ASCE 7-22 tornado provisions

by

Perry K Foster

B.S., Kansas State University, 2023

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

G.E. Johnson Department of Architectural Engineering and Construction Science
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2023

Approved by:

Major Professor
Bill Zhang, Ph.D., P.E., S.E., LEED AP

Copyright

Abstract

The recently published ASCE 7-22 *Minimum Design Loads and Associated criteria for Buildings and Other Structures* added a new chapter (Chapter 32) for tornado provisions. In the past there have been many devastating tornados that have caused considerable damage and many casualties, but prior to the 2022 version there were no provisions in ASCE 7 addressing tornado effects. The provisions in Chapter 32 aim to provide design methods against tornado loads for buildings that pose a significant risk to life safety or are essential to survival (Risk Categories III and IV buildings). The new tornado design method is based on modifying current methods of wind design used in Chapter 26, 27 and 30 of the code for Main Wind Force Resisting Systems (MWFRS) and Component and Cladding (C&C) design. While the methodology is the same, there are many changes in the parameters and factors used for the actual calculations due to the unique nature of tornados. With the parametric changes there are also specifications for the envelope and the enclosure classification as well as requirements for openings. This report introduces the tornado provisions in Chapter 32 by highlighting the different parameters used in load calculation between tornado and regular wind. The impact to Risk Category III and IV buildings is illustrated by two building examples.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank my family and friends for their support in this endeavor to achieve my educational goals. I could not have done this without the help of my major professor Dr. Bill Zhang. I would also like to thank my aunt for proofreading this paper. I would not be where I am today without the amazing people in my life and this short thank you is a small way of expressing my gratitude to everyone whose been a part of this adventure.

Chapter 1: Introduction

Tornado is defined by Merriam Webster as "A violent destructive whirling wind accompanied by a funnel-shaped cloud that progresses in a narrow path over the land" (Merriam-Webster, 2023). In an average year there are about 1,000 tornados in the U.S. Many of these tornados occur in the midwestern United States. This area is called "Tornado Alley", spanning from south Texas to North Dakota and from the continental divide to West Virginia. Tornadoes are most common in the spring of the year but can also occur during the summer and fall months. In 2022 there were more tornados in the months of March, April and May than the rest of the year combined (Insurance Information Institute, 2023). Tornados kill more people per year in the U.S. than hurricanes and earthquakes combined as reported by The National Institute of Standards and Technology (NIST, 2014). Tornadoes have also caused more catastrophic losses than hurricanes and tropical storms as reported by the Insurance Information Institute (Insurance Information Institute, 2023). These statistics are a small part of the reason that ASCE 7-22 Chapter 32 Tornado Loads are an important addition to the design of buildings. This addition to the building design will provide a more robust structural design for buildings with great risk to human life or buildings that need to remain operational in case of emergency, namely, Risk Category III and IV buildings.

To quote John D. Rockefeller "I always tried to turn every disaster into an opportunity." The new provisions have taken advantage of the knowledge gained from previous disasters and used it as an opportunity to prepare for others. In the case of natural disasters, we learn about building failures, what caused them and how to prevent them. Unfortunately, these disasters come at a great cost, but we can learn from these events how to improve our structures. Past research has provided tornado shelter design standards in the ICC 500 *Standard for the Design and Construction of Storm Shelters* and the FEMA P-361 *Safe Rooms for Tornados and Hurricanes*. Those two standards are used for structures that are designated storm shelters. Recent research for the tornado provisions has also provided the first ever engineering-derived tornado wind speed maps, as well as new values for multiple design parameters. Wind tunnel testing can recreate scale cyclones in order to observe their effects. However, there are limitations, as research has shown. From this limited research and what we have learned from past disasters there has been large strides in the development of tornado loading, enough so that there is now a chapter in the ASCE 7-22 dedicated to that very topic.

The ASCE 7-22 is responsible for providing minimum design loads and other criteria for designing a building. The ASCE 7-22 version added a new chapter: Chapter 32 Tornado Loading. The goal of this chapter is to allow buildings imposing a greater threat to life safety and buildings critical to human survival to remain standing and operational in the case of a tornado (this does not include tornado shelter design). These provisions added methodology to determine tornado load to design the building's Main Wind Force Resisting Systems (MWFRS) and Components and Cladding (C&C). This load calculation is based on the same methods used in the previous chapters for wind design (chapters 27 and 30). The equations used for the tornado design and the wind design are similar and use the same concepts, while the main difference is in some of the parameters of these equations. The new chapter also provides guidelines on proper opening protection requirements and methods. There are many distinct aspects of this provision, but it emphasizes the importance of the envelope of the building as well as the enclosure category.

The goal of this report is to discuss this new chapter of the ASCE 7-22 and its importance to structural engineering and the design procedure. The first chapter is an introduction and provides an overview of the topics and the purpose of this report. The second chapter gives a look into recent literature about tornados and tornado research. The second chapter also provides insight into the history of tornados and the damage they have caused, as well as the characteristics of tornados and how they affect buildings. The third chapter discusses the ASCE 7-22 tornado provision and the new and changed parameters from wind loading applicable to tornado loading. Finally, in Chapter Four, a case study of tornado loads on two different buildings is presented, an elementary school (Risk Category III) and a powerplant (Risk Category IV). It provides a reference for what to expect when comparing tornado loads to wind loads on the building.

Chapter 2: Literature Review

2.1 Tornado characteristics

Tornadoes are an extreme weather event typically associated with severe thunderstorms and other similar atmospheric conditions. In the United States, tornadoes mostly occur in the Midwest regions, typically during the spring of the year. The area where tornados occur most often is referred to as “Tornado Alley”. In ASCE 7-22, this area is defined as the tornado prone region. Tornadoes are like hurricanes in the fact that they are high velocity cyclones. Tornadoes are based on land, and hurricanes originate from the ocean. Hurricanes are typically much larger in size than tornados, but the extreme wind speeds are similar between the two. Tornados create a lot of wind-borne debris due to the rotation discussed below.

The Enhanced Fujita Scale also known as the EF Scale provides a rating system of tornadoes (McDonald & Mehta, 2012). This is typically determined post disaster and based on the damage of various buildings and other objects in the wreckage of a tornado. The EF scale is determined using twenty-eight damage indicators (DI) based on buildings of all types and sizes, landscaping and other site structures. For each DI there are several degrees of damage (DOD) to estimate the encountered wind speed more accurately. From these DI they can work backwards to determine the wind speed experienced in these areas. The windspeed associated with each level of the EF scale can be seen in Table 2.1. Methods of post event analysis similarly have been used in determining the intensity of earthquakes.

Table 2.1. EF Scale

EF number	Wind Speed (mph)
EF0	65-85
EF1	86-110
EF2	111-135
EF3	136-165
EF4	166-200
EF5	>200

In a Report by the National Institute of Standards and Technology (NIST) titled *Technical Investigation of the May 22, 2011, Tornado in Joplin, Missouri* (NIST, 2014), the characteristics of tornado wind field regions are described. Wind fields of a tornado can be divided into five different flow regions, as can be seen in Figure 2.1. The first zone (Ia), called the outer flow, is a spiraling flow extending outward from the core (region Ib). The outer flow extends at least 1 km and is made up of air that approaches and rises around the core (Davies-Jones, Trapp, & Bluestein, 2001). The core (Ib) surrounds the center axis and extends outward typically tens to hundreds of meters (Davies-Jones, Trapp, & Bluestein, 2001). The core is so stable that very little air is brought in from the outer flow (Ia), but instead it is mostly being brought in through the boundary layer (region II), the corner region (region III), or the upper region (region IV). The boundary layer (II) is an inflow region that is having a frictionless interaction with the earth's surface, causing the flow of air to be more towards the center of the tornado when compared to the flow in the outer flow (Ia). The corner region (Region III) is named so due to the flow going from horizontal to vertical or "turn the corner". The corner zone typically causes the most damage and most debris is generated in this zone (Davies-Jones, Trapp, & Bluestein, 2001).

