 7–22 Chapter 32 requires that Risk Category III and IV structures located in tornado–prone regions be designed and constructed to resist the greater of tornado loads in Chapter 32, or wind loads determined in Chapters 26–31. A flowchart is included in ASCE 7, Figure 32.1–2, to help the user quickly determine if design for tornado loads is required. The following 4 steps follow the process outlined in the ASCE 7 flowchart.

1. Risk category

Using the criteria outlined in ASCE 7, Section 1.5 and Table 1.5–1, schools are considered buildings which could pose a substantial risk to human life in the event of structural failure. As such, the building is classified risk category III. For jurisdictions which adopt ASCE 7 by reference from the International Building Code (IBC), the risk category is determined using IBC Table 1604.5. Using the IBC criteria, buildings used for educational purposes through the 12^{th} grade are classified as Group "E" occupancies. IBC Table 1604.5 indicates that Group E occupancies with an occupant load greater than 250 persons are classified as Risk Category III.

2. Tornado prone region

Tornado–prone regions are indicated in ASCE Figure 32.1–1. Indiana is located in tornado–prone region.

3. Calculate V_T > 60 mph

The tornado speed for the structure is determined per Section 32.5.1. The first step in determining the tornado speed is calculating the effective plan area, A_e, per Section 32.5.4. The effective plan area is for this building is 54,633 ft^2 using the convex polygon shown in Figure 2.

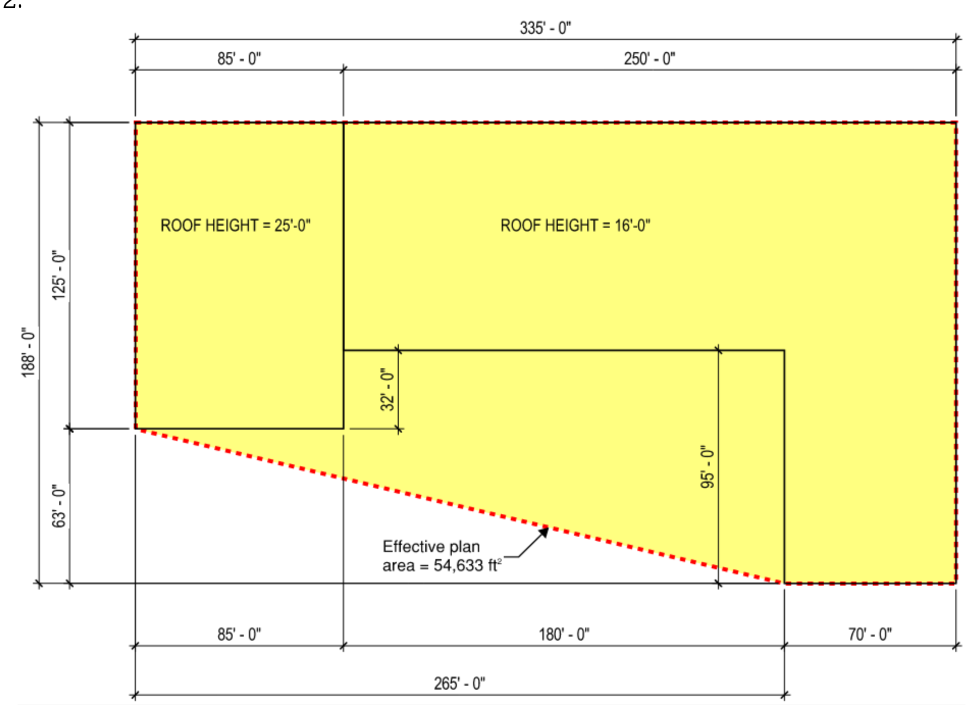


Figure 2: Building effective plan area

The tornado speed is selected from the appropriate Figure, 32.5–1A through 32.5–1H. The ASCE 7 Hazard Tool (https://asce7hazardtool.online) may also be used to determine the tornado speed. The effective plan area is rounded up to the next available mapped effective plan area, 100,000 ft^2 in this case. Using Fig 32.5–1E, the Tornado speed V_T = 80 mph. The user may also interpolate between maps using the logarithm of the effective plan area size. The interpolation between Figure 32.5–1D (A_e = 40,000 ft^2, V_T = 59 mph) and Figure 32.5–1E for this building is demonstrated below.

$$V_T = 59\,mph + (\log 54{,}633\,ft^2 - \log 40{,}000\,ft^2) * \frac{80\,mph - 59\,mph}{\log 100{,}000\,ft^2 - log 40{,}000\,ft^2} = 66.1\,mph$$

For this example, a conservative tornado speed, V_T = 80 mph, will be used for design.

4. <u>V_T Compared to V</u>
   Review the threshold tornado speeds specified in Section 32.5.2. For exposure C conditions, V_T must be greater than or equal to 0.6*V.
   V = 113mph
   0.6*V = 67.8 mph < V_T = 80 mph
   Therefore, design for tornado loads is required for this building. However, it is important to note that the tornado speed V_T = 80 mph used for this example is based on conservatively rounding up the effective plan area to the 100,000 ft^2 tornado speed map. Taking advantage of the interpolation between maps demonstrated in the previous check would exempt this building from design for tornado loads.

CALCULATING TORNADO LOADS – DETERMINE TORNADO LOAD PARAMETERS

ASCE 7 Figure 32.1–3 outlines the general parameters required for determining tornado loads for both the MWFRS and C&C. The tornado load criteria outlined in this section generally follow the process shown in Figure 32.1–3.

1. <u>Effective plan area and tornado speed:</u>
   The effective plan area and tornado speeds are determined in the previous section.

   A_e = 54,633 ft^2
   V_T = 80 mph

2. <u>Tornado directionality factor</u>
   The tornado directionality factor is determined per Section 32.6 & Table 32.6–1.

   K_{dT} = 0.80 for main wind force resisting system loads.
   K_{dT} = 0.90 for components & cladding located in roof zone 1' indicated in Figure 30.3–2A.
   K_{dT} = 0.75 for all other components & cladding.

3. Ground elevation factor
   The ground elevation factor, K_e is determined per Section 32.9 and Table 32.10.2. K_e can conservatively be taken as 1.0, however calculating K_e as shown below results in a small reduction in design tornado and wind pressures for this example.

   $$K_e = e^{-0.0000362 * z_e} = 0.986$$

4. Tornado velocity pressure
   Tornado velocity pressure exposure coefficients KzTor and KhTor are determined per Section 32.10.1 and Table 32.10–1. KzTor is constant from the ground elevation up to 200 ft above ground, with KzTor = 1.0. For taller structures, KhTor decreases with increasing height. Note that this is different from traditional boundary layer wind loads, in which velocity pressure increases with height above ground.

