Calculation Design Tornado Loads for Structures According to ASCE 7-22 and IBC 2024

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Credit: 2 PDH

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This course was adapted from the Federal Emergency Management Agency, Publication FEMA/NIST Design Guide 2023, "Design Guide for New Tornado Load Requirements in ASCE 7-22", which is in the public domain.

COURSE CONTENT

Introduction and Background

This instructional course is for design professionals and building officials to help them determine when a building or other structure is required to be designed to minimum tornado loads and how to calculate design tornado forces. This guide is in accordance with the updated requirements of the American Society of Civil Engineers (ASCE) / Structural Engineering Institute (SEI) standard ASCE 7-22, Minimum Design Loads and Associated Criteria for Buildings and Other Structures.

This Design Guide is intended for users with a basic understanding of ASCE 7 and who know how to determine wind loads using ASCE 7 methodology, as presented in Chapters 26 through 31.

Tornadoes have historically killed more people in the United States than hurricanes and earthquakes combined (NWS, 2020; USGS, 2015). According to the Insurance Information Institute, Inc. (2020), the average annual insured catastrophe losses for events involving tornadoes exceeded those for both hurricanes and tropical storms combined, for the period of 1997–2016. The 2011 Joplin tornado disaster was the deadliest and costliest tornado in the U.S. since 1950 and was one of the primary drivers for the addition of tornado load provisions in ASCE 7 (NIST, 2022). **With the publication of ASCE 7-22 (ASCE; 2021), tornado load requirements are now considered as a minimum design load in conventional building design when buildings are located in tornado-prone areas**. **The new ASCE 7 tornado load provisions do not apply to storm shelters or safe rooms.** The ASCE 7 tornado load requirements will be included in the 2024 International Building Code (IBC), the 2024 National Fire Protection Association (NFPA) 5000 Building Construction and Safety Code, and the 2023 Florida Building Code. The adoption of the ASCE 7 tornado load provisions by the State of Florida is an example of local Authorities Having Jurisdiction incorporating the most current design guidance prior to their inclusion in the model building codes.

Storm shelters and safe rooms are specifically designed for life safety protection during the most extreme wind events and require more extreme design hazard intensities than conventional buildings. Buildings and other structures designed per Chapter 32 of ASCE 7 do not meet the requirements for storm shelters or safe rooms.

Storm shelters and safe rooms must adhere to the ICC 500, *Standard for the Design and Construction of Storm Shelters* (ICC/NSSA, 2020) specifications, and/or FEMA P-361, *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms* (FEMA, 2021), respectively.

Section 423 of the IBC requires that storm shelters are provided for K-12 school buildings with an occupant load of 50 or more people; 911 call stations; fire, rescue, ambulance, and police stations; and emergency operations centers where the design tornado wind speed is 250 mi/h per Figure 304.2(1) in ICC-500.

The new tornado load requirements are based on a decade of research by the National Institute of Standards and Technology (NIST), working with Applied Research Associates, Inc (ARA), the ASCE 7-22 Tornado Task Committee, and others. Tornado hazard maps were developed to define design tornado speeds for a range of return periods. The mapped tornado speeds represent the 3-second-gust tornado speed at 33 feet above the ground. Design tornado speeds use a 1,700- and 3,000-year return period for Risk Category III and IV buildings, respectively. Design tornado speeds are also a function of the plan size and shape of the building, other structure, or facility, as measured by the effective plan area, Ae, the larger the facility, the greater the tornado strike probability. For a given return period, this means that a larger facility has a greater design tornado speed than a smaller facility at the same geographic location. Design tornado speeds are mapped for a wide range of effective plan areas for each Risk Category/return period.

The tornado speed return periods for each risk category are the same mean recurrence intervals (MRIs) used for basic wind speeds in ASCE 7, Chapter 26, and are approximately consistent with the target reliabilities defined in the first row of ASCE 7, Table 1.3-1. Figure 1 presents an example comparison of a basic wind speed map versus tornado speed map for a Risk Category IV structure (3,000-year return period). Basic wind speeds are greater than the tornado speeds everywhere, for the A_e = 100,000 ft^2 map shown. Design tornado speeds range from 60 to 138 mi/h, as a function of Risk Category, effective plan area, and geographic location. This approximately corresponds to tornado intensities of EF0-EF2 on the Enhanced Fujita Scale. In most instances, the design tornado speed will be less than the basic wind speed for a specific structure, However, this does not mean design wind pressures govern over design tornado pressures in most cases for that structure, as will become evident throughout this Design Guide and the design example at the end of this guide.

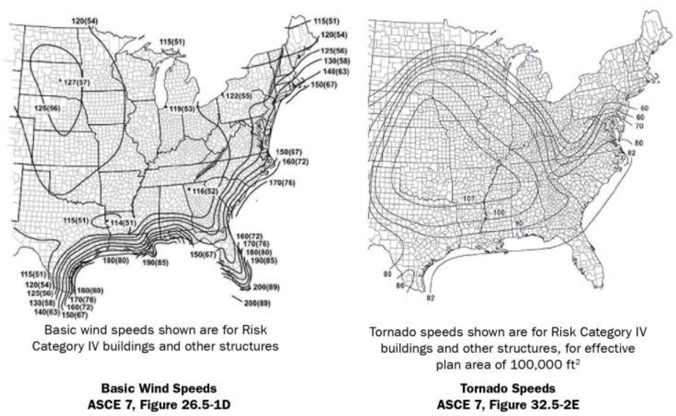


Figure 1: Basic wind speed map versus tornado speed map. Speeds are in mi/h (m/s) (Source: ASCE 7, used with permission from ASCE)

Building stakeholders may elect to design a more resilient structure to higher tornado speeds based on personal risk management decisions. A more resilient structure can be achieved through performance-based design per ASCE 7, Section 1.3.1.3, using mapped basic wind and tornado speeds for longer return periods (10,000-, 100,000-, 1,000,000-, and 10,000,000-year return periods) provided in ASCE 7, Appendices F and G.

Terminology and Basic Design Parameters in ASCE 7-22

The following design guide and basic design parameter definitions refer to the provisions of Chapters 26 through 32 of ASCE 7. This guide uses general design terms applied throughout Chapters 26 through 32. Basic design parameters are coefficients used in the determination of tornado loads on both the MWFRS and C&C per Chapter 32.

Design Guide Terminology

The design guide terms are listed below in alphabetical order.

♣ ASCE 7 Hazard Tool: Online tool that provides site-specific structural design parameters for wind, seismic, snow, ice, rain, flood, tsunami, and tornado load types: https://asce7hazardtool.online/.

♣ Components and Cladding (C&C): Elements of the building envelope or elements of building appurtenances and rooftop structures and equipment that do not qualify as part of the MWFRS.

♣ Enhanced Fujita Scale (EF-Scale): Tornado rating scale that rates the intensity of tornadoes based on theseverity of damage they cause. A tornado is rated as one of six categories (EF0, EF1, EF2, EF3, EF4, or EF5) on this scale, with EF5 being the most intense.

♣ Impact-Protective System: Construction that has been shown by testing to withstand the impact of test missiles and that is applied, attached, or locked over exterior glazing (Section 26.12.3.2).

♣ Main Wind Force Resisting System (MWFRS): An assemblage of structural elements assigned to provide support and stability for the overall building or other structure. The system generally receives wind loading from more than one surface.

♣ Performance-Based Procedures: An alternative to the prescriptive procedures in ASCE 7 that is characterized by project-specific engineering analysis, optionally supplemented by limited testing, to demonstrate that the design is generally consistent with the target reliabilities stipulated in Section 1.3.1.3 (see also Section 32.1.3).

♣ Tornado-Prone Region: The area of the conterminous United States most vulnerable to tornadoes (Figure 32.1-1, which is reproduced in Figure 2).

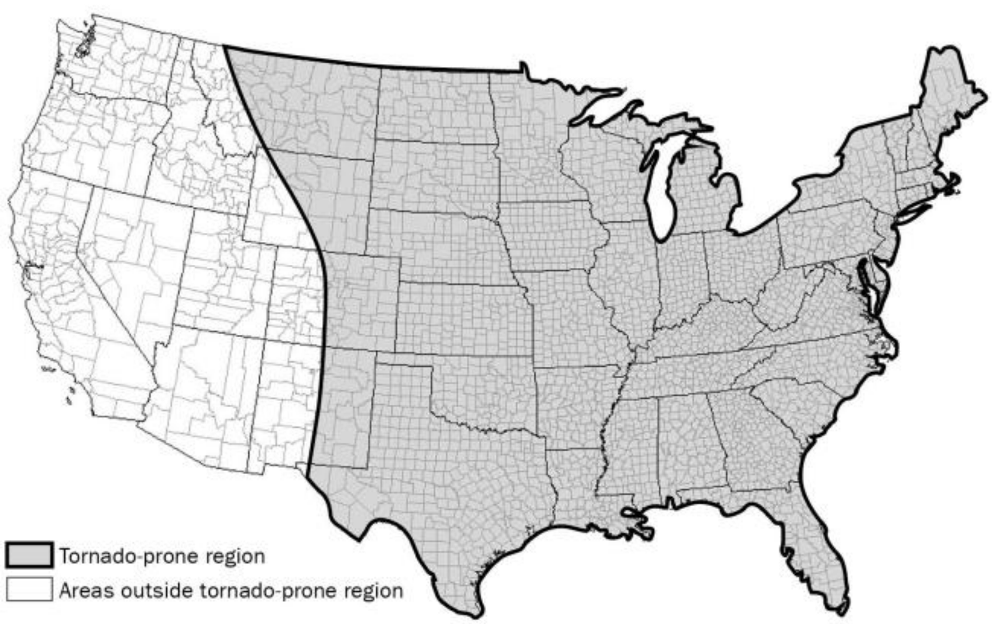


Figure 2: Tornado-prone region (Adapted from ASCE 7, Figure 32.1-1; used with permission from ASCE)

Introduction to Design Parameters Used in the Determination of Tornado Loads

The design parameters are listed below in alphabetical order. Where tornado load parameters are modified versions of corresponding wind load parameters, they are designated with the addition of a subscript $_T$ or $_{Tor}$ on the wind load parameter.