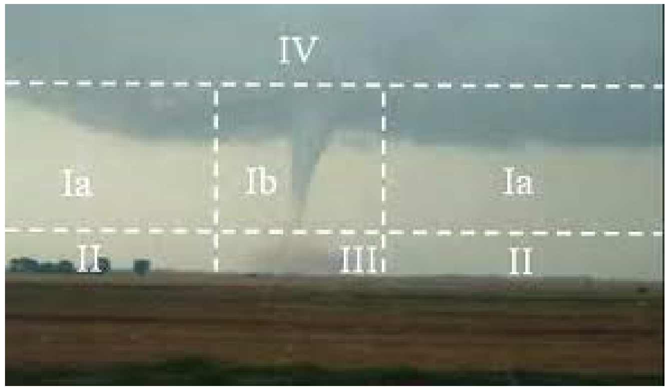


Figure 2.1 General tornado flow regions **(NIST, 2014)**

2.2 Tornado Damages

On May 22, 2011, the Joplin Tornado, as it is known, struck the city of Joplin, Missouri. This Tornado caused 161 fatalities and $1.228 Billion in commercial property loss. Of the 161 fatalities, 59% of these were in commercial buildings (NIST, 2014).The Joplin Tornado was the largest in a string of 1,625 tornados in the southwest, amassing a total of $25 billion in economic losses, 223 fatalities and 13,000 damaged buildings in 2011 (Prevatt, et al., 2012). Because of the large amount of damage, this tornado outbreak has been the cause for significant research about the development of tornadoes in general, and the building design for tornadoes. One of the many reports on this outbreak is specific to the Joplin Tornado by NIST in 2014 (NIST, 2014). This report includes accounts and firsthand stories of people in the path of the tornado and the forensic analysis of multiple buildings in the path of the tornado. In the study, there were many different factors the research committee analyzed.

From the path of the tornado seen in Figure 2.2, the committee put together a map of the destruction and tried to recount exactly the path and strength of the tornado, then to determine the forces experienced in each area as well as the wind speeds and fatalities associated. Between

40% and 90% of all fatalities were associated with EF3 or lower windspeeds. Most tornadoes are small and short lived in nature. Even for larger tornadoes, a majority of them consist of lower wind speeds. From 1995 to 2016 of the 1,200 recorded tornadoes, 97.1% of the tornadoes were category EF0-2 (ASCE, 2021). In the case of the Joplin Tornado in 2011, 72% of the area was impacted by wind speeds rated EF0 to EF2, and 38% EF3 to EF5 (NIST, 2014). From the destruction, the committee then selected twenty-five buildings to do an in-depth forensic analysis. From this, they summarized the damage of buildings in a table. This summarization allows for a broad overview of the building performance in the path of the tornado.

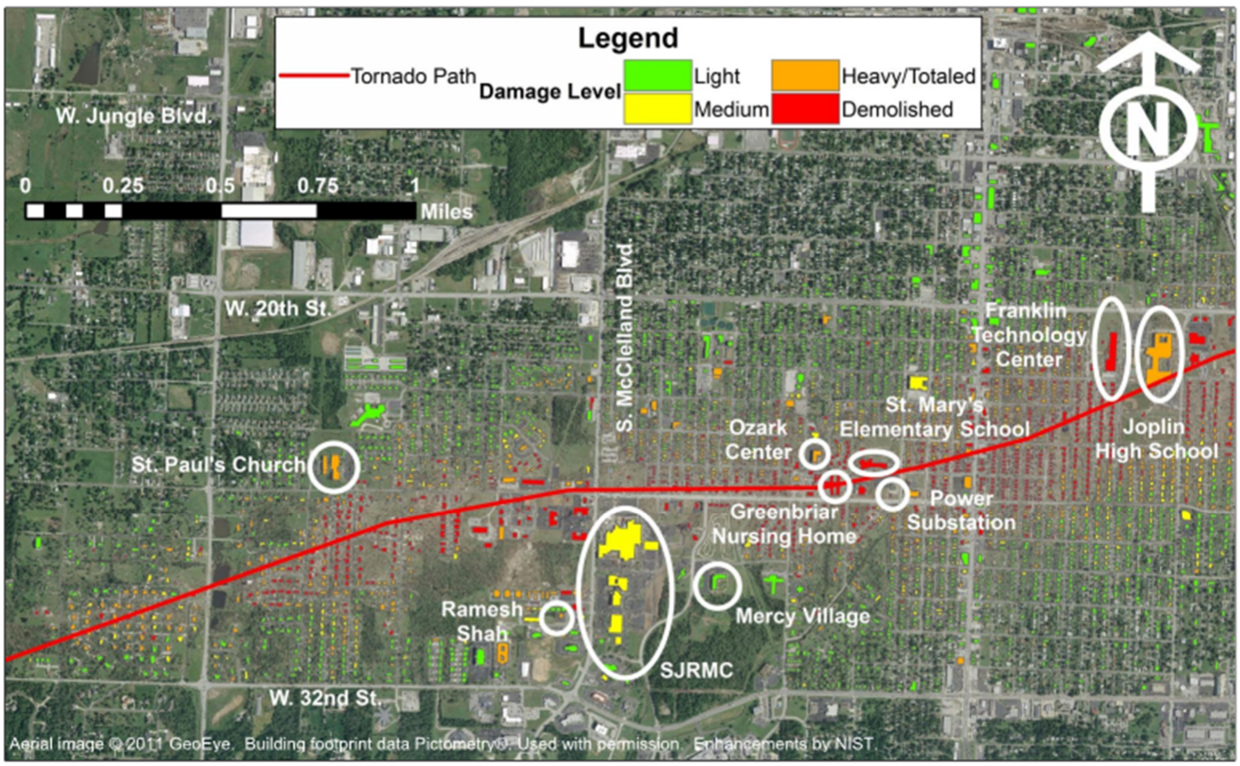


Figure 2.2 Westernmost (earliest) segment of the tornado path through Joplin, MO (NIST, 2014)

The forensic analysis concluded that all buildings incurred severe damage to the building envelope. In the case of St. John's Regional Medical Center (SJRMC), this envelope failure allowed water and other debris into the facility, which led to the building being unusable for a period after the tornado. While all buildings suffered severe damage to their envelope, about half of the buildings suffered a total collapse of the main wind force resisting system (MWFRS). The buildings that collapsed were all box type structures (BTS), and the BTS failed due to wind uplift causing a failure in the roof deck to joist connections or the joist to wall connections. Because of this, the walls lost their lateral stability and collapsed due to rotation from lateral loading. Steel and concrete framed structures with redundant lateral bracing and those that didn't depend on the roof system for lateral stability performed much better as can be seen in Table 1.2 of the NIST report (NIST, 2014). It was also noted that aggregate roofs were allowed per code in Joplin for buildings with a roof height less than 110 ft, including all buildings in the NIST report. Aggregate roofs are not allowed in hurricane prone regions per IBC (2012) due to the potential of aggregates being blown off the roofs and contributing to the building envelope damage. This exact occurrence was observed in the SJRMC Hospital, where roof aggregates were found in the debris inside the building. If aggregates are used as a ballast, and are blown off, it will lead to the roof of the building being torn off due to loss of aggregates to counter the uplift. This is a very possible outcome as tornado wind flows lift a lot of wind-borne debris. The corner zone (III) as mentioned above creates a lot of this debris as the wind "turns the corner".