   The tornado velocity pressure is calculated in accordance with 32.10.2 and equation 32.10–1. Note that in ASCE 7–22 the directionality factor, K_d and K_{dT}, has been moved from the velocity pressure equation to the design pressure, p and p_T, equations.
   $$q_{zT} = 0.00256 K_{zTor} K_e V_T^2$$

   Where:
   K_{zTor} = 1.0 at all heights of the building
   K_e = 0.99
   V_T = 80 mph

   $$q_{zT} = q_{hT} = 16.2\ psf$$

5. Tornado gust effect factor
   The tornado gust effect factor G_T is determined per Section 32.11. For tornado loads, the tornado gust effect factor can be taken as G_T = 0.85 for all cases, or can be calculated for rigid buildings using equation 26.11–6 with exposure C terrain constants. The gust effect factor for flexible buildings and other structures, G_f, is not applicable for tornado loads.
   Use G_T = 0.85

6. Tornado enclosure classification and internal pressure coefficients
   The tornado enclosure classification is determined per Section 32.12. This section states that non–essential structures without protection for glazed openings shall be re–evaluated for classification as partially enclosed, with all unprotected glazed opening on each assumed windward wall considered as openings. While details of the building openings are omitted from this example for brevity, it is determined that the building has a window configuration that results in A_o >1.1A_{oi}. Therefore, the building is considered partially enclosed for determining tornado loads. The tornado internal pressure coefficients are taken from Table 32.13–1.

   GC_{piT} =+0.55, –0.55

7. Tornado pressure coefficient adjustment factor
The Tornado pressure coefficient adjustment factor, K_{vT} is determined per Section 32.14. This factor accounts for increased tornado uplift pressures on roof components and is taken from Table 32.14-1.

Building Element	K_{vT}
MWFRS roof uplift pressures	1.1
C&C Zone 1 roof uplift pressures (θ<7°)	1.2
C&C Zone 2 roof uplift pressures (θ<7°)	1.05
C&C Zone 3 roof uplift pressures (θ<7°)	1.05
MWFRS rooftop equipment uplift pressures	1.1
C&C rooftop equipment uplift pressures	Same as for roof C&C
Positive (downward) roof pressures	1.0
Wall pressure	1.0
All other cases	1.0

DETERMINE MWFRS TORNADO PRESSURES ON WALLS AND ROOFS

Tornado loads on the main wind force resisting system for buildings are determined using Chapter 27 provisions, as modified by Section 32.15.

1. External pressure coefficients
External pressure coefficients are determined for each element of the building from Section 27.3.1 and Figure 27.3-1. The L, B, and h dimensions used to determine the Cp values are summarized in Figure 1.

Surface	C_p Loads in east-west direction	C_p Loads in north-south direction
Windward wall	+0.8	+0.8
Leeward wall	−0.34 (L/B = 1.8)	−0.5 (L/B <1)
Side walls	−0.7	−0.7
Roof (0–h/2), for h/L < 0.5	−0.9, −0.18	−0.9, −0.18
Roof (h/2–h), for h/L < 0.5	−0.9, −0.18	−0.9, −0.18
Roof (h–2h), for h/L < 0.5	−0.5, −0.18	−0.5, −0.18
Roof (>2h), for h/L < 0.5	−0.3, −0.18	−0.3, −0.18

2. MWFRS pressures on each surface
The design tornado pressure applied to each surface of the building is determined using Equation 32.15-1, which replaces Equation 27.3-1. Note that the tornado directionality factor, K_{dT} is applied to external pressures, but not internal pressures when determining the design tornado pressure.
$p_T = qG_T K_{dT} K_{vT} C_p - q_i(GC_{piT})$

Per Section 32.15.1, the velocity pressure q in the design pressure equation is $q=q_{zT}$ for external pressures on all walls, where q is evaluated at height z above ground. For external pressures on roofs, $q=q_{hT}$ evaluated at height h. For internal pressures in enclosed buildings, $q_i=q_{zop}$ in the design pressure equation, where q_{zop} is evaluated at the level of the lowest opening in the building that could affect positive internal pressures. Since the building height is less than 200 ft, the velocity pressure coefficient is constant over the height of the structure, and the velocity pressure is equal for all conditions.

$q_{zT} = q_{hT} = q_{zop} = 16.2$ psf

Substituting all variables except C_p reduces the pressure equations to:

$p_T = 16.2*0.85*0.80*1.0*C_p - (16.2*(\pm0.55))$
$= 18.0*C_p - [\pm8.9]$ psf for walls

$p_T = 16.2*0.85*0.80*1.1*C_p - (16.2*(\pm0.55))$
$= 12.1*C_p - [\pm8.9]$ psf for roof uplift pressure

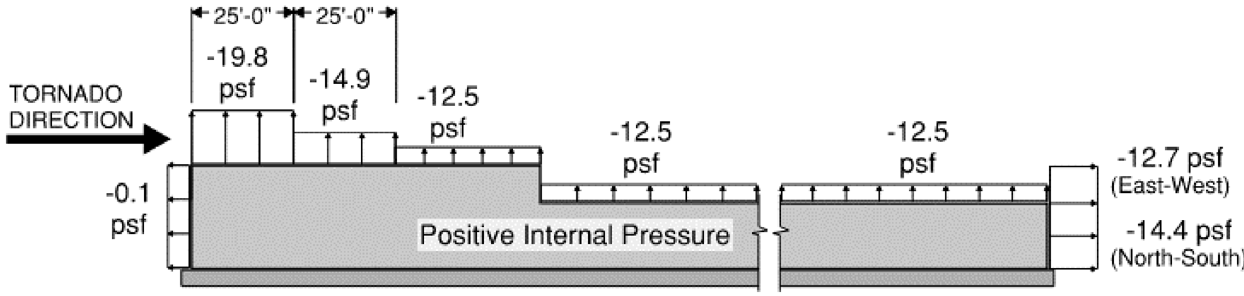
The MWFRS design tornado pressures are tabulated for each direction below, and shown graphically on a building section in Figure 3.

East-west direction MWFRS tornado pressures

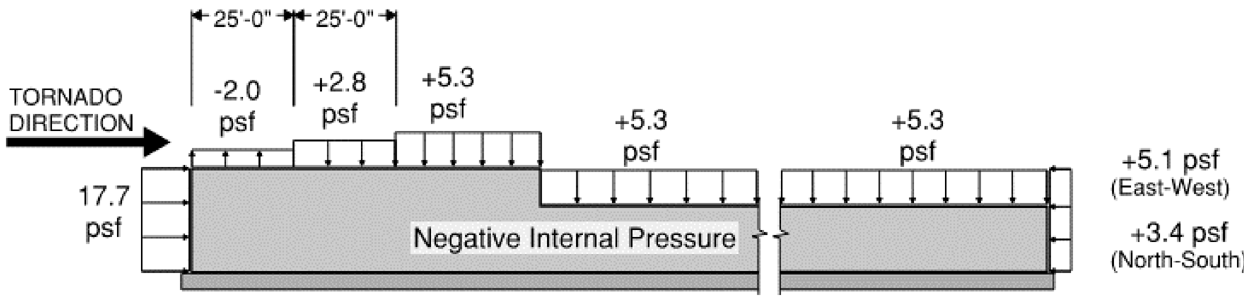
Surface	**C_p**	**Design pressure, p_T (psf)** With positive internal pressure	**Design pressure, p_T (psf)** With negative internal pressure
Windward wall	+0.8	−0.1	+17.7
Leeward wall	−0.34	−12.7	+5.1
Side walls	−0.7	−16.6	+1.2
Roof (0–h/2)	−0.9, −0.18	−19.8, −11.1	−2.0, +6.7
Roof (h/2–h)	−0.9, −0.18	−19.8, −11.1	−2.0, +6.7
Roof (h–2h)	−0.5, −0.18	−14.9, −11.1	+2.8, +6.7
Roof (>2h)	−0.3, −0.18	−12.5, −11.1	+5.3, +6.7