♣ **Basic Wind Speed (V):** The area Basic wind speed obtained from Figures 26.5-1A through 26.5-1D, mi/h (m/s); the basic wind speed corresponds to a 3-second gust at 33 feet (10 meters) above the ground in Exposure Category C.

♣ **Effective Plan Area (A_e)*:** The area of the smallest convex polygon enclosing the plan of the building, other structure, or facility, used in the determination of V_T (Section 32.5.4).

♣ **External Pressure Coefficient (C_p or GC_p):** External pressure coefficient for use in determining MWFRS (C_p) or C&C (GC_p) loads (Chapters 27, 29, 30, and Section 32.18).

♣ **Ground Elevation Factor (K_e):** Adjustment factor to account for the reduced mass density of air as the height of the local ground level above sea level increases (Section 32.9).

♣ **Tornado Design Pressure (p_T)*:** Design tornado pressure to be used in determination of tornado loads for buildings and for certain other structures (Sections 32.15–32.17).

♣ **Tornado Directionality Factor (K_{dT})*:** Factor to account for the less than 100% probability that the maximum tornado winds impacting the building or structure come from any given direction and that the maximum magnitude of pressure coefficient occurs for any given wind direction (Table 32.6-1).

♣ **Tornado Gust Effect Factor (G_T)*:** Factor to account for the decorrelation of wind gusts over the size of the structure (Section 32.11.1).

♣ **Tornado Internal Pressure Coefficient (GC_{piT})*:** Pressure coefficient that accounts for the combined effects of wind-induced internal pressure and atmospheric pressure change (Section 32.13).

♣ **Tornado Pressure Coefficient Adjustment Factor (K_{vT})*:** New modifier on external pressure coefficients to account for effects of vertical components (i.e., strong updrafts) of tornadic wind (Section 32.14), which increase the uplift on roof surfaces.

♣ **Tornado Speed (V_T)***: Three-second gust tornado speed at 33 feet above the ground used in the determination of tornado loads on buildings and other structures, obtained from the tornado hazard maps (Figures 32.5-1A through 32.5-2H or Appendix G).

♣ **Tornado Velocity Pressure (q_{zT} or q_{hT})*:** Velocity pressure evaluated at height z or h above ground (Section 32.10.2).

♣ **Tornado Velocity Pressure Exposure Coefficient (K_{ZTor} or K_{hTor})*** : Coefficient to account for the tornado wind loading profile at different heights above ground level (Table 32.10-1).

* New ASCE 7-22 tornado design parameters

Procedure for Determining When Design for Tornado Loads is Required (ASCE 7, Section 32.5.2)

Not all structures located in the tornado-prone region are required to consider tornado loads per Chapter 32 of ASCE 7. Registered design professionals must determine whether tornado loads are required. If tornado loads are required, the effective plan area of the building, the tornado velocity pressure, and the tornado pressure are to be determined as described in each step below.

Determining Whether Tornado Loads are Required

Buildings and other structures that are classified as Risk Category III or IV and are in the tornado-prone region per Figure 2 (ASCE 7, Figure 32.1-1, modified) may be required to be designed and constructed with consideration for tornado loads determined in accordance with Chapter 32 of ASCE 7. Figure 3 provides a flowchart of the process for determining when design for tornado loads is required. Structures are to be designed using the greater of the wind loads in accordance with Chapters 26 through 31 of ASCE 7 and the tornado loads in accordance with Chapter 32 of ASCE 7 using the load combinations in Chapter 2 of ASCE 7. Depending on tornado speed and the ratio of tornado speed to basic wind speed, tornado loads may not control over wind loads. Hence, two additional criteria for determining if the design requires consideration of tornado loads are provided in the flowchart in Chapter 32 of ASCE 7, and Figure 3 below, to save the designer time when it is clear tornado loads will not control over wind loads.

Building stakeholders have the option, even if not required per ASCE 7, to consider tornado loads or to use a greater risk category or mean recurrence interval in the building design, in addition to performance-based design procedures. Enhanced performance may be an important option for building stakeholders concerned about maintaining functionality of their operations during and after a design-level tornado.

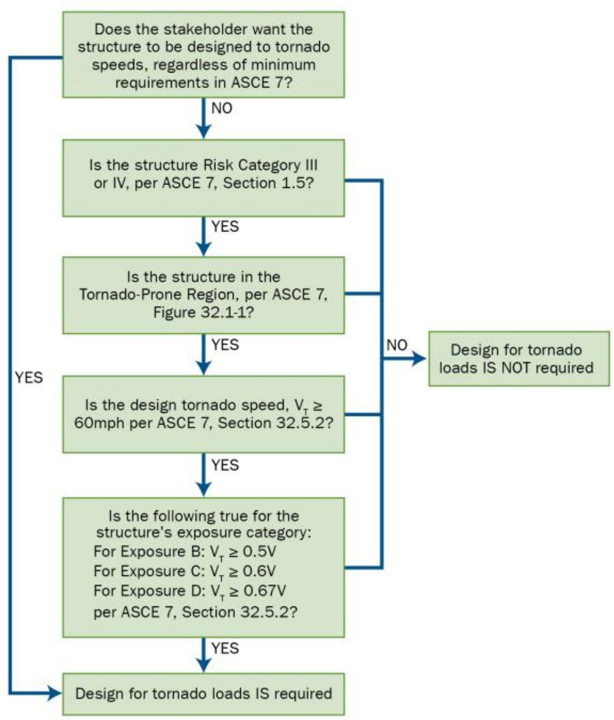


Figure 3: Flowchart for determining when design for tornado loads is required (Adapted from ASCE 7, Figure 32.1-2; used with permission from ASCE)

Procedure for Determining Design Tornado Loads (ASCE 7, Chapter 32)

Figure 4a is a flowchart outlining the design procedure for determining tornado loads in accordance with ASCE 7. This section will discuss the parameters in this flowchart which are unique to tornado load calculations.

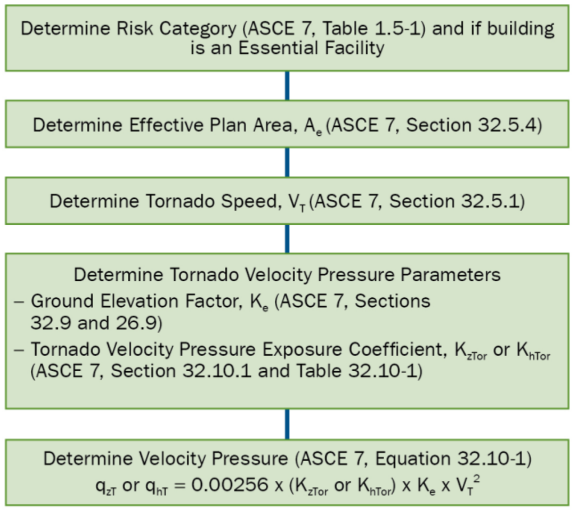


Figure 4a: Determining tornado velocity pressures

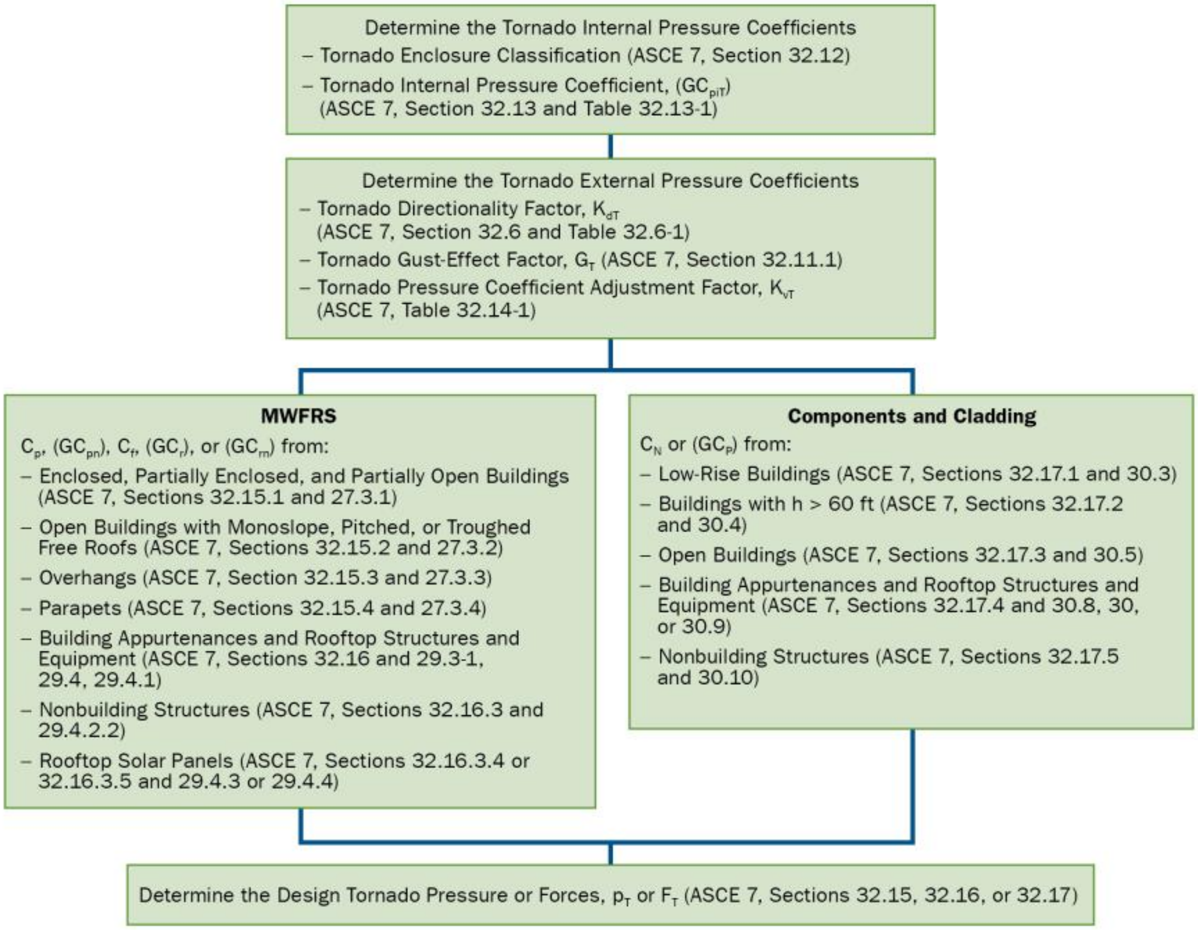


Figure 4b: Determining tornado design pressures and forces

Determining Effective Plan Area (ASCE 7, Section 32.5.4)