The NIST report made some recommendations for code updates. The first recommendation is for performance standards in tornado resistant design of buildings. The report outlined some recommended performance objectives for buildings shown in Figure 2.3. The recommendations for Risk category II buildings are for them to be repairable in EF1 Tornados, to provide life safety in EF2, and to prevent collapse in EF3. For Risk category III it is recommended that the building be reparable up to EF3 tornados, provide life safety in EF4, and prevent collapse in EF5 tornados. Finally, for Risk category IV it is recommended the building remain operational up to EF4 tornados and be in repairable condition for EF5. While the new provisions provide no design for Risk category II, for Risk category III and IV the design windspeeds are in the range of EF2. While this does not meet the full recommendations, it must also remain economical. They also recommend a risk consistent design procedure for building design that includes the structural system, envelope and MEP systems. For the design of ordinary buildings, they also propose provisions for adding tornado shelters to existing buildings and requiring them in mercantile buildings, schools, and buildings with assembly occupancies in tornado prone regions. It was also suggested that roofs with aggregates used as surfacing or used as a ballast be prohibited at any height in tornado prone regions.

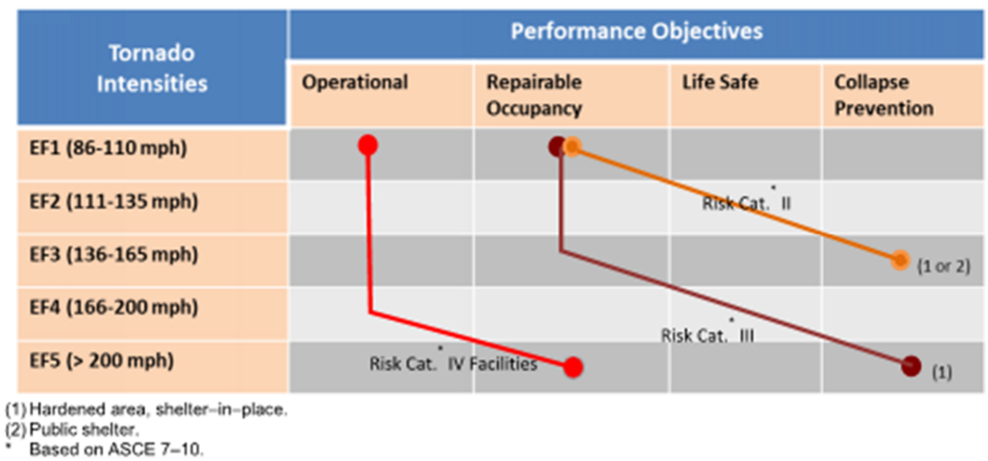


Figure 2.3 Performance objectives stated in the NIST Report of the Joplin tornado

2.3 Cost Analysis

In its Technical Note 2214 "Economic Analysis of ASCE 7-22 Tornado Load Requirements" (Kneifel, et al., 2022) NIST performed an economic analysis of multiple buildings with different design considerations. The methodology they used is as follows. First, the design wind pressures for exposure categories B and C, and the design tornado pressures using ASCE 7-22, were calculated. Then the construction costs for building elements were estimated for every case by Huckabee, Inc. Finally, the study compared the individual element costs and the total costs. In the report NIST states “There are five building element construction designs impacted by tornado loads considered in this cost analysis: diaphragm, joists and wide flange beams and girders, foundation anchorage, exterior wall framing, and roofing.” (Kneifel, et al., 2022)

Each of these five building elements has been designed for various loadings and different criteria. The diaphragm is designed for uplift in Zone 2 for C&C with an effective wind area (EWA) of 10 ft^2. The construction options designed with conventional methods use 5/8” arc puddle welds support fastener, 36/4 support pattern, and #12 TEK screw sidelap fasteners. The amount of sidelap fasteners varied from 3 to 8 per span based on the loading requirement. The roof diaphragm was designed for concurrent uplift and diaphragm shear. The roof joists, wide flange beams and girders were designed using Zone 1’ uplift. The typical framing is a 25ft x 25ft bay with joists at 6’-6” on-center. The beams are assumed to not have their bottom flanges braced for lateral torsional buckling in an uplift case. The combined construction of the wide flange beam and joist roof system has a maximum uplift value of 33 psf for both tornadoes and wind. The foundation anchorage design loads for MWFRS are limited to increases of 35% to 75% from wind to tornado loads. The wall framing is based on Zone 4 wind loads. The studs are assumed to have 1-5/8 in wide flange, span 15ft vertically and be backing masonry veneer. For loads less than 31.8 psf, 18ga studs may be used, and between 31.8 psf and 39.8 psf, 16 ga studs are to be used. Finally, the roofing construction is a mechanically attached single ply membrane and coverboard with insulation and a steel roof deck. The steel roof deck and its attachment are the same for all loading. For the other roofing material, the only variable is the number of fasteners. These design considerations are summarized in Table 2.2.

Table 2.2 Load Values for Construction Assembly Design Options **(Kneifel, et al., 2022)**

Building Assembly, Material and Load Categories		**Construction Description**	**Max load Value (psf)**
Roof	Diaphragm Zone 2 uplift EWA 10 ft^2	#12 TEK,3	42
		#12 TEK,4	72
		#12 TEK,5	91.5
		#12 TEK,6	103.5
		#12 TEK,7	111
		#12 TEK,8	116
	Joist & Wide Flange Zone 1' Net uplift (5 psf deadload)	Joist \$1.20/ft^2, W16x26, 1.04 psf	12
		Joist \$1.22/ft^2, W14x30, 1.2 psf	14
		Joist \$1.24/ft^2, W14x30, 1.2 psf	21
		Joist \$1.25/ft^2, W14x34, 1.36 psf	25
		Joist \$1.25/ft^2, W14x38, 1.52 psf	31
		Joist \$1.25/ft^2, W16x40, 1.6 psf	33
Foundations	Anchorage MWFRS Roof Field	Minimum Fractional Increase	0.300
		Minimum Fractional Increase	0.750
Exterior Walls	Framing Zone 4 C&C Pressure	6 in wall cold-formed metal studs, 18 ga	31.8
		6 in wall cold-formed metal studs, 16 ga	39.8
Roofing	Roof Membrane Fasteners Min. Uplift Resistance Class	9.5 ft oc, with fasteners 12 in oc	60
		9.5 ft oc, with fasteners 12 in oc	75
		7.5 ft oc, with fasteners 12 in oc	90
		9.58 ft oc, with fasteners 6 in oc	105
		9.38 ft oc, with fasteners 6 in oc	120

Initial cost data was provided by Huckabee for the elementary school and high school examples located in Dallas Fort Worth area in 2019. The budget for the elementary school is $20 million, and the high school has a budget of $200 million. The diaphragm costs were based on a

200 ft x 200 ft roof area and were given by the manufacturer. The joist manufacturer and Huckabee provided the joist and wide flange costs respectively for price data in 2019, with a steel price of $4000/ton. The cost breakdown for the structural steel is 36.6% to 29.1% for joists decreasing as the max load increases, and the wide flange share being 63.4% to 70.9% as the load value increases (Kneifel, et al., 2022). The cost of foundation anchorage is mostly based on the expert judgement by Huckabee. It is shown that the amount of foundation anchorage required is related to the roof area. The cost increase is approximated at $20,000 and is associated with a maximum increase of 75% in roof loading. If the loading increase is less than 30% then there is no cost increase and if the value is between 30% and 75% it is interpolated between those two price points. Exterior wall values are based on the 18 ga and 16 ga walls using the same unit price of $4000/ton as provided earlier. For roofing, the change in construction cost is linear based on the number of fasteners assuming an open shop labor type in RSMeans Commercial New Construction Assembly database. The exact cost breakdown is shown in Table 2.3.