North-south direction MWFRS tornado pressures

Surface	**C_p**	**Design pressure, p_T (psf)** With positive internal pressure	**Design pressure, p_T (psf)** With negative internal pressure
Windward wall	+0.8	−0.1	+17.7
Leeward wall	−0.50	−14.4	+3.4
Side walls	−0.7	−16.6	+1.2
Roof (0–h/2)	−0.9, −0.18	−19.8, −11.1	−2.0, +6.7
Roof (h/2–h)	−0.9, −0.18	−19.8, −11.1	−2.0, +6.7
Roof (h–2h)	−0.5, −0.18	−14.9, −11.1	+2.8, +6.7
Roof (>2h)	−0.3, −0.18	−12.5, −11.1	+5.3, +6.7



Building Section



Building Section

Figure 3 MWFRS Design Tornado Pressure

DETERMINE C&C TORNADO PRESSURES ON WALLS AND ROOFS

Tornado loads on components and claddings for buildings are calculated using Chapter 30 provisions, as modified by Section 32.17. The building in this example is a low-rise building, and the design C&C Tornado pressures are calculated using Section 32.17.1.

1. External pressure coefficients
   External pressure coefficients, GC_p, are determined for each element of the building from Section 30.3.2.1 and Figures 30.3-1 and 30.3-2A. For this example, pressures are evaluated for C&C having a small effective wind area of 10 ft^2, and a large effective wind area of 100 ft^2. The external pressure coefficients for walls are reduced by 10% as permitted by Note 5 in Figure 30.3-1.

Surface	GC_p Effective wind area = 10 ft^2		GC_p Effective wind area = 100 ft^2	
	+	–	+	–
Roof Zone 1'	0.3	–0.9	0.2	–0.9
Roof Zone 1	0.3	–1.7	0.2	–1.29
Roof Zone 2	0.3	–2.3	0.2	–1.77
Roof Zone 3	0.3	–3.2	0.2	–2.14
Wall Zone 4	0.9	–0.99	0.74	–0.83
Wall Zone 5	0.9	–1.25	0.74	–0.94

2. <u>Pressures on each surface</u>
   The design tornado pressure applied to each surface of the building is calculated using Equation 32.17–1, which replaces Equation 30.3–1. Note that the tornado directionality factor, K_{dT} is applied to external pressures, but not internal pressures when determining the design tornado pressure.
   $p_T = q_{hT}[(K_{dT}K_{vT}(GC_p) - (GC_{piT})]$

   Substituting all variables except K_{vT} and GC_p reduces the pressure equations to:
   p_T = 16.2*0.75*K_{vT}*GC_p – 16.2*(±0.55)
   = 12.3*K_{vT}*GC_p – (±8.9) psf

   The component and cladding design tornado pressures are summarized in the following table. Note that some pressure values are less than the 16 psf minimum design pressure specified in Chapter 30. The user should compare the calculated tornado pressures to the calculated wind pressures, and use 16 psf minimum for design if neither tornado nor wind pressures exceed this code minimum pressure. The roof pressures and roof zones are shown in Figure 4. The roof zoning incorporates the requirements for stepped roofs from Figure 30.3–3.

Component and Cladding Pressures

Surface	K_{vT}		Design pressure, p_T (psf) Effective wind area = 10 ft^2		Design pressure, p_T (psf) Effective wind area = 100 ft^2	
	+	–	+	–	+	–
Roof Zone 1'	1.0	1.2	12.5	–24.6	11.3	–24.6
Roof Zone 1	1.0	1.2	12.5	–33.6	11.3	–27.6
Roof Zone 2	1.0	1.05	12.5	–38.2	11.3	–31.4
Roof Zone 3	1.0	1.05	12.5	–49.6	11.3	–36.1
Wall Zone 4	1.0	1.0	19.8	–20.9	17.9	–19.0
Wall Zone 5	1.0	1.0	19.8	–24.2	17.9	–20.3

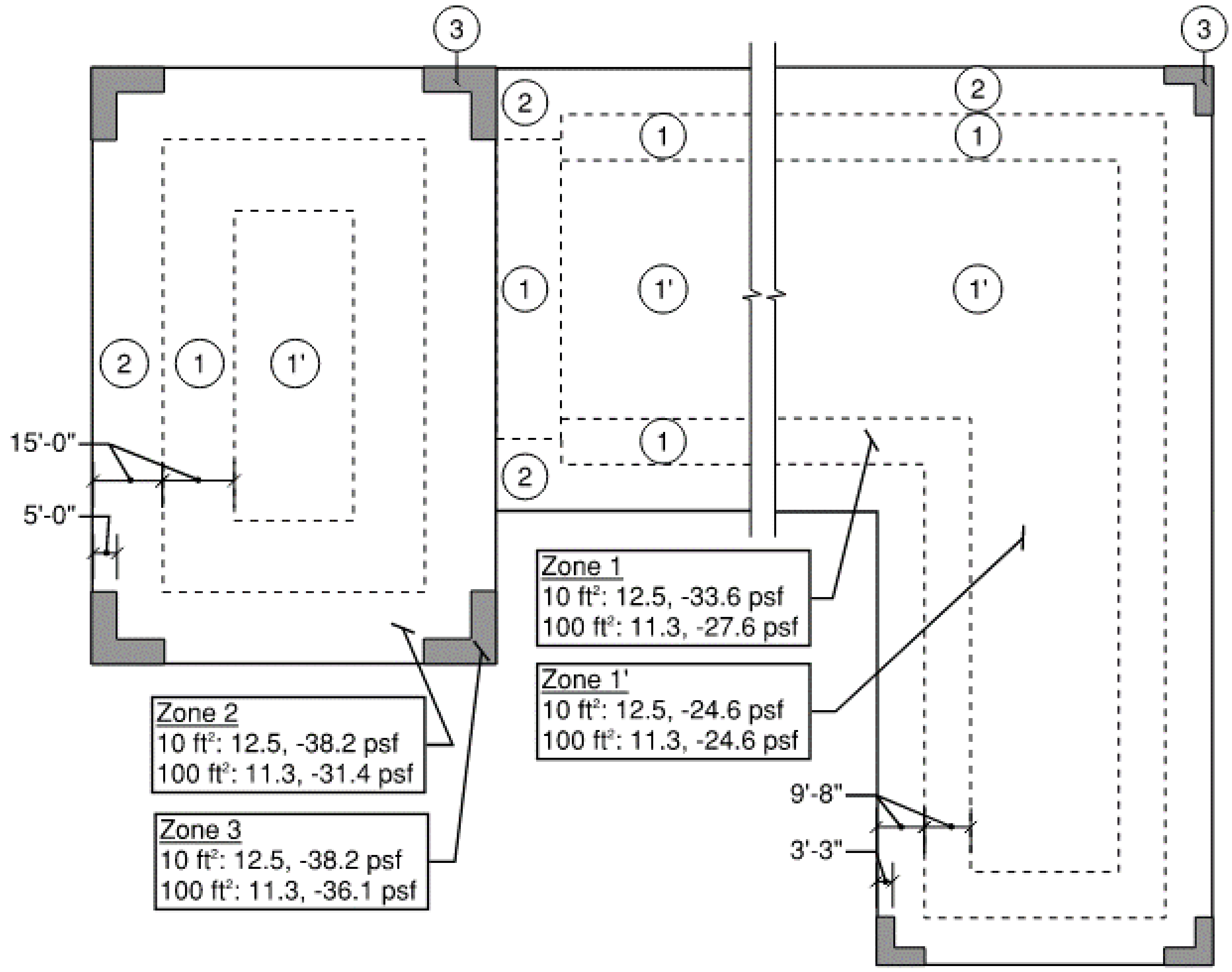


Figure 4: Roof component and cladding pressures and zones

COMPARISON OF TORNADO AND WIND LOADS:

The intent of this example problem is to demonstrate the calculation of tornado loads using the new Chapter 32 provisions. Detailed calculations for wind loads on this building are not included, however design wind pressures for various surfaces of the building are presented in this section for comparison to the design tornado pressures.