The effective plan area, A_e, is defined in ASCE 7, Section 32.5.4, which provides different requirements for Essential Facilities, buildings that are not Essential Facilities, and Ground-Mounted Photovoltaic Panel Systems. The effective plan area of buildings and structures that are not Essential Facilities, is equal to the area of the smallest convex polygon enclosing the plan of the building, as shown in Figure 5. As a more conservative estimate, A_e is equal to the area of the smallest rectangle that encloses the maximum plan area, also shown in Figure 5. For Essential Facilities, the effective plan area includes the area of the smallest convex polygon enclosing both the Essential Facility and all the buildings and other structures required to maintain the functionality of the Essential Facility. An example of this situation could be a hospital with a nearby central utility plant, as illustrated in Figure 6. If the site includes multiple facilities that are structurally independent from each other, then the convex polygon should enclose the Essential Facility and any supporting structure required to maintain operational capabilities of the Essential Facility, as illustrated in Figure 7. Structurally and operationally independent facilities do not need to be included in the same convex polygon.

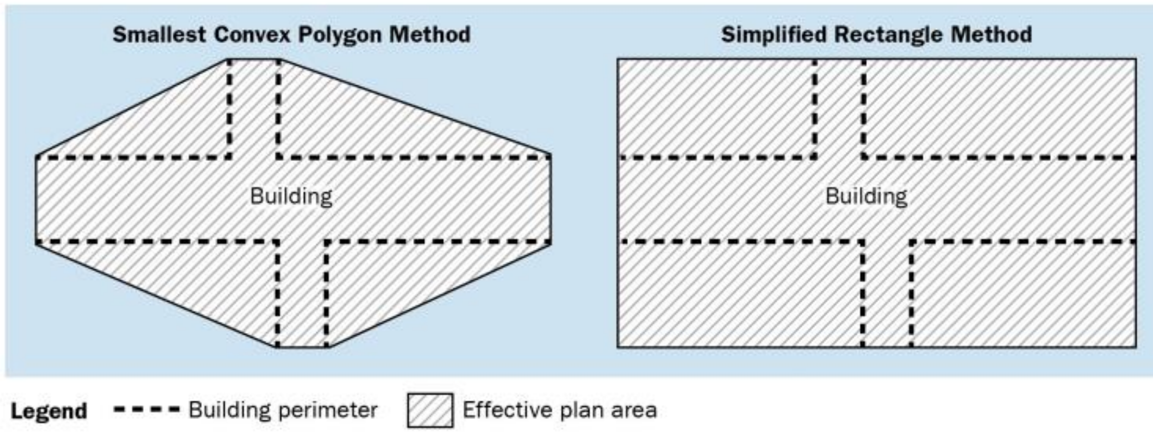


Figure 5: Effective plan areas for buildings that are not essential facilities (Adapted from ASCE 7, Figure C32.5- 1; used with permission from ASCE)

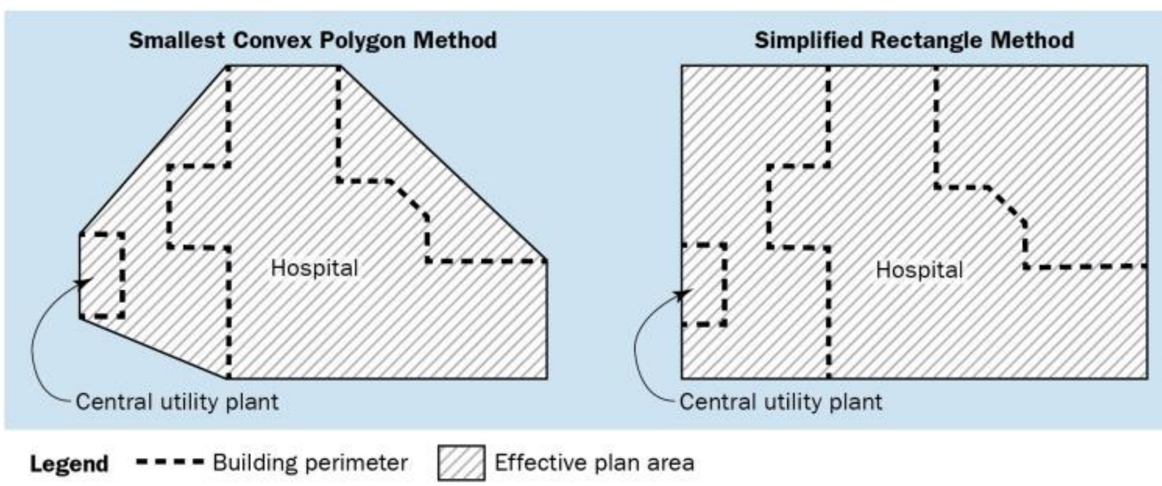


Figure 6: Effective plan area for essential facilities (Adapted from ASCE 7, Figure C32.5-2; used with permission from ASCE)

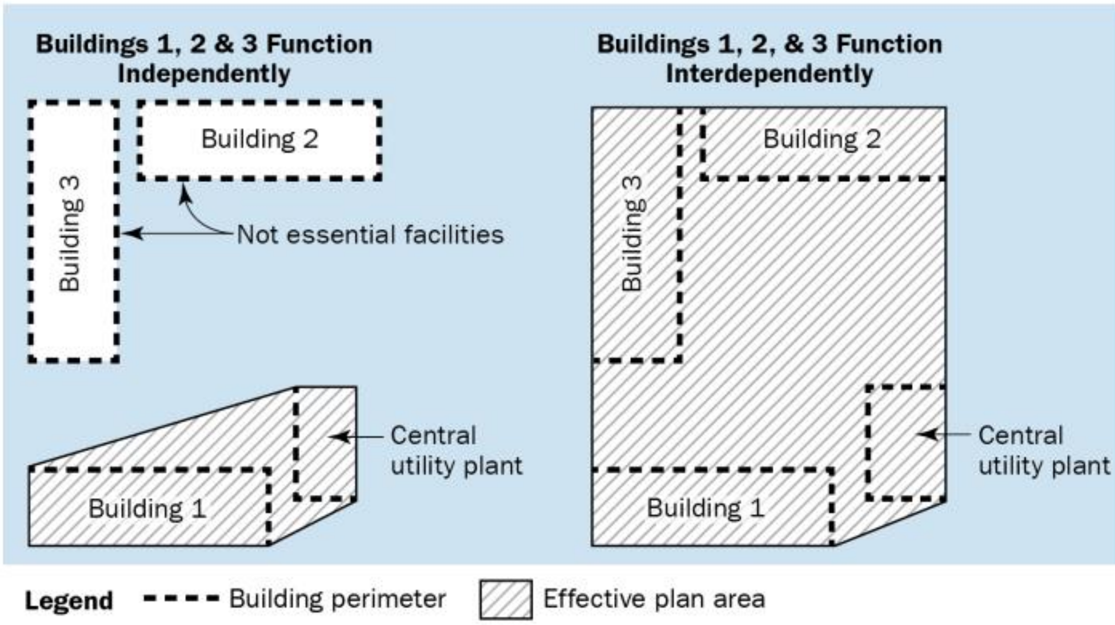


Figure 7: Effective plan for essential facility complexes with multiple buildings

The effective plan area is an important parameter used for determining the design of tornado speed, since tornado strike probabilities and associated maximum tornado speeds increase as the effective plan area increases. Design tornado speed maps are provided for eight different effective plan area sizes: 1, 2,000, 10,000, 40,000, 100,000, 250,000, 1,000,000, and 4,000,000 ft^2

To select the appropriate tornado hazard map to use for the assigned risk category of the building, the effective plan area, A_e, should be rounded up to the next available mapped A_e. Alternatively, linear interpolation of tornado speed between mapped sizes is permitted, using the logarithm of the effective plan area size. For an example of this interpolation methodology, refer to ASCE 7, Commentary C32.5.1.

Determining Tornado Velocity Pressure (ASCE 7, Section 32.10)

The tornado velocity pressure equation in Chapter 32 of ASCE 7 is similar to the wind velocity pressure equation in Chapter 26 of ASCE 7. The tornado velocity pressure is determined by multiplying the square of the tornado speed by the ground elevation factor (K_e), which adjusts for air density at the local ground elevation above sea level, and the tornado velocity pressure exposure coefficient (K_{zTor}), which adjusts for height above ground level. Below is the equation for the tornado velocity pressure evaluated at height z above the ground. The 0.00256 accounts for the air density, along with unit conversions, that allow for velocity pressure units of pounds per square foot when a wind speed, in miles per hour, is squared (See ASCE 7 Commentary Section C26.10.2).

- Tornado Velocity Pressure $q_{zT} = 0.00256 K_{zTor} K_e V_T^2 \left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 32.10-1]

Compare the tornado velocity pressure to the wind velocity pressure equation. The topographic factor, K_{zt}, is not used in the tornado velocity pressure.

- Wind Velocity Pressure $q_z = 0.00256 K_z K_{zt} K_e V^2 \left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 26.10-1]

Exposure and topographic effects are not considered in the determination of the tornado velocity pressure in ASCE 7 because of the difficulty in quantifying the influence that exposure and topography have on the characteristics of a tornado near the ground surface.