The cost data was then compared when the example buildings were designed for Exposure B, C and tornado loads. The comparison yielded three outcomes: design for tornado loads cost less than design for wind loads, design for tornado loads cost the same as design for wind loads, and design for tornado loads cost more than design for wind loads. In Table 2.4 when the first two situations occurred, the amount is listed a zero. When the third situation arose, the amount was the tornado design cost minus the wind design cost. Overall, this table gives the cost increases caused by tornado design.

Table 2.3 Cost Per Unit (ft^2) by Maximum Load Value for Schools in DFW, TX **(Kneifel, et al., 2022)**

Building Assembly, Material and Load Categories		Max Load Value (psf)	Cost Unit (ft^2)	DFW (\$/ft^2)
Roof	Diaphragm Zone 2 Uplift EWA 10 ft^2	42	Roof Area	$0.1834
		72	Roof Area	$0.1852
		91.5	Roof Area	$0.1871
		103.5	Roof Area	$0.1890
		111	Roof Area	$0.1909
		116	Roof Area	$0.1928
	Joist & wide Flange Zone 1' Net Uplift (5 psf deadload)	12	Roof Area	$3.28
		14	Roof Area	$3.62
		21	Roof Area	$3.642
		25	Roof Area	$3.97
		31	Roof Area	$4.29
		33	Roof Area	$4.45
Foundations	Anchorage MWFRS Roof Field	0.300	Roof Area	$ -
		0.750	Roof Area	$0.0518
Exterior Walls	Framing Zone 4 C&C Pressure	31.8	Ext Wall Area	$3.47
		39.8	Ext Wall Area	$3.83
Roofing	Roof Membrane Fasteners Min. Uplift Resistance	60	Roof Area Impacted	$0.48
		75	Roof Area Impacted	$0.48
		90	Roof Area Impacted	$0.61
		105	Roof Area Impacted	$0.95
		120	Roof Area Impacted	$0.97

Table 2.4 Estimated cost impacts from tornado loads – DFW **(Kneifel, et al., 2022)**

Building Element	**Elementary School**		**High School**	
	B	**C**	**B**	**C**
Roofing Fasteners	$0	$0	$300	$0
Diaphragm	$0	$0	$0	$0
Joists & Wide Flange	$24,240	$0	$139,778	$8495
Wall Frame	$0	$0	$90 000	$0
Found. Anchor.	$3693	$0	$20,000	$15,574
Total	$27,933	$0	$250,077	$24,069
Budget ($Million)	$20.00	$20.00	$200.00	$200.00
Percent of Budget	0.14%	0.00 %	0.13 %	0.01 %

The results show that the largest construction cost increases occur in Exposure Category B and are concentrated in joist and wide flange roof framing and in foundation anchorage. However, these increases are minimal in comparison to the total estimated budget. The NIST report studied multiple other locations, but of these, DFW has the largest percent budget increase; the other locations are all less than DFW and some have no increase. It should also be noted that Risk Category IV Buildings have not been included and it is stated that they would have a greater relative cost increase (Kneifel, et al., 2022). Risk category IV Buildings are required to have impact-resistant glazing or impact protective systems, which may also add to construction costs.

In conclusion tornadoes, through their unique and destructive features, show design characteristics that can be improved. Tornadoes utilize not just their high wind speeds, but also their strong uplift forces to exploit weak roof connections and the reliance on the roof as the MWFRS. The destruction of tornados that were studied in Joplin and other tornadoes showed that engineered buildings, even when they remain standing, may not be occupiable. In the case of the SJRMC and other buildings that are required for survival, it is critical they remain operational. From this report came many recommendations, with the main recommendation being the creation of provisions for tornado resistant design for ordinary buildings. The provisions were added in ASCE 7-22 in Ch 32 with some other recommendations. Finally, the cost analysis of these provisions was conducted which showed that the cost of providing a tornado resistant design is minimal.

Chapter 3: Design for Tornado Loads

The basis of this report is the newly added Chapter 32 Tornado Loads in the ASCE 7-22. The nature of this addition is to provide a method to determine tornado loads applied to buildings of Risk Category III and IV in tornado prone regions. This method is not intended to provide loading for a storm shelter design, which should be done in accordance with ICC 500 or FEMA P-361. The tornado provisions provide the first ever engineer derived tornado wind speed maps for the US (ASCE, 2021). These maps are based on a probabilistic load and resistance modeling framework using the EF-scale tornado intensity rating system (Texas Tech University, 2006). These maps provide a 1,700-year return period tornado wind speed for Risk Category III buildings and a 3,000-year return period tornado wind speed for Risk Category IV buildings respectively. For longer return periods Appendix G of the ASCE 7-22 has tornado wind speed maps that may be used for performance-based design.

3.1 Key Parameters

There are many new design parameters, variables and design considerations for tornado loading in chapter 32 of ASCE 7-22. Many provisions in chapter 32 are similar to those in Chapters 26, 27 and 30. All the parameters have had a notational change. Typically, this was as simple as adding a subscript “T”. Many of them have also had some value changes. There are also some new parameters unique to tornado loading. These changes were based on recent research in order to establish new provisions for tornado design. The new and modified parameters, and their purposes are discussed below, along with an overview of the research that went into them.

3.1.1 Tornado Windspeed Maps and Effective Plan Area (A_e)

The new parameter, Effective Plan Area, is used in conjunction with risk category, return period and geographic location, to determine design tornado wind speed. This is based on the fact that the probability of tornado speed is a direct function of the plan area being considered. What this means, in terms of the building, is the larger the building, the more likely it is to experience a higher wind speed and thus an increase in the design wind speeds. Hence, Chapter 32 has multiple tornado wind speed maps for each Risk Category for different Effective Plan Areas. The Effective Plan Area, A_e in the ASCE 7-22 commentary, is described as "the area of the smallest convex polygon enclosing the plan or footprint" (ASCE, 2021). This plan or footprint includes the building and any buildings that are essential to the building's functionality.

The tornado wind speed maps themselves shown in section 32.5.1 and Appendix G of ASCE 7-22 are part of the first-ever engineering-derived tornado wind speed maps for the contiguous United States (ASCE, 2021). The maps were created based on a probabilistic approach using data with multiple different geographic and tornado characteristics. The wind speeds were then approximated based on the EF ratings of tornado and the DI from each tornado. As is the case with the regular wind speed maps, the speeds shown are 3 second gust horizontal wind speeds at a height of 33 ft. The ASCE commentary states explicitly "The tornado hazard maps were developed through probabilistic models that are "best estimates" rather than "conservatively based."" (ASCE, 2021).