1. MWFRS
   The following two tables present a comparison of design MWFRS pressures for the building. The lateral pressures are combined windward plus leeward pressures typically used in evaluating story and base shears. For a building without expansion joints, the internal pressure cancels out in determining the net pressure. Roof uplift pressures are presented using the positive internal pressure condition, which results in the highest tornado uplift pressures.

Net lateral pressure, east–west direction

Level	Height (ft)	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
Hi Roof	25	20.9	12.6	0.60
Low Roof	16	19.6	12.6	0.64

Roof uplift pressure with positive internal pressure

Distance from windward edge	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
0 to h/2	–20.3	–19.8	0.97
h/2 to h	–20.3	–19.8	0.97
h to 2h	–13.0	–14.9	1.15
> 2h	–9.4	–12.5	1.34

The following observations can be made from the MWFRS data:

- Design tornado lateral pressure do not control over wind pressures for this example.
- Design tornado roof pressures are higher than wind roof pressures in the interior areas of the roof. However the order of magnitude of these uplift pressures are quite small.

2. <u>C&C</u>

The following two tables present a comparison of design wall and roof component and cladding pressures for the building.

Wall C&C pressures

EWA	Zone	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
10 ft^2	4	–30.3	–20.9	0.69
	5	–37.3	–24.2	0.65
	Positive, All Zones	28.0	19.8	0.71
100 ft^2	4	–26.2	–19.0	0.72
	5	–29.1	–20.3	0.70
	Positive, All Zones	23.9	17.9	0.75

Roof C&C pressures

EWA	Zone	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
10 ft^2	1′	−28.0	−24.6	0.88
	1	−48.7	−33.6	0.69
	2	−64.2	−38.2	0.59
	3	−87.6	−49.6	0.57
	Positive, All Zones	12.4	12.5	1.01
100 ft^2	1′	−28.0	−24.6	0.88
	1	−38.0	−27.6	0.73
	2	−50.5	−31.4	0.62
	3	−60.1	−36.4	0.60
	Positive, All Zones	9.8	11.3	1.15

The following observations can be made from the C&C data:

- In an academic sense, design tornado wall pressures control positive wall pressure for this example. However, both the tornado and wind positive wall design pressures are less than the minimum 16 psf design pressure, therefore the minimum pressure governs.
- While tornado pressures do not control this example, the difference between tornado pressures decreases at the interior roof zones. As tornado speeds increase, tornado pressures may be more significant for the design of elements located away from the roof corner and edge zones.

It is important to note that the differences between design tornado and wind pressures will vary by project. Tornado impacts may be more or less significant than this example depending on the building use and occupancy category, enclosure classification, height, wind exposure category, and the difference in magnitude between design wind and tornado speeds.

Tornado Loads – Hospitals

OVERVIEW

This example demonstrates tornado load determination using ASCE 7-22 Chapter 32. The example building is a 4-story hospital facility located near Oklahoma City, OK with the following criteria:

Building use: Hospital patient tower which includes emergency surgery suites.
Building plan dimensions: See Figure 1
Building height: 4 stories with 56 ft mean roof height. The roof is flat.
The project is sited in urban terrain with exposure B conditions and no features which would create topographic effects. The site ground elevation is 1,200 ft above mean sea level.

Chapter 26 Wind Load Parameters:
Basic wind speed = 120 mph (Risk Category IV)
Exposure B
Topographic factor, K_{zt} = 1.0
Building is rigid, G = 0.85
Enclosed, GC_{pi} = +0.18, −0.18

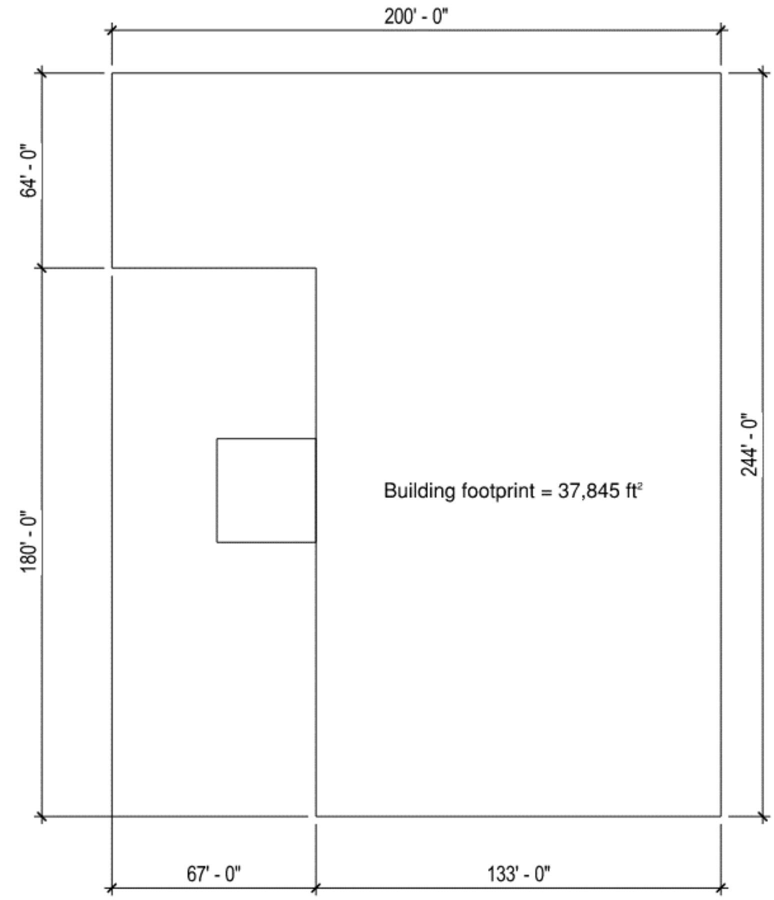


Figure 1: Building plan dimensions

DETERMINE WHETHER DESIGN FOR TORNADO LOADS IS REQUIRED

ASCE 7-22 Chapter 32 requires that Risk Category III and IV structures located in tornado-prone regions be designed and constructed to resist the greater of tornado loads in Chapter 32, or wind loads determined in Chapters 26-31. A flowchart is included in ASCE 7, Figure 32.1-2, to help the user quickly determine if design for tornado loads is required. The following four steps follow the process outlined in the ASCE 7 flowchart.

1. Risk Category
   A hospital facility having emergency surgery or emergency treatment facilities is considered an Essential Facility. This building is classified as Risk Category IV per ASCE 7 Section 1.5. For jurisdictions which adopt ASCE 7 by reference from the International Building Code (IBC), the risk category is determined using IBC Table 1604.5, which also classifies the building as Risk Category IV.