The effects of **ground elevation** on air density do not depend on the type of windstorm. The K_e factor for determining the tornado velocity pressure is the same factor as that for determining wind velocity pressure.

The **wind loading profile** for tornadoes, which is represented by the tornado velocity pressure exposure coefficient, varies greatly from the atmospheric boundary layer flows as is shown in Figure 8. Tornado wind speed profiles do not decrease near the ground like boundary-layer winds. Based on average tornado speed profiles derived from mobile doppler radar measurements K_{zTor} is approximately uniform below 200 feet with a value of 1.0, which is equal to the K_z value for Exposure C and 33 feet. Above 328 feet K_{zTor} is 0.9, and values of K_{zTor} vary linearly between 200 and 328 feet.

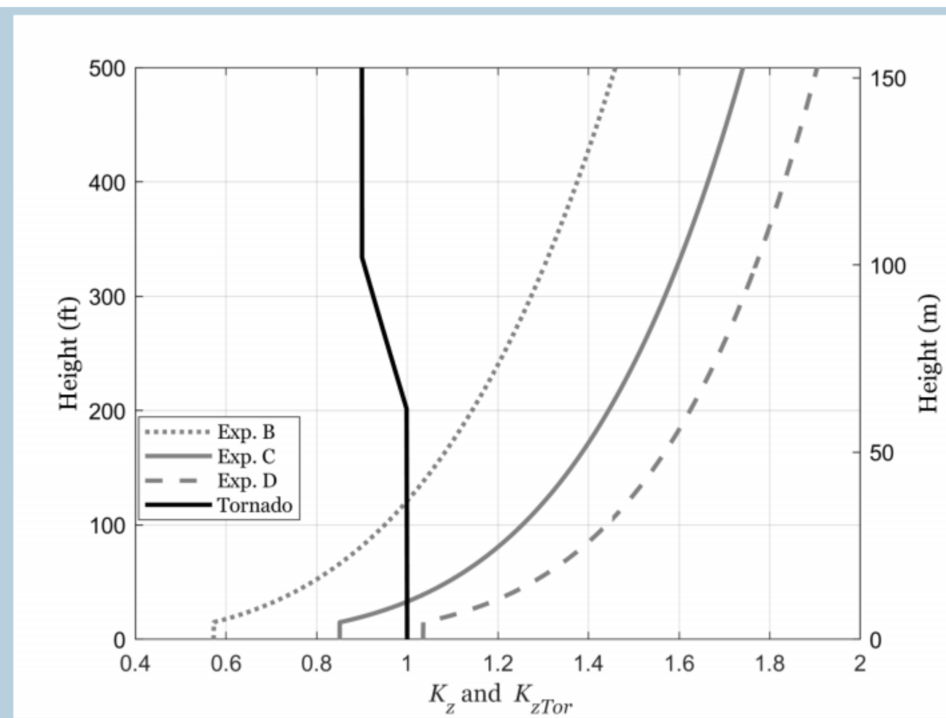


Figure 8: ASCE 7 vertical profiles of velocity pressure exposure coefficients for tornadic winds (K_{zTor}) and non-tornadic winds (K_z) for Exposure B, C, and D

Determining Enclosure Classification (ASCE 7, Section 32.12)

Per ASCE 7, Commentary section C32.12.1, wind-borne debris impacts to unprotected glazing are likely to shatter the glazing and create openings. Rapid changes in the enclosure condition of a structure, can result in a rapid increase in wind loads on MWRFS and C&C elements. To address this concern, glazed openings are to be protected. If gazed openings are not protected, they are to be considered as openings in the building for the purpose of determining the enclosure classification provided in ASCE 7, Section 32.12.2. Typically, unprotected openings will result in the enclosure classification for an enclosed building changing to a partially enclosed classification.

Protection of Glazed Openings (ASCE 7, Section 32.12.3)

Wind-borne debris hazards are greater for tornadoes than for hurricanes due to strong tornadic updrafts, that loft debris higher into the air and allow more time for horizontal acceleration of the debris. Per ASCE 7, Commentary C32.12.2, comparisons of glazing breakage rates between tornadoes and hurricanes have demonstrated higher breakage rates for tornadoes over hurricanes when experienced at approximately the same maximum wind speeds. ASCE 7, Section 32.12.3 provides glazing protection requirements for when tornado loads are being considered.

Protection of Glazed Openings

All glazed openings of Essential Facilities and structures required to maintain the functionality of Essential Facilities are required to be protected in accordance with ASCE 7, Section 32.12.3. Nevertheless, it is a best practice to provide glazed opening protection for all structures subject to tornado loads, especially those where the building owner's performance objective is to reduce loss of function and physical building damage. In addition, it may be cost effective to incorporate impact-resistant glazing in the building envelope instead of designing the structure as partially enclosed.

Protection Requirements

Glazed openings are required to be impact-resistant glazing or be protected with an impact-protective system. The two options for impact-protective systems are presented in ASCE 7, Section 32.12.3.1

ASCE 7-22, Section 32.12.3.1: Impact-protective systems shall be either (a) permanently affixed non-operable systems or (b) permanently affixed operable systems capable of being fully deployed from inside the building within five minutes and used in buildings that are staffed 24 hours per day.

Testing Requirements

Impact-resistant glazing and impact-protective systems are subject to missile tests in accordance with the ASTM International (ASTM) E1996 specifications, using the ASTM E1886 test method, and must comply with the pass/fail criteria of ASTM E1996 Section 7. Exterior windows, glazed curtain walls, and impact protective systems passing impact tests for missile level D, as described in Table 2 of ASTM E1996, satisfy the minimum impact testing requirements of ASCE 7, Section 32.12.3. For a greater level of protection, assemblies/systems passing impact tests for missile level E are recommended. While cyclic pressure tests are required for products in the hurricane wind-borne debris region, they are not required for tornadoes (ASCE 7, Section 32.12.3.1) due to the very short duration of tornadic winds at any given location. Glazed openings in sectional garage doors, rolling doors, and flexible doors are subject to the missile tests in accordance with American National Standards Institute (ANSI) / Door and Access Systems Manufacturers Association (DASMA) 115.

Tornado Missile Impact Requirements: Products that meet missile D and E requirements for use in the hurricane windborne-debris regions (ASCE 7, Section 26.12.3.2) will also meet the tornado missile impact testing requirements of ASCE 7, Section 32.12.3.1.

Determining Tornado Pressures (ASCE 7, Sections 32.15, 32.16, and 32.17)

The procedures and equations for determining tornado loads on the building in compliance with Chapter 32 of ASCE 7 are similar to the ones for determining wind loads in Chapters 26–31 of ASCE 7, exclusive of the Envelope Procedure in Chapter 28 of ASCE 7 (which is not compatible with the tornado load methodology). Basic parameters used in tornado design have been modified to account for the unique characteristics of tornado loads and their interaction with the considered structure. Below are the general equations for tornado design pressure:

- MWFRS* $p_T = qG_TK_{dT}K_{vT}C_p - q_i(GC_{piT})\left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 32.15-1]
- C&C** (h≤60 ft) $p_T = q_{hT}[K_{dT}K_{vT}(GC_p) - (GC_{piT})]\left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 32.17-1]
- C&C (h>60 ft) $p_T = qK_{dT}K_{vT}(GC_p) - q_i(GC_{piT})\left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 32.17-2]

* *Main Wind Force Resisting System*

** *Components and Cladding*

Compare the modified tornado design pressure to the general wind load design pressure equations. As seen below, the tornado design pressure equations are similar to the general wind load design pressure equations, but the tornado design pressure equations include tornado specific design coefficients. The q and q_i velocity pressures in the design tornado pressure equations variously equal q_{zT}, q_{hT} or other values as specified in the noted ASCE 7 equations.

- MWFRS $p = qk_dGC_p - q_iK_d(GC_{pi})\left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 27.3-1]
- C&C (h≤60’) $p = q_hk_d[(GC_p) - (GC_{pi})]\left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 30.3-1]
- C&C (h>60’) $p = qk_d(GC_p) - q_iK_d(GC_{pi})]\left(\frac{lb}{ft^2}\right)$ [ASCE 7, Eq. 30.4-1]

Determining Tornado Pressures for Rooftop Solar Panels (ASCE 7, Sections 32.16)

Chapter 32 of ASCE 7 shall apply when calculating the tornado pressure for rooftop solar panels for low-sloped roofs and rooftop solar panels installed parallel to the roof surface. The equations are presented below.

Rooftop Solar Panels Installed on Low-Sloped Roofs (ASCE 7, Section 32.16.3.4)

This section applies to rooftop solar panels that are not parallel to the roof surface. Equation 1 below is the minimum tornado velocity pressure to be considered per ASCE 7. However, as noted in the ASCE 7 commentary, rooftop solar panels for low-sloped roofs require additional testing to evaluate the nominal net pressure coefficient (GC_{rn}) as it relates to tornado loads. The vertical component of tornadic loads would increase the net uplift pressure acting on the rooftop PV panel. The K_{vT} factor can be applied to ASCE 7, Equation 32.16-6 to account for this increase in net uplift pressure. Equation 2, which includes the K_{vT} factor, is the recommended best practice equation for calculating tornado velocity pressure for rooftop solar panels that are not parallel to the roof surface.

$$(1)\ p_T = q_{hT} K_{dT} (GC_{rn}) \left(\frac{lb}{ft^2}\right)$$

$$(2)\ p_T = q_{hT} K_{dT} K_{vT} (GC_{rn}) \left(\frac{lb}{ft^2}\right)$$

GC_{rn} = Net pressure coefficient from ASCE 7, Section 29.4.3

Rooftop Solar Panels Installed Parallel to the Roof Surface (ASCE 7, Section 32.16.3.5)

Tornado loads on rooftop solar panels parallel to the roof surface are calculated based on external pressure coefficient for components and cladding (C&C) for the roof zone below the affixed system. The additional vertical component of the tornadic winds amplifies the net uplift pressure (ASCE 7, Commentary C32.14).

$$p_T = q_{hT} K_{dT} K_{vT} (GC_p)(\gamma_E)(\gamma_a) \left(\frac{lb}{ft^2}\right)$$

γ_E = Array edge factor from ASCE 7, Section 29.4.4

γ_a = Solar panel pressure equalization factor from ASCE 7, Section 29.4.4

GC_p = External pressure coefficient from ASCE 7, Section 29.4.4

Load Combinations (ASCE 7, Chapter 2)

Structures, components, and foundations are required to be designed so that their design strength equals or exceeds the effects of the combined static and dynamic loading conditions. A continuous load path must be provided for transmitting external forces to the foundation. The most unfavorable effects from wind loads, tornado loads, and earthquake loads should be considered in the design, but they do not need to be considered as acting simultaneously. Tornado loads are separate from wind loads in the revised load combinations in ASCE 7. The revisions to load combinations in ASCE 7 include replacing the previous wind load coefficient “W” with “(W or W_T),” for combinations where wind is the principal load.