3.1.2 Tornado Directionality Factor (K_{dT})

The tornado directionality factor, $K_{dT,}$ is modified from wind directionality factor, K_d. It was determined on the assumption that the pressure coefficients computed for boundary layer wind tunnel tests are applicable to tornadic winds. (ASCE, 2021). With tornados there are multiple other considerations, other than straight line winds. There is a large variation in wind speeds in different zones as introduced in Chapter 2 of this report, which have been considered in the determination of K_{dT}. There is also a much larger uplift force that comes with tornados that is covered in another factor discussed in 3.1.3. In the research done for the K_{dT} factor, there were 5,000 small scale tornados, varying in size and speed, simulated on three scale buildings of various sizes from 1800 ft^2 to 250,000 ft^2, including low-slope and gable roofs (ASCE, 2021). From this data, it was determined that for MWFRS there is a weak trend of the effective value of K_{dT} decreasing with the increase in size of the structural element tributary area. For C&C, however, this trend was inverted where the effective value for K_{dT} increases with the increase in size.

A value of 0.8 is recommended for all zones in MWFRS design based on the same research (ASCE, 2021). The result of this research also provided mean values of 0.65 to 0.75 for C&C in all zones except for zone 1, where the values were approximately 0.8 for the intermediate sized buildings ranging up to 0.97 for the large buildings. This larger value is due to the building size and the small variation of (GC_p) with the direction of the wind away from edges of buildings. While the effect of K_{dT} was not expressly studied on walls, a value of 0.75 was conservatively recommended for walls and zones 1, 2 and 3 while roof zone 1' has a value of 0.9 (ASCE, 2021). The zones for C&C design are shown below in Figure 3.1. This recommendation was based on research showing K_{dT} has been shown to be lower on walls than roofs for C&C. With the special considerations to the building envelope in buildings intended to remain operational after a tornado (Risk Category IV), exterior non-structural components are also of great importance as any loss of cladding can allow intrusion of water and debris from storms as what occurred in Joplin's SJRMC. In order to protect the envelope, it was decided that the K_{dT}

factor should therefore be 1 for C&C design. Due to this condition existing across the whole building it is likely that it will experience the maximum pressure coefficient at the direction of maximum winds.

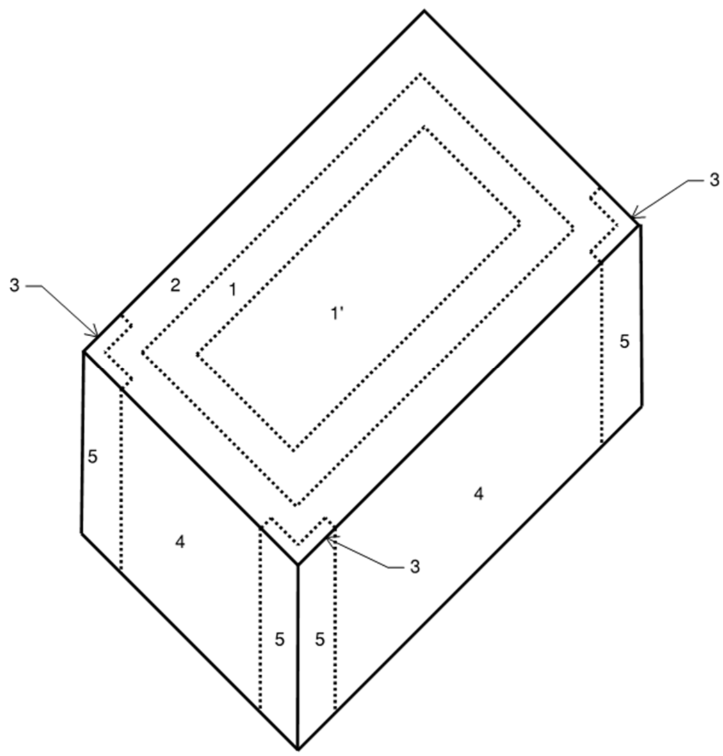


Figure 3.1 C&C zones

3.1.3 Tornado Pressure Coefficient Adjustment Factor for Vertical Winds (K_{vT})

Due to the large updrafts of tornadoes near the core of the tornado, there has been a new factor, mostly for roofs, added to account for the updraft. This factor is the tornado pressure coefficient factor, K_{vT}. This factor is used in both MWFRS and C&C load calculations. The development of this factor was led by the research consisting of 5,000 simulated tornadoes (ASCE, 2021). The pressures from these simulations were calculated with and without the updraft effects. The K_{vT} value is the maximum value of the wind pressure, including the updraft, divided by the factor without the updraft. This value is calculated for each roof deck element at the element's centroid (ASCE, 2021). For the testing and development of the K_{vT} values, the core of the tornado was over a portion of the building. While this is rare, depending on the tornado size, it does provide maximum loading values. The values that are used in the code have been reduced based on the probabilities of the core of a tornado being directly on a building.

3.1.4 Tornado Exposure and Topographic Coefficients

The velocity pressure exposure coefficient K_z accounts for the exposure category of a building based on its surrounding surface roughness. For tornado design there have been multiple studies on the effects of surface roughness. The impact near the surface is hard to identify based on radar data, making the research turn to wind tunnel testing. Most studies do show that there is some impact mostly near the ground. However, there is a lot of variability in the exact modification (Refan & Hangan, 2018). Therefore, exposure is not a consideration in tornado wind speeds. As can be seen in the next section, the tornado velocity pressure exposure coefficient is the function of only the elevation. When performing research to study the topographic effects on tornados many of the same issues with the research on exposure occurred. The wind speeds pulled from radar data are inconclusive and it is difficult to simulate multiple different topographic settings. The simulations were run on various settings and provide a wide range of results in horizontal wind speeds. Due to the inconsistent results, there is no topographic coefficients defined for tornados in the provisions. (ASCE, 2021)

3.1.5 Tornado Velocity Pressure Exposure Coefficient

The tornado velocity pressure exposure coefficient, K_{zTor}, was determined based on a variety of research. The preliminary research consists of field data, wind tunnel data and numerical studies. The tornadoes studied in all the different research were considered strong tornadoes in the EF2 category. From this preliminary data, a wind speed profile along the elevation was developed. This profile showed there was a lot a variability of the windspeeds across all heights, but the highest wind speed is near the surface. After the preliminary analysis, ASCE decided to use radar profiles because they have more data points and the most consistent data. As discussed in the previous section, topographic features and exposure categories do not affect tornado wind speed, so there were no topographic factors or exposure factors considered in the analysis. From the data, the committee created Figure 3.2 that shows in blue the square root of velocity pressure exposure coefficient, also called the normalized wind speed, $\sqrt{K_{zTor}}$. The median wind speed is represented with the solid black line, and plus one and minus one standard deviation from the median is represented with the dotted black line. From this, the tornado velocity pressure profile was defined as shown in Figure 3.3. (ASCE, 2021)