2. Tornado-Prone Region
   Tornado-prone regions are indicated in ASCE Figure 32.1-1. Oklahoma City is located in a tornado-prone region.

3. V_T > 60 mph
   The tornado speed for the structure is determined per Section 32.5.1. The first step in determining the tornado speed is calculating the effective plan area, A_e, per Section 32.5.4. For essential facilities, the effective plan area is calculated using a convex polygon enclosing the footprint of the essential facility and any other structures required to maintain the functionality of the essential facility. For this example, it is assumed that all essential services for this building are located within its footprint. The effective plan area is for this building is 42,770 ft^2 using the convex polygon shown in Figure 2.

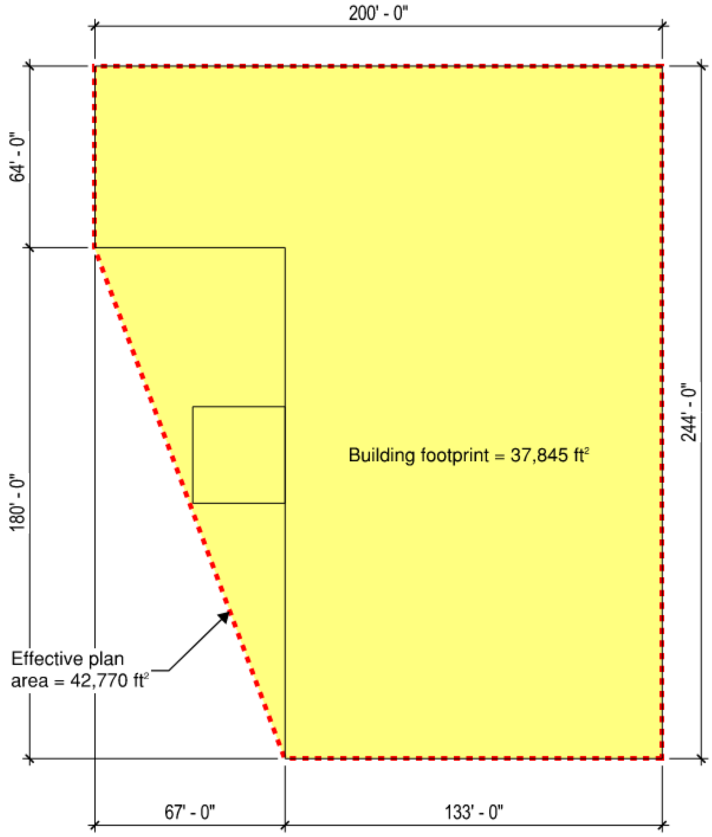


Figure 2: Building effective plan area

The tornado speed is selected from the appropriate Figure, 32.5-2A through 32.5-2H. The ASCE 7 Hazard Tool (https://asce7hazardtool.online) may also be used to determine the tornado speed. The effective plan area is rounded up to the next available mapped effective plan area, 100,000 ft^2 in this case. Using Fig 32.5-2E, the Tornado speed V_T = 107 mph. The user may also interpolate between maps using the logarithm of the effective plan area size. The interpolation between Figure 32.5-2D (A_e = 40,000 ft^2, V_T = 103 mph) and Figure 32.5-2E for this building is demonstrated below.

$$V_T = 103\,mph + (\log 42{,}770\,ft^2 - \log 40{,}000\,ft^2) * \frac{107\,mph - 103\,mph}{\log 100{,}000 ft^2 - log 40{,}000 ft^2} = 103.3\,mph$$

Use V_T = 104 mph

4. V_T compared to V

   Section 32.5.2 determines a threshold tornado speed based on the Chapter 26 wind speed and exposure category. For exposure B conditions, V_T must be greater than or equal to 0.5*V = 60 mph. For this site and effective plan area, the tornado speed exceeds the threshold value.

   Since all four flowchart checks are true, design for tornado loads is required for this building.

DETERMINE TORNADO LOAD PARAMETERS

ASCE 7 Figure 32.1–3 outlines the general parameters required for determining tornado loads for both the MWFRS and C&C. The tornado load criteria outlined in this section generally follow the process shown in Figure 32.1–3.

1. Effective plan area and tornado speed
   The effective plan area and tornado speed are determined in the previous section.

   A_e = 42,770 ft^2.
   V_T = 104 mph

2. Tornado directionality factor
   The tornado directionality factor is determined per Section 32.6 and Table 32.6–1.

   K_{dT} = 0.80 for main wind force resisting system loads.
   K_{dT} = 1.0 for all component and cladding loads for an essential facility. For non–essential facilities, K_{dT} for components and cladding varies by location on the building as indicated in Table 32.6–1.

3. Ground elevation factor
   The ground elevation factor, K_e is determined per Section 32.9. K_e can conservatively be taken as 1.0, or calculated using Table 26.9–1. This example uses the calculated ground elevation factor, as shown below.

   $$K_e = e^{-0.0000362*z_e} = 0.96$$

4. Tornado velocity pressure
   Tornado velocity pressure exposure coefficients K_{zTor} and K_{hTor} are determined per Section 32.10.1 and Table 32.10–1. K_{zTor} is constant from the ground elevation up to 200 ft above ground, with K_{zTor} = 1.0. For taller structures, K_{hTor} decreases with increasing height. Note that this is different from traditional boundary layer wind loads, in which velocity pressure increases with height above ground.

   The tornado velocity pressure is calculated in accordance with 32.10.2 and equation 32.10–1. Note that in ASCE 7–22 the directionality factor, K_d and K_{dT}, has been moved from the velocity pressure equation to the design pressure, p and p_T, equations.
   $$q_{zT} = 0.00256 K_{zTor} K_e V_T^2$$

   Where:
   K_{zTor} = 1.0 at all heights of the building
   K_e = 0.96
   V_T = 104 mph

   $$q_{zT} = q_{hT} = 26.5\ psf$$

5. Tornado gust effect factor

The tornado gust effect factor G_T is determined per Section 32.11. For tornado loads, the tornado gust effect factor can be taken as $G_T = 0.85$ for all cases, or can be calculated for rigid buildings using equation 26.11-6 with exposure C terrain constants. The gust effect factor for flexible buildings and other structures, G_f, is not applicable for tornado loads. The problem statement indicates that this building is rigid. Use $G_T = 0.85$

6. Tornado enclosure classification and internal pressure coefficients
The tornado enclosure classification is determined per Section 32.12. Enclosure classification for tornado loads requires evaluating the enclosure classification in accordance with Section 26.2 assuming that all unprotected glazed openings on a windward wall are breached openings. However, for essential facilities impact protection of glazed openings is required in accordance with Section 32.12.3.1. There are no other major openings in the envelope of this building, therefore the building is classified as enclosed for tornado load determination. The internal pressure coefficients are determined from Section 32.13 and Table 32.13-1. Note that the positive internal pressure coefficient is higher for enclosed buildings for tornado loads to account for the atmospheric pressure change that occurs in and near a tornado.

$GC_{piT} = +0.55$
$GC_{piT} = -0.18$

7. Tornado pressure coefficient adjustment factor
The Tornado pressure coefficient adjustment factor, K_{vT} is determined per Section 32.14. This factor accounts for increased tornado uplift pressures on roof components and is taken from Table 32.14-1.