D = Dead load	L = Live load	L_r = Roof live load	S = Snow load
R = Rain load	W = Wind load	W_T = Tornado Load	

Load Combinations for Strength Design

For MWFRS and C&C loads for use with Strength Design methods as indicated in ASCE 7, Section 2.3, the basic combinations of the factored loads considering tornado loads are determined using the following equations:

4a. $1.2D + 1.0\,(W \text{ or } W_T) + L + (0.5L_r \text{ or } 0.3S \text{ or } 0.5R)$

5a. $0.9D + 1.0\,(W \text{ or } W_T)$

Exception: Where using W_T in combination 4a, ($0.5L_r$ or 0.3S or 0.5R) is permitted to be replaced with 0.5 (L_r or R) per ASCE 7, Section 2.3.1, because tornadoes are generally warm weather phenomena and, therefore, snow load is unlikely to occur simultaneously with tornado load.

Load Combinations for Allowable Stress Design

For structural elements designed according to Allowable Stress Design (ASD) as indicated in ASCE 7, Section 2.4, the basic combinations of loads considering tornado loads are:

5a. $D + 0.6\,(W \text{ or } W_T)$

6a. $D + 0.75L + 0.75\,(0.6\,(W \text{ or } W_T)) + 0.75\,(L_r \text{ or } 0.7S \text{ or } R)$

7a. $0.6D + 0.6\,(W \text{ or } W_T)$

Exception: Where using W_T in combination 6a, 0.75 (L_r or 0.7S or R) is permitted to be replaced with 0.75 (L_r or R) per ASCE 7, Section 2.4.1.

Design Example

The following design example is based on a hypothetical hospital in Tulsa, Oklahoma in an area of relatively flat terrain with dense urban and suburban development extending at least 2,600 feet in all directions. The hospital consists of a main building with an independent central utility plant that is critical to the operation of the hospital. The hospital provides essential medical care to the community and is intended to remain operational after severe windstorms. The main hospital building is five stories (70 feet), with 4-foot-tall parapets, and a flat roof as shown in Figure 9. The hospital has 10-foot by 8-foot (height x width) windows on all sides of the building. The hospital consists or precast concrete wall panels supported by reinforced concrete moment frame system.

This example is intended to provide a comparison between the wind load calculations of ASCE 7, Chapters 26 through 30, and the tornado load calculations of ASCE 7, Chapter 32. This example examines roof and roof overhang design pressures on the MWFRS, C&C design pressures on walls and parapets, and MWFRS design lateral and uplift pressures on rooftop equipment.

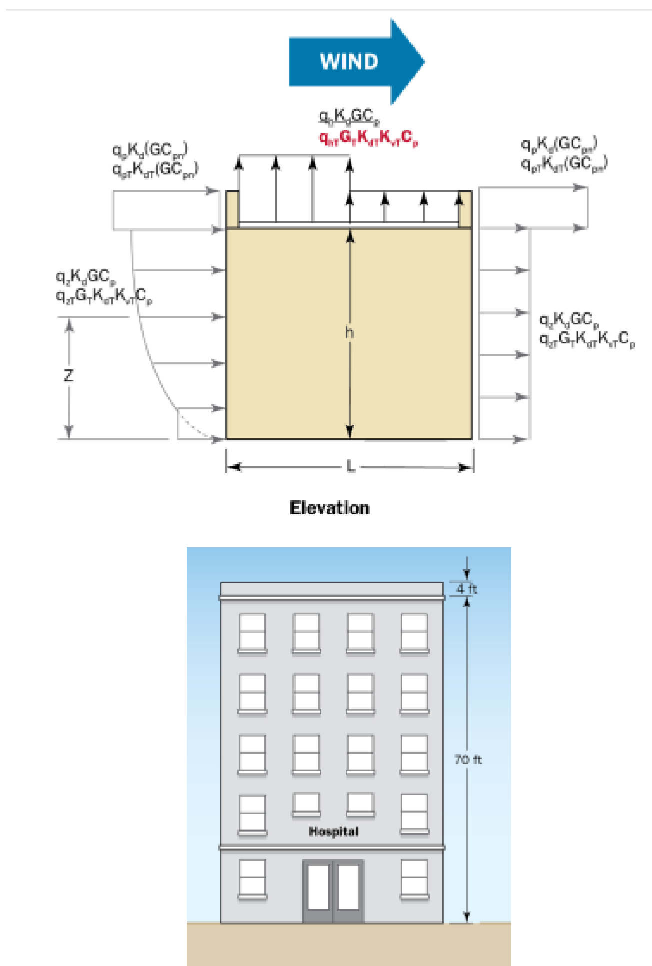


Figure 9: Elevation view of example hospital

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design
Step 1: Determine if Design for Tornado Loads is Required	

i) Per the flowchart shown in **Figure 3**, determine if design for tornado loads is required for the hospital. Hospitals are defined as Risk Category IV in ASCE 7, Table 1.5-1. This hospital is intended to remain operational in an extreme event; therefore, it is classified as an Essential Facility.

ASCE 7, Table 1.5-1
Hospital Structure: **Risk Category IV**

The hospital is a Risk Category IV Structure; therefore, tornado loads is required.

ii) Per Figure 32.1-1 in ASCE 7, Tulsa, Oklahoma is located in the tornado-prone region, star on **Figure 10** below.

Figure 10: Hospital effective plan area (Adapted from ASCE 7, Figure 32.1-1; used with permission from ASCE)

Tulsa, Oklahoma is located in the tornado-prone region; therefore, tornado loads is required.

iii) To be able to determine the design tornado speed, V_T, first the effective plan area needs to be determined. The effective plan area is needed for determination of the design tornado speed. The effective plan area was calculated using the smallest convex polygon method and includes the hospital structure and the critical support structure (central utility plant) as shown in **Figure 11**.

ASCE 7, Section 32.5.4
Effective Plan Area: A_e = **50,000 ft²**

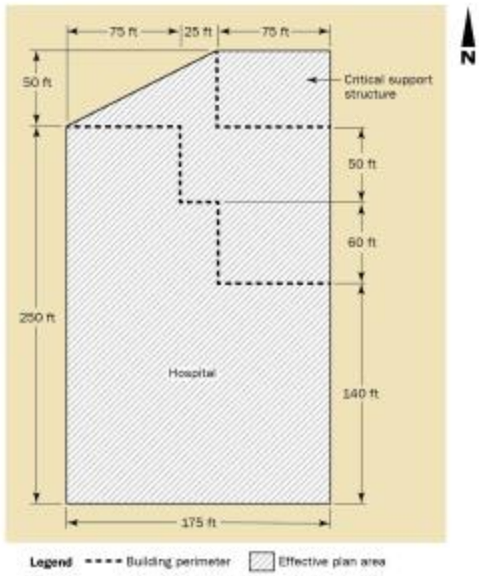


Figure 11: Hospital effective plan area

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design

iv) Basic wind and tornado speeds have been determined for the hospital location in Tulsa using the ASCE 7 hazard tool located at https://asce7hazardtool.online/ as shown in **Figure 12**. To determine the tornado speed, the effective area is rounded up to the next available mapped A_e of 100,000 ft^2. Notice that the ASCE 7 hazard tool provides data for higher mean recurrence intervals per ASCE 7, Appendix G, for use with performance-based tornado design (see ASCE 7 Section 32.1.3 and associated commentary).

ASCE 7, Fig. 26.5-1D	ASCE 7, Fig. 32.5-2E
Basic Wind Speed: V = 120 mi/h	Tornado Speed: V_T = 107 mi/h

Figure 12: ASCE 7 hazard tool located at https://asce7hazardtool.online/ (Adaption, used with permission from ASCE)

V_T is greater than 60 mi/h; therefore, tornado loads is required.

v) To satisfy the requirements of Section 32.5.2, the exposure category of the hospital is to be determined. The Exposure Category for the hospital area was determined to be B based on the definitions provided in ASCE 7, Sections 26.7.2 and 26.7.3.

<u>ASCE 7, Sec. 26.7.2</u> Exposure Category: B (Tulsa, Dense Urban and Suburban)	Not applicable

With the exposure category B determined for the project location, verify that $V_T > 0.5V$.

$0.5V = 0.5 \times 120\ mi/h$ $0.5V$ = 60 mi/h	V_T = 107 mi/h

V_T is greater than 0.5V, 60 mi/h; therefore, tornado loads is required. All of the requirements in the flowchart shown in Figure 3 have been confirmed, requiring that tornado loads be developed for the hospital.