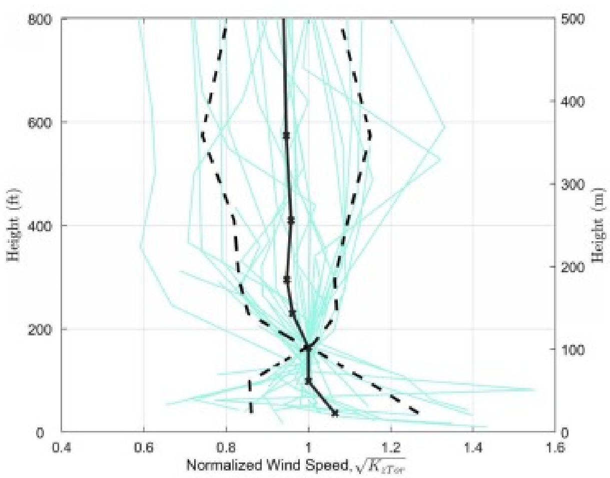


Figure 3.2 Vertical profiles of normalized windspeeds for tornados (ASCE, 2021)

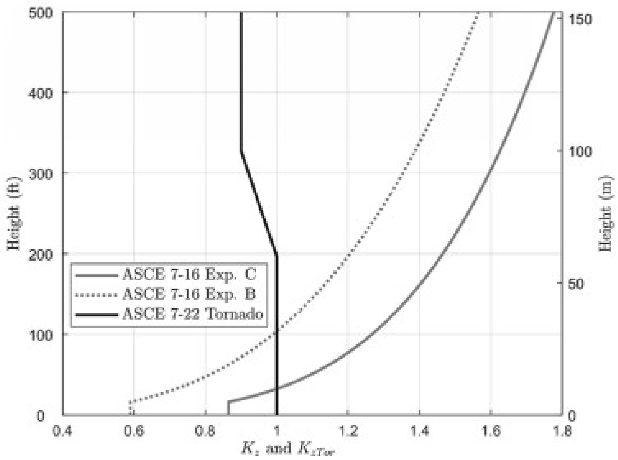


Figure 3.3 Vertical profiles of tornado velocity pressure exposure coefficient (K_{zTor}) (ASCE, 2021)

3.1.6 Tornado Internal Pressure Coefficients and Enclosure Classification

In tornado wind design, there is a new enclosure classification, “Sealed other structure”, in addition to the four categories used in wind loads. The structures of this enclosure classification are susceptible to atmospheric pressure changes (APC) caused by tornadoes. The intent of this category is to capture the effect of APC on buildings where the change in static pressure is not transmitted fast enough, creating large positive internal pressure, which is discussed later in this section. Since the porosity of the building envelope is directly related to internal pressure, and the ability to keep debris and storm water out of the building, there is a special importance on openings on the building envelope. Because tornadoes create more wind-borne debris, unprotected windows are prone to failure, especially windows that are not protected as described in ASCE 7-22 Section 31.12.3.1. For enclosed buildings with unprotected openings, they should be reevaluated as a partially enclosed building, given all unprotected openings on the windward wall are broken. The guidelines for defining window protection are stated in the code as “shall be subjected to missile tests in accordance with ASTM E1996 using missile test level D or E as described in Table 2 of ASTM E1996.” The commentary also recommends “For significantly enhanced protection to resist breaching of exterior glazing by more intense tornados, glazing assemblies can be specified that have been tested in accordance with AAMA 512 (2011), using tornado test missiles given in ICC 500 (2020) or FEMA P-361 (2021a).” (ASCE, 2021).

In the case of wind loads, internal pressure is based on the intrusion of exterior pressure through openings. For tornadoes, this factor still applies and is impacted by APC. This is caused by the suction effect of the tornado, where the air being sucked into the core from the corner region creates an area of greatly reduced static pressure. So as the core of the tornado moves over a building, the static pressure drops rapidly and the internal pressure cannot normalize fast enough, creating a positive internal pressure. This can cause the building to act like a balloon and can create a large envelope load.

In the determination of the internal pressure coefficient (GC_{piT}), the research performed was on three enclosure classifications; sealed, enclosed and partially enclosed. (ASCE, 2021) A series of 5,000 tornado simulations were performed measuring the tornado induced wind pressures on the roof and walls. The enclosed and partially enclosed structures were analyzed with and without the APC effects. In the analysis the maximum or minimum values were kept based on the combination of internal pressure and APC. During the analysis, it was assumed that the flow in or out occurred instantaneously and that there was no net in or out. It was determined that the effective internal pressure was a combination of standard internal pressure due to tornadic winds and the difference between external static pressure due to APC and internal static pressure. There is also a consideration on how the internal pressure can vary due to the APC possibly being a small area relative to the size of a building. Finally, the internal pressures were established as +0.55, -0.18 for enclosed buildings with the increase in the positive pressure when compared to wind loads being due to the APC effect. For sealed structures, the value of +1.0 is reserved for tanks or vessels having controlled ventilation. While a building being classified as a sealed structure is rare, in the case of a building containing hazardous materials, the sealed category may be a viable option.

3.2 Design Procedure

In chapter 32 the design procedures for tornado loading are similar to those for wind loads with some additional steps and modified parameters. It is explicitly stated that these provisions are not intended for design of designated storm shelters, which must be designed in accordance with ICC 500 or FEMA P-361. First, there are checks to determine if tornado loads will be required and possibly control over wind loads. These checks are in the chart shown in Figure **3.4**, where one can determine if Chapter 32 is applicable. If tornado design is required, then you will follow along with the design procedure outlined in Chapter 32. This design procedure includes tornado loads for the MWFRS, and C&C elements. The procedure is adapted from chapters 26-31, excluding chapter 28.

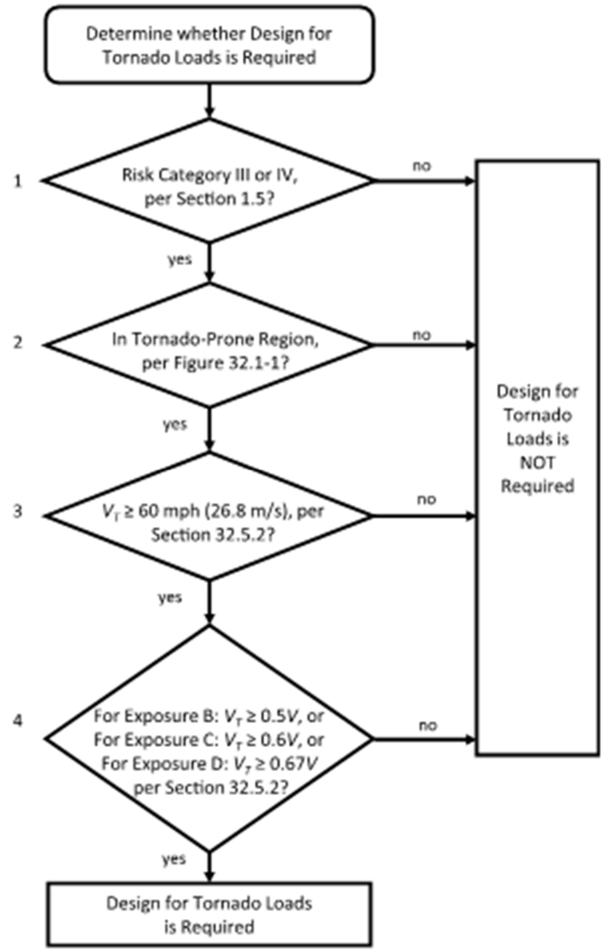


Figure 3.4 Flowchart for the process for determining when tornado loads are required. **(ASCE, 2021)**

3.2.1 General Requirements

Most parameters of Chapter 32 are based on the same ones in the procedure for wind loads. Some of these parameters that may have already been determined for wind loads will need to be reevaluated for their applicability to tornado loads. First, the building location is checked on a map indicating the tornado prone region. If your building is not located in this region, then the use of Chapter 32 is not required. If the building is located within the tornado prone region, the next step is to determine the tornado speed, V_T. The risk category is used in combination with the building location on the wind hazard maps to determine the wind speed. However, tornado speed is not only the function of the risk category, but also the function of the effective plan area, A_e, as introduced earlier in this chapter. So, there are various maps for Risk Category III and IV depending on A_e. In each risk category there are 8 maps, varying in effective plan area from 1 square foot (SF) to 4,000,000 SF. Overall, the tornado wind speeds might not be higher than the typical wind speed, especially in the regions where the wind speeds are already high.