Building Element	K_{vT}
MWFRS roof uplift pressures	1.1
C&C Zone 1 roof uplift pressures (θ<7°)	1.2
C&C Zone 2 roof uplift pressures (θ<7°)	1.05
C&C Zone 3 roof uplift pressures (θ<7°)	1.05
MWFRS rooftop equipment uplift pressures	1.1
C&C rooftop equipment uplift pressures	Same as for roof C&C
Positive (downward) roof pressures	1.0
Wall pressure	1.0
All other cases	1.0

DETERMINE MWFRS TORNADO PRESSURES ON WALLS AND ROOFS

Tornado loads on the main wind force resisting system for buildings are determined using Chapter 27 provisions, as modified by Section 32.15.

1. External pressure coefficients
   External pressure coefficients are determined for each element of the building from Section 27.3.1 and Figure 27.3–1.

Surface	**C_p** Loads in east–west direction	**C_p** Loads in north–south direction
Windward wall	+0.8	+0.8
Leeward wall	–0.5 (L/B < 1)	–0.46 (L/B = 1.22)
Side walls	–0.7	–0.7
Roof (0–h/2), for h/L < 0.5	–0.9, –0.18	–0.9, –0.18
Roof (h/2–h), for h/L < 0.5	–0.9, –0.18	–0.9, –0.18
Roof (h–2h), for h/L < 0.5	–0.5, –0.18	–0.5, –0.18
Roof (>2h), for h/L < 0.5	–0.3, –0.18	–0.3, –0.18

2. Pressures on each surface
   The design tornado pressure applied to each surface of the building is determined using Equation 32.15–1, which replaces Equation 27.3–1. Note that the tornado directionality factor, K_{dT} is applied to external pressures, but not internal pressures when determining the design tornado pressure.
   $p_T = qG_TK_{dT}K_{vT}C_p - q_i(GC_{piT})$

   Per Section 32.15.1, the velocity pressure q in the design pressure equation is $q=q_{zT}$ for external pressures on all walls, where q is evaluated at height z above ground. For external pressures on roofs, $q=q_{hT}$ evaluated at height h. For internal pressures in enclosed buildings, $q_i=q_{zop}$ in the design pressure equation, where q_{zop} is evaluated at the level of the lowest opening in the building that could affect positive internal pressures. Since the building height is less than 200 ft, the velocity pressure coefficient is constant over the height of the structure, and the velocity pressure is equal for all conditions.
   $q_{zT} = q_{hT} = q_{zop} = 26.5$ psf

   Substituting all variables except C_p reduces the pressure equations to:
   $p_T = 18.0\ C_p$ – [+14.6, –4.8] psf for walls ($K_{vT} = 1.0$)
   $p_T = 19.8\ C_p$ – [+14.6, –4.8] psf for roof negative pressure ($K_{vT} = 1.1$)

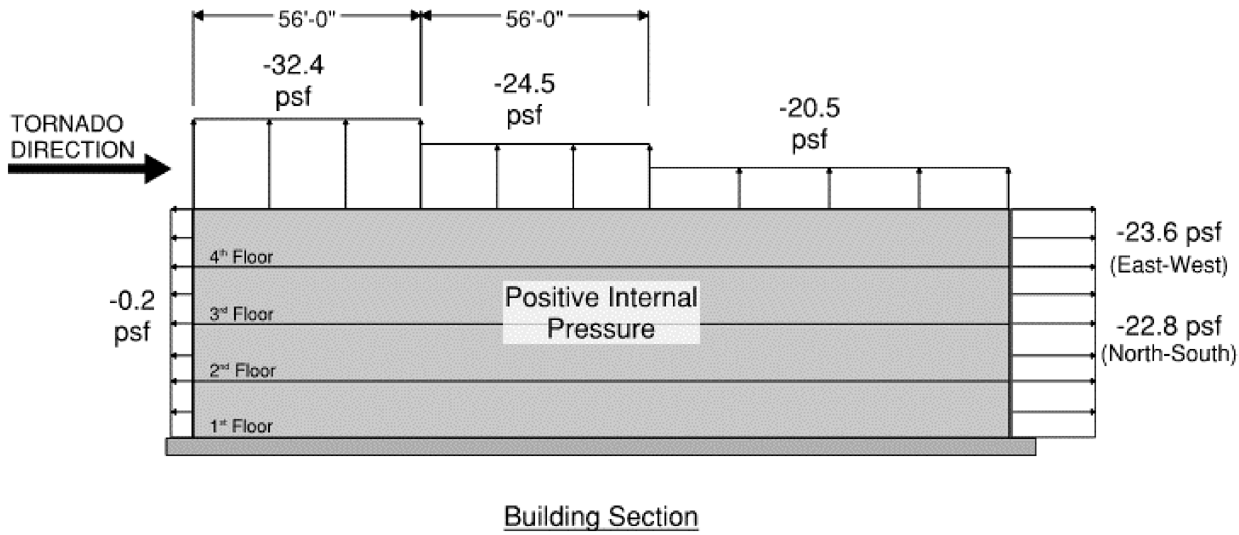
The MWFRS design tornado pressures are tabulated for each direction below, and shown graphically on a building section in Figure 3.

East–west direction MWFRS tornado pressures

Surface	C_p	Design pressure, p_T (psf) With positive internal pressure	Design pressure, p_T (psf) With negative internal pressure
Windward wall	+0.8	−0.2	+19.2
Leeward wall	−0.5	−23.6	−4.2
Side walls	−0.7	−27.2	−7.8
Roof (0–h/2)	−0.9, −0.18	−32.4, −18.2	−13.1, +1.2
Roof (h/2–h)	−0.9, −0.18	−32.4, −18.2	−13.1, +1.2
Roof (h–2h)	−0.5, −0.18	−24.5, −18.2	−5.1, +1.2
Roof (>2h)	−0.3, −0.18	−20.5, −18.2	−1.2, +1.2

North–south direction MWFRS tornado pressures

Surface	C_p	Design pressure, p_T (psf) With positive internal pressure	Design pressure, p_T (psf) With negative internal pressure
Windward wall	+0.8	−0.2	+19.2
Leeward wall	−0.46	−22.8	−3.4
Side walls	−0.7	−27.2	−7.8
Roof (0–h/2)	−0.9, −0.18	−32.4, −18.2	−13.1, +1.2
Roof (h/2–h)	−0.9, −0.18	−32.4, −18.2	−13.1, +1.2
Roof (h–2h)	−0.5, −0.18	−24.5, −18.2	−5.1, +1.2
Roof (>2h)	−0.3, −0.18	−20.5, −18.2	−1.2, +1.2