<table>
<tr><th colspan="2">Step 2: Determine Velocity Pressure</th></tr>
<tr><td colspan="2">i) The topographic factor adjusts the wind velocity pressure to account for speedup effects where hills, ridges, or escarpments are present. No such terrain is present at the hospital site; therefore, the topographic factor has been taken as 1.0. Topographic effects on tornadic wind speeds are not fully understood and, therefore, the topographic factor is not currently used in the tornado load procedure.</td></tr>
<tr><td><u>ASCE 7, Sec. 26.8.2</u>
Topographic Factor: K_{zt} = 1.0</td><td>Not applicable</td></tr>
<tr><td colspan="2">ii) The ground elevation factor adjusts for air density and is based on the elevation of the site above sea level. The ground elevation for the proposed site is less than 1,000 feet; therefore, the ground elevation factor is taken as 1.0. This is slightly conservative; a value of 0.97 could alternately be used for this site having an elevation of 713 feet above sea level, per ASCE 7, Table 26.9-1.</td></tr>
<tr><td>Chapters 26–30: Wind Load Design</td><td>Chapter 32: Tornado Load Design</td></tr>
<tr><td colspan="2"><u>ASCE 7, Sec. 26.9 and 32.9</u>
Ground Elevation Factor: K_e = 1.0</td></tr>
<tr><td colspan="2">iii) The wind and tornado velocity pressure coefficients are tabulated in ASCE 7, Chapters 26 and 32, respectively. In the case of Wind Load Design, the velocity pressure coefficient is selected based on the height above ground level and the Exposure Category. Separate values have been determined for the roof level (h= 70 feet) and the parapet level (z=h_p = 74 feet) because of the difference in height. The tornado velocity pressure coefficient is determined solely on the height above ground level and the same value applies to both the roof and parapet level in this case, since K_{zTor} = 1.0 for all heights below 200 feet.</td></tr>
<tr><td><u>ASCE 7, Table 26.10-1</u>
Velocity Pressure Exposure Coefficient (Walls, Roof):

K_h= 0.86

Velocity Pressure Exposure Coefficient (Parapet):

K_{h_p} = 0.88</td><td><u>ASCE 7, Table 32.10-1</u>
Tornado Velocity Pressure Coefficient:

$K_{hTor} = K_{h_pTor}$ = 1.0</td></tr>
<tr><td colspan="2">iv) The velocity pressure is found by multiplying the square of the wind speed by the velocity pressure coefficient, ground elevation factor, and topographic factor. The tornado velocity pressure equation does not include a topographic factor.</td></tr>
<tr><td><u>ASCE 7, Eq. 26.10-1</u>
$q_h = 0.00256 K_h K_{zt} K_e (V)^2$

Wind Velocity Pressure (Walls, Roof):
$q_h = 0.00256 \times 0.86 \times 1.0 \times 1.0 \times (120\ mi/h)^2$

q_h = 31.7 psf</td><td><u>ASCE 7, Eq. 32.10-1</u>
$q_{hT} = 0.00256 K_{hTor} K_e (V_T)^2$

Tornado Velocity Pressure:
$q_{hT} = 0.00256 \times 1.0 \times 1.0 \times (107\ mi/h)^2$

q_{hT} = 29.3 psf</td></tr>
</table>

Velocity Pressure (Parapet): $q_p = 0.00256 \times 0.88 \times 1.0 \times 1.0 \times (120\ mi/h)^2$ q_p = 32.4 psf	For tornado loads, the velocity pressure for the parapet is the same as for the remainder of the structure. q_{pT} = 29.3 psf
Step 3: Determine Internal Pressure Coefficients	
i) The enclosure classification, for Wind Load Design, is made using definitions in ASCE 7, Section 26.2 and guidance provided in Sections 26.12 and 26.13. The hospital, located in Tulsa, Oklahoma, is outside of the hurricane-prone region and does not have an imbalance of openings on the building enveloped. As result, for Wind Load Design, the building classification is Enclosed. The enclosure classification, for Tornado Load Design, is made using the guidance per ASCE 7, Section 32.12. The hospital is an Essential Facility and per ASCE 7, Section 32.12.3. protected glazed openings is required. Therefore, for Tornado Load Design, the Tulsa hospital is defined as Enclosed.	
<u>ASCE 7, Sec. 26.12</u> Building Classification: **Enclosed**	<u>ASCE 7, Sec. 32.12</u> Building Classification: **Enclosed**
Chapters 26–30: Wind Load Design	**Chapter 32: Tornado Load Design**
ii) The internal pressure coefficients are selected from the relevant table based on the corresponding enclosure classification. Note the large positive pressure coefficient for tornado loads, which is due to the contribution of Atmospheric Pressure Change (APC) to wind-induced internal pressure for enclosed buildings.	
<u>ASCE 7, Table 26.13-1</u> Internal Pressure Coefficient: GC_{pi} = (+0.18; -0.18)	<u>ASCE 7, Table 32.13-1</u> Tornado Internal Pressure Coefficient: GC_{piT} = (+0.55; -0.18)
Step 4: Determine the Directionality Factor, Gust-Effect Factor and External Pressure Coefficients	
i) The directionality factors are determined based on the type of structure being considered. Under wind loading, the Tulsa hospital has the same directionality factor for the MWFRS, C&C, and rooftop equipment. Under tornadic loads, the hospital has distinct directionality factors for MWFRS and C&C. Note that K_{dT} =1.0 for C&C since this hospital is an Essential Facility. Rooftop equipment is defined as "All other structures" and has a third directionality factor taken from ASCE 7, Table 26.6-1 (as referenced by ASCE 7, Table 32.6-1).	
<u>ASCE 7, Table 26.6-1</u> Directionality Factor: K_d = 0.85	<u>ASCE 7, Table 32.6-1</u> Tornado Directionality Factor: MWFRS: K_{dT} = 0.8 C&C: K_{dT} = 1.0 Rooftop Equipment: K_{dT} = 0.85 (ASCE 7, Table 26.6-1 as referenced by ASCE 7, Table 32.6-1)

ii) A simplified gust-effect factor for rigid buildings is provided in ASCE 7, Sections 26.11.1 and 32.11.1 and is the same for both wind and tornado loads. Alternatively, ASCE 7, Sections 26.11.4 and 26.11.5 provide a more detailed equation for gust effect factors for rigid and flexible buildings, respectively. If using the detailed method for rigid buildings, the gust effect factor for wind would be computed based on Exposure B in this case, while tornado gust effect factor is always computed using Exposure C.

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design
ASCE 7, Sec. 26.11.1 Gust-Effect Factor: **G = 0.85**	ASCE 7, Sec. 32.11.1 Tornado Gust-Effect Factor: **G_T = 0.85**

iii) The tornado pressure coefficient adjustment factor modifies the external pressure portion of design tornado pressure equations to account for the vertical winds (i.e. updrafts) in tornados. The adjustment factors are tabulated with a corresponding structure type.

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design
	ASCE 7, Table 32.14-1 Tornado Pressure Coefficient Adjustment Factor: Uplift Pressure on MWFRS Roofs: **K_{vT} = 1.1** Downward Acting Pressure on MWFRS Roofs: **K_{vT} = 1.0** Wall Pressures: **K_{vT} = 1.0** Uplift Pressure on Rooftop Equipment: **K_{vT} = 1.1**

Chapters 26–30: Wind Load Design | **Chapter 32: Tornado Load Design**

iv) ASCE 7 organizes external pressure coefficients into tables separated by design system (MWFRS vs C&C), enclosure classification, building size, and the element being considered. For this example, the MWFRS loads for the roof and overhang components of the Tulsa hospital are determined with respect to wind blowing from East to West, i.e., the Eastern face of the building is the windward wall. The hospital is an enclosed structure, so ASCE 7, Figure 27.3-1 is used. The hospital has a low slope roof (θ<10°) and h/L = -70 feet / 175 feet = 0.4 ≤ 0.5 in this direction; therefore, the external pressure coefficients are selected from the center table of ASCE 7, Figure 27.3-1. Loads are calculated in this example for the windward portion of the roof, which extends from the windward edge to a distance of h/2 = 35 feet inward.

ASCE 7, Fig. 27.3-1
Roof Pressure Coefficients:
C_p = (-0.18; -0.9)

v) The MWFRS external pressure coefficient for roof overhangs is determined per ASCE 7, Section 27.3.3. This additional positive pressure acting on the bottom surface of the windward overhang is combined with the uplift pressure on the roof overhang as shown in **Figure 15**. This is done by adding 0.8 from the windward wall/underside of the overhang to the roof surface pressure coefficients from Step 4-iv.

ASCE 7, Sec. 27.3.3
Roof Overhang Pressure Coefficients:
C_p = (-0.18 + -0.8; -0.9 + -0.8)
C_p = (-0.98; -1.7)

vi) For this example, the C&C loads for the window and windward parapet elements of the Tulsa hospital are determined. ASCE 7, Figure 30.4-1 is selected because the hospital is an enclosed structure over 60 feet in height. When considering the wall pressures, the effective wind area is taken as the area of the 10-foot by 8-foot (height x width) windows or 80 ft^2. Note that there are two zones to be considered for the walls as shown in Figure 13. The outer edge, Zone 5, experiences significantly greater suction pressures than the middle section, Zone 4.

<u>ASCE 7, Fig. 30.4-1</u>

Wall Pressure Coefficients for Windows:

Zone 4: $(GC_p) = (+0.8; -0.8)$

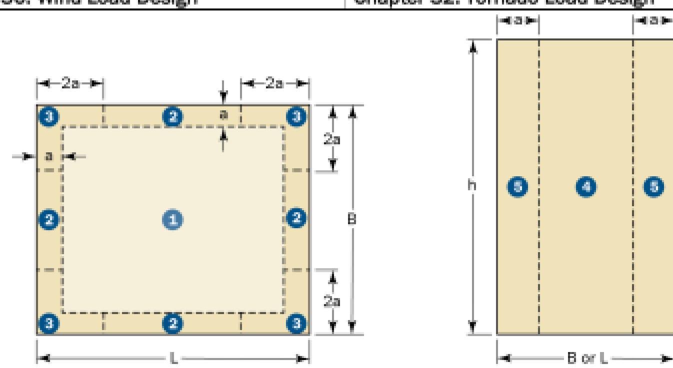
Zone 5: $(GC_p) = (+0.8; -1.45)$

The width of Zone 5, a, is 10% of the least horizontal dimension (10% of 175 feet), but not less than 3 feet.