The first equation used in this chapter, is the computation of the tornado velocity pressure, q_{zT}, shown in Equation 3.1. This equation is like the one in Chapter 26 for wind loads. The wind speed, V, is replaced by the tornado speed, V_T. The ground elevation factor, K_e, is the same as the wind design. The Tornado Velocity Pressure Coefficient, K_{zTor}, is used in place of K_z. The table for K_{zTor} is much smaller than that of K_z, where the coefficient is 1 from heights of 0 to 200 ft, above that it decreases to 0.9 at heights greater than 328 ft. Similar to K_z table, there are equations in the footnotes to calculate K_{zTor}. In Equation 3.1 the topographic factor, K_{zt}, has been removed. The topographic factor was removed due to the uncertainty of its effects on buildings shown in the research as previously discussed.

Equation 3.1 Tornado Velocity Pressure **(ASCE, 2021)**

$$q_{zT} = 0.00256 K_{ZTor} K_e V_T^2$$

The internal pressure coefficients and the enclosure classification are slightly different from wind loads, as reasons being discussed above. For tornado provisions, the partially enclosed classification has positive and negative factor of 0.55, an increase from 0.18. The enclosed classification has a negative pressure of -0.18, and the positive pressure for tornadoes also has an increase of 0.55. The increase in these factors is due to the APC. For the classification of the enclosure category the code states, "If a building or other structure satisfies both the "open" and "partially enclosed" tornado enclosure classification definitions, it shall be classified as a “partially open” building or other structure.” (ASCE, 2021). This assumes that most windows and other glazed openings will be broken due to debris in a tornado. Because of this, the code also requires that glazed openings be protected in buildings considered essential facilities or buildings required to remain operational. These protection systems should be either always affixed non-operable, or they should be operable systems that can be deployed in five minutes and can only be used in buildings that are in use by people 24 hours a day. If the openings are not required to be protected, enclosed buildings and other structures should be reevaluated for partially enclosed with all unprotected openings being considered openings.

3.2.2 Main Wind Force Resisting System (MWFRS) Design

The MWFRS loads are used for determining the base shear and designing lateral force resisting systems. The methods for doing this for tornado and for wind are similar, with some small differences. The equation for determining the design tornado pressures, P_T, is shown in Equation 3.2. The equation and its coefficients are similar to that in Chapter 27 with one major difference in the equation itself. For tornadoes, the directionality factor is only applied to external pressure, while for wind loads it’s applied to both external and internal pressures. The values for the directionality factor are different from those of wind design. The tornado pressure coefficient adjustment factor for vertical winds, K_{vT}, has also been added to the equation to account for the large amount of uplift created by tornadoes. The gust effect factor is 0.85 or can be calculated using Exposure Category C. The external pressure coefficient, C_p, is the same as what you would use for wind loads and can be found in Chapter 27. The internal pressure coefficient as discussed above is different from that of wind design. It is important to note that when it comes to the design load cases for wind coming at angles, or torsional wind, as covered in Chapter 27 Figure 27.3-8, the exception in appendix D of the code allowing some buildings to not be designed for torsional cases is no longer allowed.

Equation 3.2 MWFRS Design Tornado Pressures **(ASCE, 2021)**

$$P_T = qG_TK_{dT}K_{vT}C_p - q_i(GC_{piT})$$

3.2.3 Components and Cladding (C&C) Design

The components and cladding (C&C) wind pressures are used for design of specific elements of the building and are dependent on the effective wind area of the elements. The equation for determining the C&C pressure is shown below in Equation 3.3. This equation is essentially the same as what is used for wind loads, except that the tornado pressure calculation includes the K_{vT}. The value for K_{vT} also varies depending on which zone is under consideration. Most zones have a value of 0.75, except for the roof zone 1'. The GC_{pi} is the same as what was determined earlier. The GC_p is determined based on the effective wind area and of the same values as the wind loading.

Equation 3.3 C&C Design Tornado Pressures **(ASCE, 2021)**

$$p_T = q_{hT}\left[K_{dT}K_{vT}\left(GC_p\right) - \left(GC_{piT}\right)\right]$$

Finally, once the loads have been calculated, the next step is to go to the load combinations in chapter 2 of the ASCE 7-22. There are no new load combinations to account for the tornado loads. The only modifications for strength design load combinations are on combo 4a. and 5a. The change is simply using the largest value between wind loads and tornado loads. For allowable stress design, there are also no new load combinations. However, there are three load combinations using the larger of wind loads or tornado loads. Overall, in the comparison of the differences between wind loads and tornado loads, there are many small changes and few major ones. The changes to the equations themselves are minimal. Many of the changes come from the new values for similar parameters and some new ones entirely. These new parameters do not add any complexity to the calculations. The biggest impact to buildings may not be the loading, as it may not control the design, but the necessity to have protected openings to prevent any envelope failures.

Chapter 4: Design Examples

Two example buildings were used to compare the design loads for tornado vs wind in ASCE 7-22. The detailed design calculations are provided in Appendix A: Building Loading Examples. The two examples include wind pressures on MWFRS with base shears, and wind pressures for C&C loading. The first building is an elementary school in Branson, Missouri, which is a Risk Category III building according to chapter 1 of ASCE 7-22. The second building is a coal power plant located in Manhattan, Kansas, a Risk Category IV building. These two buildings cover a variety of different load parameters, which are summarized in Table 4.1. The results of the calculations are shown below in various tables and the comparisons are based on wind loads, therefore negative numbers in the change columns represent tornado loads being lesser than the wind loads.

The elementary school is a one-story building with a 500 ft by 300 ft plan area with a roof height of 15 ft and a 2 ft parapet. Calculations were performed for both exposure categories (B and C) to see their effects on the buildings and how they impact the loading. The MWFRS and C&C loads were then calculated for different zones. Figure 3.1 (Not To Scale), shows the C&C zones on the roof and walls. The location of Branson, MO was chosen specifically based on the regular wind speed and tornado wind speed maps. The location is in the greatest tornado wind speed area and is also in the smallest possible wind speed in the same area. This provides a sort of worst-case scenario for tornado loads giving the highest probability of tornado loads controlling.

The Power Plant located in Manhattan, KS is a multi-story structure where the roof height is 60 ft and has a 2 ft parapet. The plan area of the structure is loosely based on a similar power plant located near the area, which gives a 1,000 ft by 1,000 ft plan area. A plan view of the building is shown in Figure 4.2 with the C&C zones shown, the drawing is not to scale. For this example, the main purpose was to look at the impact of tornado loads on a large-scale risk category IV building. For the case of a power plant, the likelihood of it being in exposure category B is very low so it's not considered. Thus, Exposure Category C is used for wind load. The location of Manhattan, KS was chosen because it's within the largest tornado wind speed zone. Tornado wind speed (125 mph) is higher than the design wind speed (123 mph) in this example, while in the previous example the design wind speed (114 mph) is higher than the tornado speed (95 mph). However, at the height of 60 ft and the exposure C, K_z, has a value of 1.13 compared to the value of 1 used for K_{zTor} under tornado design. This combination gives a greater wind velocity pressure.