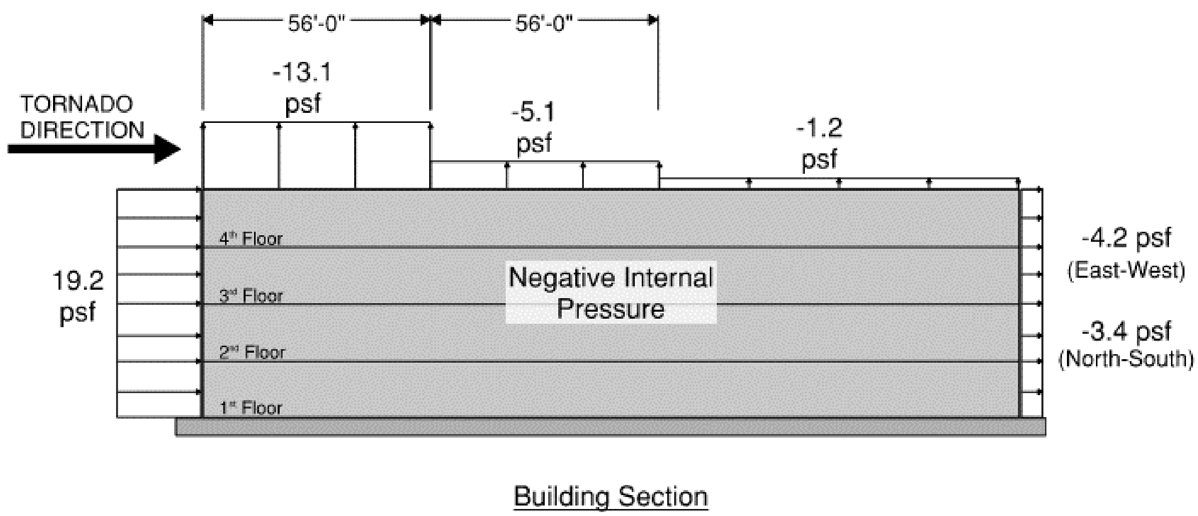


Figure 3: MWFRS Design Tornado Pressures

DETERMINE C&C TORNADO PRESSURES ON WALLS AND ROOFS

Tornado loads on components and claddings for buildings are calculated using Chapter 30 provisions, as modified by Section 32.17. The building in this example is a low-rise building, and the design C&C Tornado pressures are calculated using Section 32.17.1.

1. External pressure coefficients
   External pressure coefficients, GC_p, are determined for each element of the building from Section 30.3.2.1 and Figures 30.3-1 and 30.3-2A. For this example, pressures are evaluated for C&C having a small effective wind area of 10 ft^2, and a large effective wind area of 100 ft^2. The external pressure coefficients for walls are reduced by 10% as permitted by Note 5 in Figure 30.3-1.

Surface	**GC_p** Effective wind area = 10 ft^2		**GC_p** Effective wind area = 100 ft^2	
	+	**–**	**+**	**–**
Roof Zone 1'	0.3	–0.9	0.2	–0.9
Roof Zone 1	0.3	–1.7	0.2	–1.29
Roof Zone 2	0.3	–2.3	0.2	–1.77
Roof Zone 3	0.3	–3.2	0.2	–2.14
Wall Zone 4	0.9	–0.99	0.74	–0.83
Wall Zone 5	0.9	–1.25	0.74	–0.94

2. Pressures on each surface
   The design tornado pressure applied to each surface of the building is calculated using Equation 32.17-1, which replaces Equation 30.3-1. Note that the tornado directionality factor, K_{dT} is applied to external pressures, but not internal pressures when determining the design tornado pressure.
   $p_T = q_{hT}\left[K_{dT}K_{vT}(GC_p) - (GC_{piT})\right]$

   Substituting all variables except K_{vT} and GC_p reduces the pressure equations to:
   $p_T = 26.5\ K_{vT}\ C_p - [+14.6, -4.8]$ psf

   The component and cladding design tornado pressures are summarized in the following table. The roof pressures and roof zones are shown in Figure 4. Based on the building geometry in this example, Zone 1' does not exist on the roof, however the pressures are calculated for completeness. Additionally, some pressure values are less than the 16 psf minimum design pressure specified in Chapter 30. The user should compare the calculated tornado pressures to the calculated wind pressures, and use 16 psf for design if neither tornado nor wind pressures exceed this code minimum pressure.

Component and Cladding Pressures

Surface	K_{vT}		Design pressure, p_T (psf) Effective wind area = 10 ft²		Design pressure, p_T (psf) Effective wind area = 100 ft²	
	+	–	+	–	+	–
Roof Zone 1'	1.0	1.2	12.7	–43.2	10.1	–43.2
Roof Zone 1	1.0	1.2	12.7	–68.7	10.1	–55.6
Roof Zone 2	1.0	1.05	12.7	–78.6	10.1	–63.9
Roof Zone 3	1.0	1.05	12.7	–103.7	10.1	–74.2
Wall Zone 4	1.0	1.0	28.6	–40.8	24.4	–36.6
Wall Zone 5	1.0	1.0	28.6	–48.0	24.4	–39.6

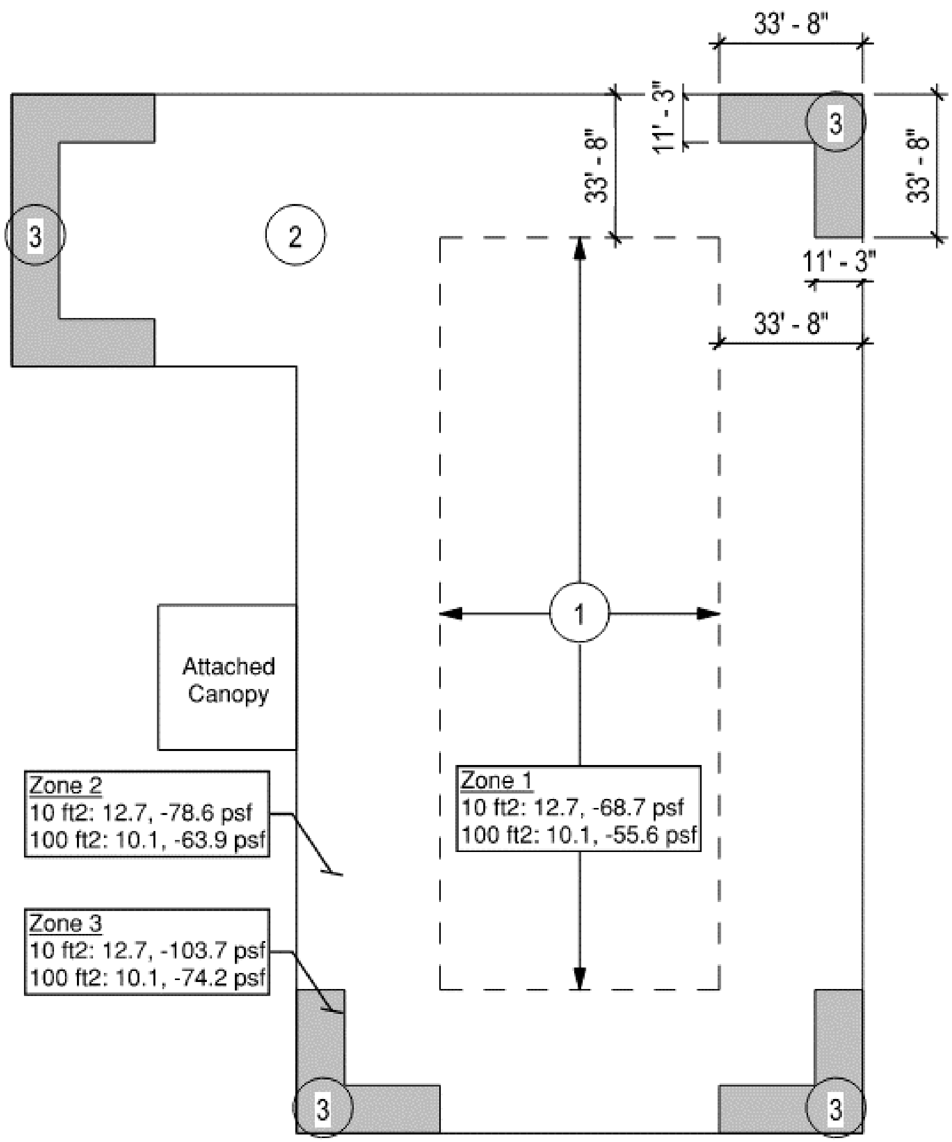


Figure 4: Roof component and cladding pressures and zones

DETERMINE C&C TORNADO PRESSURES ON BUILDING APPURTENANCES & ROOFTOP STRUCTURES AND EQUIPMENT

1. Attached Canopy Pressures

An attached canopy is located above the entrance to the building at h=14 ft. The tornado design C&C pressures is calculated for the canopy using Section 32.17.4.3 and Section 30.9.