<u>ASCE 7, Fig. 30.4-1</u>

a = 17.5 feet

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design



Roof Plan **Wall Elevation**

Figure 13: Roof and Wall Pressure C&C Zone Diagram

vii) The parapet external pressure coefficients are the combined values of the adjacent wall and roof coefficients as shown in Figure 16. For the parapet, the effective wind area is the span multiplied by the tributary width used to evaluate (GC_p). The parapet is constructed of reinforced precast concrete; therefore, the effective tributary width need not be taken as less than one-third the length of the area (see ASCE 7, Commentary C26.2). The calculated effective wind area is 4 feet x (4 feet/3) = 5.3 ft^2 Because the parapet is greater than 3 feet tall and provided around the perimeter of the roof with $\theta < 10°$, Zone 3 should be treated as Zone 2 (Note 7 in ASCE 7, Figure 30.4-1). The calculations below consider the windward load Case A as shown in ASCE 7, Figure 30.6-1 and Figure 16. Per ASCE 7, Commentary C29.5, since the parapet is constructed from a solid material, the internal pressure is zero because there is not internal cavity.

ASCE 7, Fig. 30.6-1

Windward Face of Windward Parapet (pressure 'p_1' of ASCE 7, Figure 30.6-1) – use Windward Wall Pressure Coefficients per ASCE 7, Figure 30.4-1 (pressure 'p_5' of ASCE 7, Figure 30.6-1):

Zone 4: $(GC_p) = +0.9$

Zone 5: $(GC_p) = +0.9$

Leeward Face of Windward Parapet (pressure 'p_2' of ASCE 7, Figure 30.6-1) – use Roof Pressure Coefficients per ASCE 7, Figure 30.4-1 (pressure 'p_7' of ASCE 7, Figure 30.6-1):

Zone 3: $(GC_p) = -3.2$

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design

viii) The rooftop equipment in this example is assumed to have an area less than 0.1B x h and 0.1B x L.

ASCE 7, Sec. 29.4-1

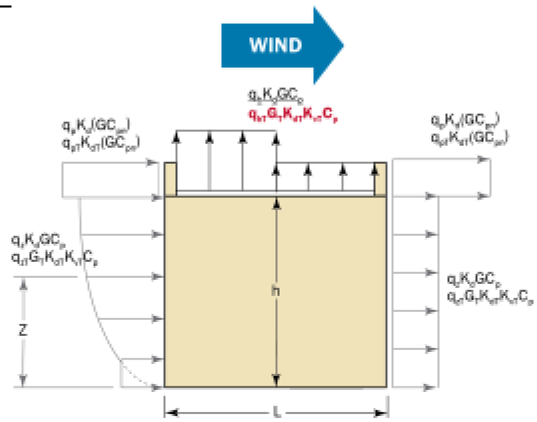
Rooftop Equipment – Horizontal Pressure Coefficient: $(GC_r) = 1.9$

Rooftop Equipment – Vertical Pressure Coefficient: $(GC_r) = 1.5$

Step 5: Determine Design Wind/Tornado Pressure – MWFRS

i) The design wind and tornado pressure equations are selected based on the enclosure classification and the element being designed. For external pressures, the velocity pressure is multiplied by an external pressure coefficient and directionality factor and a gust factor (either explicit or combined with the pressure coefficient). The design tornado pressure also includes the pressure coefficient adjustment factor from step 4.iii as a modification of the external pressure to account for the additional uplift on roof surfaces due to tornado updrafts. While the pressure coefficients are the same for both tornado and wind load design, the directionality factor and velocity pressures are distinct.

The external vertical design pressures applied to the roof system (black underlined and red bold text) and the external horizontal design pressures applied to the walls and parapets (dark grey non-underlined, non-bold text) are shown in Figure 14. For the roof design, external pressure coefficients from step 4.iv are used. Internal and external pressure coefficient combinations have been selected to provide upper and lower bounds.



Elevation

Figure 14: MWFRS external pressure diagram

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design
ASCE 7, Eq. 27.3-1 MWFRS Roof Wind Pressures: $p = qK_dGC_p - q_iK_d(GC_{pi})$ $p = 31.7\,psf \times 0.85 \times 0.85 \times (-0.18) - 31.7\,psf \times 0.85 \times (-0.18)$ **p = +0.7 psf** $p = 31.7\,psf \times 0.85 \times 0.85 \times -0.9 - 31.7\,psf \times 0.85 \times (+0.18)$ **p = -25.5 psf**	ASCE 7, Eq. 32.15-1 MWFRS Roof Tornado Pressures: $p_T = q_TG_TK_{dT}K_{vT}C_p - q_i(GC_{piT})$ $p_T = 29.3\,psf \times 0.85 \times 0.8 \times 1.0 \times (-0.18) - 29.3\,psf \times (-0.18)$ **p_T = +1.7 psf** $p_T = 29.3\,psf \times 0.85 \times 0.8 \times 1.1 \times -0.9 - 29.3\,psf \times (+0.55)$ **p_T = -35.8 psf**

For this design example, the windward MWFRS roof would be designed for a maximum uplift pressure of 35.8 psf. The tornado pressure governs over wind pressure in uplift load combinations 5a for Strength Design, or 7a for ASD. Tornado also controls the downward acting wind pressure on the roof (1.7 psf). This would be used in load combinations that maximize wind effects concurrent with gravity loads, i.e., Strength Design combination 4a or ASD combinations 5a and 6a. The downward acting wind pressure of 0.7 psf would be used in Strength Design combination 3a, or ASD combination 6a where snow loads control over roof live and rain loads.

ii) The design pressure coefficients applied to the roof overhang are shown in **Figure 15.** For the roof overhang design, external pressure coefficients from step 4.v are used. In step 4.v, there are two external pressure coefficients; the larger value will govern by inspection and as such the smaller value does not need to be tabulated. The internal pressures act in opposing directions on the bottom and top of the overhang surface and, therefore, are not considered when determining MWFRS roof overhang pressures.

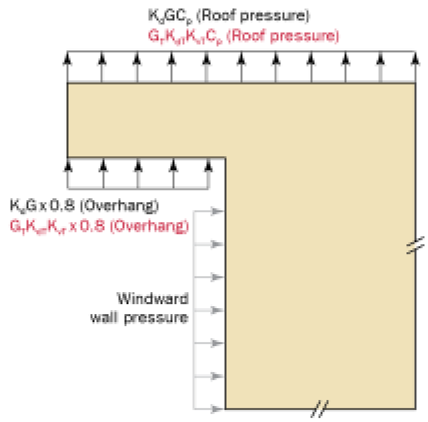


Figure 15: MWFRS overhang external pressure coefficient diagram

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design
<u>ASCE 7, Eq. 27.3-1</u> MWFRS Roof Overhang Wind Pressures: $p = qK_dGC_p - q_iK_d(GC_{pi})$ $p = 31.7\ psf \times 0.85 \times 0.85 \times -1.7$ **p = -38.9 psf**	<u>ASCE 7, Eq. 32.15-1</u> MWFRS Roof Overhang Tornado Pressures: Please note that K_{vT} is to be applied for both the roof (1.1) and the walls (1.0). $p_T = q_TG_TK_{dT}K_{vT}C_p - q_i(GC_{piT})$ $p_{hT} = 29.3\ psf \times 0.85 \times 0.8 \times [1.1 \times (-0.9) + 1.0 \times (-0.8)]$ **p_T = –35.7 psf**

For this design example, the MWFRS roof overhang would be designed for an uplift pressure of 38.9 psf. The wind load design pressure governs over the tornado pressure. Note, internal pressures cancel out MWFRS overhang pressures and thus are not included in the calculations.

Step 6: Determine Design Wind/Tornado Pressure – C&C

i) The design wind and tornado pressure equations for C&C are selected based on the building height, enclosure classification and the element being designed. For external pressures, the velocity pressure is multiplied by an external pressure coefficient and directionality factor. The design tornado pressure also includes the pressure coefficient adjustment factor from step 4.ii. While the basic pressure coefficients are the same for both tornado and wind load design, the directionality factor and velocity pressure are distinct.

The windows will be designed for a C&C wind or tornado pressure. The window external pressure coefficients from step 4.vi are used. Internal and external pressure coefficients have been selected to provide upper and lower bounds. For Zone 4 and 5 definitions, refer to Figure 13.

<u>ASCE 7, Eq. 30.4-1</u>

C&C Design Wind Pressures – Zone 4 Windows:

$$p = qK_d(GC_p) - q_iK_d(GC_{pi})$$

$$p = 31.7\ psf \times 0.85 \times (+0.8) - 31.7\ psf \times 0.85 \times (-0.18)$$

p = +26.4 psf

$$p = 31.7\ psf \times 0.85 \times (-0.8) - 31.7\ psf \times 0.85 \times (+0.18)$$

p = -26.4 psf

<u>ASCE 7, Eq. 32.17-2</u>

C&C Design Tornado Pressures – Zone 4 Windows:

$$p_T = qK_{dT}K_{vT}(GC_p) - q_i(GC_{piT})$$

$$p_T = 29.3\ psf \times 1.0 \times 1.0 \times (+0.8) - 29.3\ psf \times (-0.18)$$

p_T = +28.7 psf

$$p_T = 29.3\ psf \times 1.0 \times 1.0 \times (-0.8) - 29.3\ psf \times (+0.55)$$

p_T = -39.6 psf

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design
C&C Design Wind Pressure – Zone 5 Windows:	C&C Design Tornado Pressures – Zone 5 Windows:
$p = qK_d(GC_p) - q_i K_d(GC_{pi})$	$p_T = qK_{dT}K_{vT}(GC_p) - q_i(GC_{piT})$
$p = 31.7\ psf \times 0.85 \times (+0.8) - 31.7\ psf \times 0.85 \times (-0.18)$	$p_T = 29.3\ psf \times 1.0 \times 1.0 \times (+0.8) - 29.3\ psf \times (-0.18)$
p = +26.4 psf	**p_T = +28.7 psf**
$p = 31.7\ psf \times 0.85 \times (-1.45) - 31.7\ psf \times 0.85 \times (+0.18)$	$p_T = 29.3\ psf \times 1.0 \times 1.0 \times (-1.45) - 29.3\ psf \times (+0.55)$
p = -43.9 psf	**p_T = -58.6 psf**

For this design example, the windows within Zone 4 would be designed for a positive (i.e., inward acting) pressure of 28.7 psf and a negative (i.e., outward acting) pressure of 39.6 psf. The windows within Zone 5 would be designed for a positive pressure of 28.7 psf and a negative pressure of 58.6 psf. The tornado pressures govern in each case.

ii) Equations for the design wind/tornado pressure for parapets have been selected from the C&C portions of ASCE 7, Chapters 30 and 32. These equations are similar for both wind and tornado design. The effective wind area and resultant design pressures coefficients, which were determined in step 4.vii, are applied to the windward parapet (Load Case A from ASCE 7, Figure 30.6-1) are shown in Figure 16.