External pressure coefficients for the canopy surfaces are determined from Figures 30.9–1A and 30.9–1B. For this example, pressures are evaluated for C&C having a small effective wind area of 10 ft^2, and a large effective wind area of 100 ft^2.

Surface	**GC_p** Effective wind area = 10 ft^2		**GC_p** Effective wind area = 100 ft^2	
	+	**–**	**+**	**–**
Upper Surface	0.8	–1.15	0.6	–0.80
Lower Surface	0.8	–0.8	0.6	–0.65
Net Pressure (h_c/h_e < 0.5)	0.9	–0.6	0.65	–0.5

The design tornado pressure applied to each surface of the attached canopy is determined using Equation 32.17–6, which replaces Equation 30.9–1.

$p_T = q_{hT}K_{dT}(GC_p)$

Attached Canopy C&C Pressures

Surface	**Design pressure, p_T (psf)** Effective wind area = 10 ft^2		**Design pressure, p_T (psf)** Effective wind area = 100 ft^2	
	+	**–**	**+**	**–**
Upper Surface	21.3	–30.5	15.9	–19.9
Lower Surface	21.3	–21.3	15.9	–17.3
Net Pressure	23.9	–16.0	17.2	–13.3

2. Rooftop Equipment

Various rooftop mechanical equipment will be mounted to the roof surface. The tornado design force for rooftop equipment is calculated using Section 32.16.3.2 and Section 29.4.1. It should be noted that Chapter 32 does not provide specific C&C provisions for rooftop equipment. Since the Chapter 29 wind provisions for rooftop equipment address both MWFRS & C&C loads, it is presumed that the same approach can be used for tornado loading.

Lateral Force:

The product of external pressure coefficient and gust–effect factor, (GC_r), is determined from Section 29.4.1. This value can be reduced as the vertical projected area, A_f, of the rooftop equipment increases, but will be taken as the maximum value for this example, (GC_r) = 1.9

The design lateral tornado force applied to rooftop equipment is determined using Equation 32.16-3, which replaces Equation 29.4-2.
$F_T = q_{hT} K_{dT} (GC_r) A_f$

Substituting all variables except A_f reduces the resultant force equation to:
$F_T = 50.4\ A_f$ (lb)

Vertical Uplift Force:
The product of external pressure coefficient and gust-effect factor, (GC_r), is determined from Section 29.4.1. This value can be reduced as the horizontal projected area, A_r, of the rooftop equipment increases, but will be taken as the maximum value for this example, $(GC_r) = 1.5$

The design tornado vertical uplift force applied to rooftop equipment is calculated using Equation 32.16-4, which replaces Equation 29.4-3.
$F_T = q_{hT} K_{dT} K_{vT} (GC_r) A_r$

Using $K_{vT} = 1.2$ assuming the equipment is located in the field of the roof, and substituting all variables except A_r reduces the resultant force equation to:
$F_T = 47.7\ A_f$ (lb)

COMPARISON OF TORNADO AND WIND LOADS

The intent of this example problem is to demonstrate the calculation of tornado loads using the new Chapter 32 provisions. Detailed calculations for wind loads on this building are not included, however design wind pressures for various surfaces of the building are presented in this section for comparison to the design tornado pressures.

1. MWFRS
   The following two tables present a comparison of design MWFRS pressures for the building. The lateral pressures are combined windward plus leeward pressures typically used in evaluating story and base shears. For a building without expansion joints, the internal pressure cancels out in determining the net pressure. Roof uplift pressures are presented using the positive internal pressure condition, which results in the highest tornado uplift pressures.

Net lateral pressure, north-south direction

Level	Height (ft)	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
Roof	56.00	26.1	22.6	0.87
4th Floor	42.00	24.8	22.6	0.91
3rd Floor	28.00	23.3	22.6	0.97
2nd Floor	14.00	21.2	22.6	1.07
1st Floor				

Roof uplift pressure with positive internal pressure

Distance from windward edge	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
0 to h/2	−23.1	−32.4	1.41
h/2 to h	−23.1	−32.4	1.41
h to 2h	−14.8	−24.5	1.66
> 2h	−10.6	−20.5	1.93

The following observations can be made from the MWFRS data:

- Design tornado lateral pressure controls at the lowest floor, but wind pressures increase with height above ground and exceed the tornado pressures at the 3rd floor and above.
- Design tornado roof pressures are higher than wind roof pressures along the entire length of roof.
- The ratio of tornado pressure to wind pressure increases significantly at the interior portions of the roof.

2. C&C

The following two tables present a comparison of design wall and roof component and cladding pressures for the building.

Wall C&C pressures

EWA	Zone	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
10 ft^2	4	−28.6	−40.8	1.43
	5	−35.2	−48.0	1.36
	Positive, All Zones	26.4	28.6	1.09
100 ft^2	4	−24.7	−36.6	1.48
	5	−27.4	−39.6	1.44
	Positive, All Zones	22.5	24.4	1.09

Roof C&C pressures

EWA	Zone	Design wind pressure, p (psf)	Design Tornado pressure, p_T (psf)	Tornado / Wind
10 ft^2	1′	−26.4	−43.2	1.64
	1	−45.9	−68.7	1.50
	2	−60.6	−78.6	1.30
	3	−82.5	−103.7	1.26
	Positive, All Zones	11.7	12.7	1.09
100 ft^2	1′	−26.4	−43.2	1.64
	1	−35.9	−55.6	1.55

	2	−47.6	−63.9	1.34
	3	−56.7	−74.2	1.31
	Positive, All Zones	9.3	10.1	1.09

The following observations can be made from the C&C data:

- Design tornado wall pressures control in all cases for this example.
- The magnitude of positive tornado wall pressures is only slightly greater than wind pressures. The use of impact rated glazing allows the building to be designed as enclosed and results in lower negative internal pressures. Buildings constructed without impact resistant glazing, when permitted by the ASCE 7 standard, will have increased positive wall pressures.
- Design tornado roof pressures control in all cases for this example.
- The ratio of tornado pressure to wind pressure increases significantly at the interior roof zones.

It is important to note that the differences between design tornado and wind pressures will vary by project. Tornado impacts may be more or less significant than this example depending on the building use and occupancy category, enclosure classification, height, wind exposure category, and the difference in magnitude between design wind and tornado speeds.