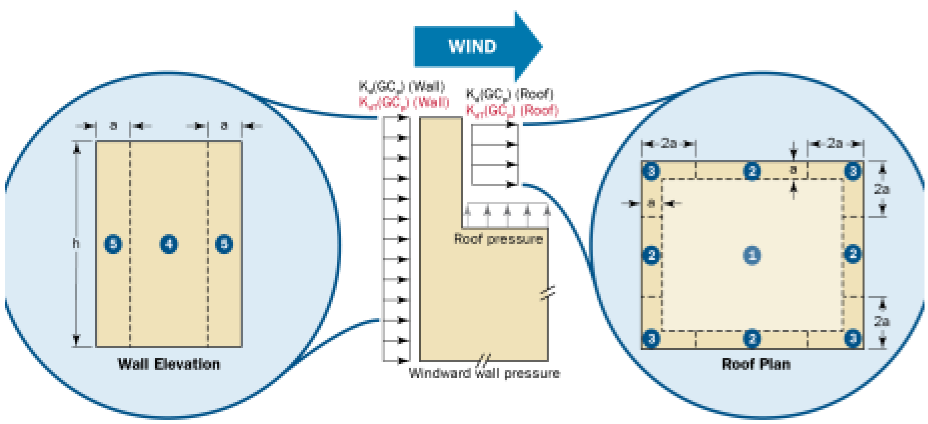


Figure 16: Parapet C&C External Pressure Coefficient Diagram

<table>
<tr><th>Chapters 26–30: Wind Load Design</th><th>Chapter 32: Tornado Load Design</th></tr>
<tr><td><u>ASCE 7, Eq. 30.6-1</u>
C&C Windward Face of Windward Parapet Design Wind Pressure – Zones 4 & 5:
$p = q_p K_d((GC_p) - (GC_{pi}))$
Per C29.5, the internal pressure coefficient, is zero as the parapet is composed of a solid material.
$p = 32.4\, psf \times 0.85 \times ((+0.9) - (0.0))$

p = +24.8 psf

C&C Leeward Face of Windward Parapet Design Wind Pressure – Zone 3:
$p = q_p K_d((GC_p) - (GC_{pi}))$
$p = 32.4\, psf \times 0.85 \times ((-3.2) - (0.0))$
p = -88.1 psf</td><td><u>ASCE 7, Eq. 32.17-4</u>
C&C Windward Face of Windward Parapet Design Tornado Pressure – Zones 4 & 5:
$p_T = q_{pT}[K_{dT}(GC_p) - (GC_{piT})]$

$p_T = 29.3\, psf \times [1.0 \times (+0.9) - (0.0)]$

p_T = +26.4 psf

C&C Leeward Face of Windward Parapet Design Tornado Pressure – Zone 3:
$p_T = q_{pT}[K_{dT}(GC_p) - (GC_{piT})]$
$p_T = 29.3\, psf \times [1.0 \times (-3.2) - (0.0)]$
p_T = -93.4 psf</td></tr>
<tr><td colspan="2">**For this design example, the parapet would be designed for a positive (i.e., inward acting) pressure of 26.4 psf and a negative (i.e., outward acting) pressure of 93.4 psf. Note, internal pressures cancel out MWFRS parapet pressures, and thus are not included in the calculations. Per ASCE 7 Commentary 29.5, the internal pressure coefficient, is zero, as the parapet is composed of a solid material. If the parapet were composed of a material that had a void space, the internal pressure coefficient for wind load design would be +/- 0.18 and for tornado loads would be -0.18/+0.55 for enclosed buildings.**</td></tr>
<tr><td colspan="2">**Step 7: Determine MWFRS Design Wind/Tornado Pressures on Rooftop Equipment**</td></tr>
<tr><td colspan="2">i) The MWFRS design wind/tornado pressures for rooftop equipment are given as a function of the velocity pressure, directionality factor and rooftop equipment pressure coefficient. Vertical uplift pressure coefficients under tornadic loading are modified by the pressure coefficient adjustment factor for vertical winds. Rooftop equipment pressure coefficients for both the horizontal and vertical directions were calculated in Step 4.viii. For this example, the projected area has been removed to yield design pressures as shown in Figure 17 rather than forces.</td></tr>
</table>

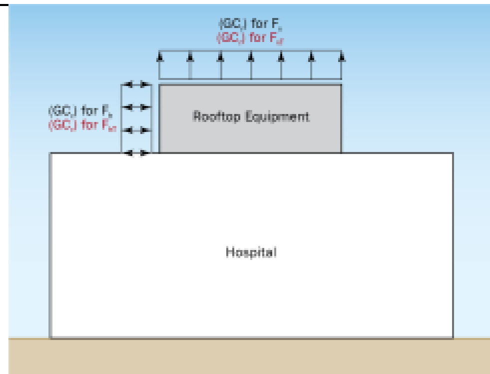


Figure 17: MWFRS wind pressures on rooftop equipment

Chapters 26–30: Wind Load Design	Chapter 32: Tornado Load Design
Eq. 29.4-2	Eq. 32.16-3
Horizontal Wind Pressure on Rooftop Equipment:	Horizontal Tornado Pressure on Rooftop Equipment:
$p_h = q_h K_d (GC_r)$	$p_{hT} = q_{hT} K_{dT} (GC_r)$
$p_h = 31.7\ psf \times 0.85 \times (1.9)$	$p_{hT} = 29.3\ psf \times 0.85 \times (1.9)$
p_h = 51.2 psf	p_{hT} = 47.3 psf
Eq. 29.4-3	Eq. 32.16-4
Vertical Uplift Wind Pressure on Rooftop Equipment:	Vertical Uplift Tornado Pressure on Rooftop Equipment:
$p_v = q_h K_d (GC_r)$	$p_{vT} = q_{hT} K_{dT} K_{vT} (GC_r)$
$p_v = 31.7\ psf \times 0.85 \times (1.5)$	$p_{vT} = 29.3\ psf \times 0.85 \times 1.1 \times (1.5)$
p_v = 40.4 psf	p_{vT} = 41.1 psf

For our design example, the rooftop equipment would be designed for a maximum horizontal pressure of 51.2 psf and a vertical uplift pressure of 41.1 psf. The wind pressure governs for the horizontal loads, while tornado pressure governs for the vertical loads. For design of components effected by both loads (e.g., windward anchor bolts transmitting both uplift and shear forces from the rooftop unit to the roof structure), the wind load case and the tornado load case would need to be checked separately, since wind and tornado loads do not occur simultaneously.

As demonstrated in this example, the overall tornado load procedures are similar to the wind load procedures that registered design professionals are already familiar with.

However, most tornado load parameters and equations are somewhat different from their parallel wind parameters and equations, yielding a range of differences in the resulting design pressures for various elements of the building.

For specific hospital building example in Tulsa, tornado design pressures exceed wind load design pressures for upward and downward acting MWFRS roof loads, inward and outward acting C&C pressures on the windows, windward and leeward face C&C pressures on the windward parapet wall, and uplift on the rooftop equipment. Wind loads control MWFRS roof overhang pressures and lateral loads on the rooftop equipment. MWFRS tornado uplift pressures on the windward roof were 40% greater than the corresponding wind uplift pressures.

For a case where this same hospital is located in Exposure C instead of Exposure B, the wind loads would increase by approximately one-third over the values shown here due to greater values of the velocity pressure exposure coefficients K_z and K_h. Tornado loads would no longer control over wind for uplift on the rooftop equipment and most of the window cases. Where tornado loads would still control, the relative increase in design pressures over wind pressures would be greatly reduced.

This case study demonstrates a key difference between tornado loads and wind loads – they each have a different shape distribution of pressures over the building surfaces. For example, MWFRS and C&C roof uplift pressures are greater in magnitude relative to windward wall pressures for tornado loads than wind loads, due primarily to differences in K_{zTor}, K_{dT}, K_{vT}, and (GC_{piT}). This means that on average, tornado load requirements are more likely to control over wind load requirements for roof uplift than inward acting pressure on the windward wall. However, whether tornado or wind controls the design of any particular element of the MWFRS or C&C is highly building and location specific. Tornado loads are more likely to control at least some element(s) of the overall wind load design for buildings/structures that have one or more the following non-exhaustive list of characteristics:

- ♣ located in the central and southeast US, except near the coast where the extreme wind climate is dominated by hurricanes,
- ♣ Risk Category IV,
- ♣ designated as Essential Facilities,
- ♣ large effective plan areas,
- ♣ located in Exposure B,
- ♣ low mean roof heights, or
- ♣ classified as enclosed buildings for wind loads.

In some cases, particularly for buildings having a combination of several of these characteristics, tornado loads on certain elements of the building may be more than twice the corresponding wind loads. Associated impacts on costs are anticipated to be only a fraction of one percent of total construction costs. Case studies comparing tornado and wind loads and cost impacts of tornado loads on several building types (elementary school, high school, fire station, hospital) were reported in NIST Technical Note 2214: Economic Analysis of ASCE 7-22 Tornado Load Requirements (NIST; 2022).

References

1) Design Guide for New Tornado Load Requirements in ASCE 7-22, FEMA/NIST Design Guide, January 2023