Table 4.1 Example Building Load Parameters

Variable	Wind (Ch. 26-30)		Tornado (Ch. 32)	
	Elem. School	Power Plant	Elem. School	Power Plant
A_e (SF)	N/A		150,000	1,000,000
V or V_T (MPH)	114	123	95	125
Exposure	B/C	C	N/A	N/A
Mean Roof Height, h (ft)	15	60	15	60
K_d or K_{dT}	0.85	0.85	0.75-0.9	
K_{zt}	1	1	N/A	
K_e	0.969	0.960	0.969	0.960
K_z or K_{zTor}	0.57/0.85	1.13	1	1
G or G_T	0.85	0.85	0.85	0.85
Enclosure	Partially Encl.	Partially Encl.	Partially Encl.	Partially Encl.
GC_{pi} or GC_{piT}	+/-0.55	+/-0.55	+/-0.55	+/-0.55
K_{vT}	N/A	N/A	1 - 1.1	1 - 1.2

Table 4.2 MWFRS Base Shear Comparison Elementary School

Load Direction	Exposure	Wind Base Shear, V_w, (Kips)	Tornado Base Shear, V_T, (Kips)	Change (Kips)	% Change
N-S	B	102.2	115.9	13.5	13.2
	C	151.9		-35.9	-23.7
E-W	B	157.4	178.0	20.3	13.1
	C	233.3		-55.3	-23.7

Base shears from the MWFRS wind loads and tornado loads for the elementary school are listed in Table 4.2, and the wind pressures for C&C are shown in Table 4.3 for Exposure B and Table 4.4 for Exposure C. From these results, there is a strong correlation between the wind load values and the exposure category. This is caused by the K_z factor being drastically lower for Exposure B (0.57) than Exposure C (0.85). The tornado equivalent K_{zTor} is a factor of 1 so tornado load is not exposure category dependent. This makes sense that the tornado wind speed is not affected by exposure category. For Exposure Category B, the wind speed drops near the surface, so the velocity pressure is lower, which causes the base shear to be lower than that of the tornado load. For Exposure Category C wind speed does not drop as much near the surface, so the base shear is higher than that of a tornado load. From inspection of the results when tornado loads control, the increase is not significant. This is also shown in the NIST economic analysis report (Kneifel, et al., 2022) where the increase in loads did not cause a major increase in the cost of construction (Kneifel, et al., 2022).

Table 4.3 C&C Exposure B Comparison elementary School

Zones	Wind (psf)	Tornado (psf)	Change	% Change
-4	-23.5	-28.2	-4.7	20.1
-5	-25.8	-30.6	-4.9	18.9
Positive Wall	21.9	26.5	4.6	21.0
-1’	-20.4	-30.4	-10	49.2
-1	-26.9	-35.8	-8.9	32.9
-2	-33.9	-40.7	-6.8	20.0
-3	-37.2	-44.4	-7.2	19.3
Positive Roof	11.8	16.3	4.6	38.8
Parapet				
Windward				
-2	43.5	45.0	1.5	3.4
-3	50.6	52.4	1.7	3.4
Leeward				
-4	29.1	30.1	1.0	3.4
-5	31.4	32.5	1.1	3.4

Table 4.4 C&C Exposure C Comparison Elementary School

Zones	Wind (psf)	Tornado (psf)	Change (psf)	% Change
-4	-34.9	-28.2	6.7	-19.2
-5	-38.3	-30.6	7.6	-20
Positive Wall	32.5	26.5	-6.0	-18.6
-1’	-30.3	-30.4	-0.1	0.4
-1	-40.0	-35.8	4.2	-10.5
-2	-50.4	-40.7	9.7	-19.2
-3	-55.3	-44.4	10.9	-19.7
Positive Roof	17.5	16.3	-1.1	-6.6
Parapet				
Windward				
-2	58.8	45	-19.1	-29.8
-3	63.8	52.4	-22.3	-29.8
Leeward				
-4	42.9	30.1	-12.8	-29.8
-5	46.3	32.5	-13.8	-29.8

The C&C loads for the elementary school show a similar trend to that of the MWFRS with Exposure B being controlled by tornado loads and Exposure C is mostly controlled by wind loads. The exception is the negative roof pressure for Zone 1’ as it is controlled by tornado loads. The roof is an area of importance in tornado design due to the large vertical wind component of tornados. Because of that, there is a possibility of the tornado loads controlling on the roof especially in Zones 1’ and 1. These two zones will be controlled by tornados before the other roof zones, due to Zones 1’ and 1 having a K_{vT} value of 1.2, while the other roof zones have a value of 1.05. Zone 1’ will be controlled by tornado loads before Zone 1 due to the K_{dT} value for Zone 1’ being 0.9 compared to the other zones being 0.75. The parapet is of less concern when it comes to C&C as it is considered a non-structural component and is not critical to building function.

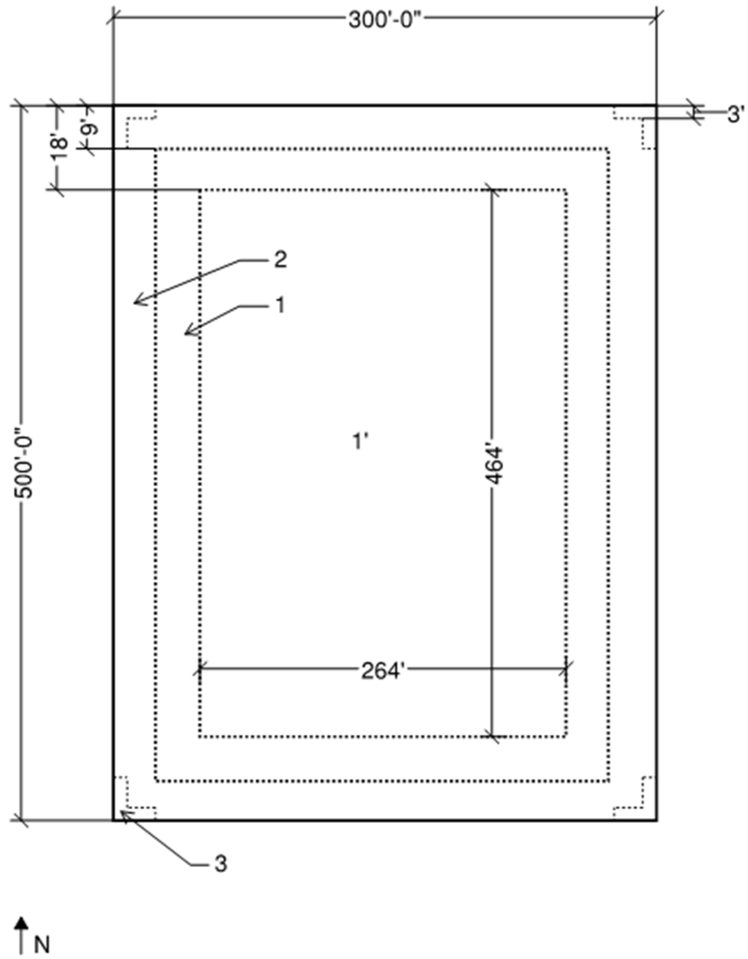


Figure 4.1 Plan view of the elementary school with the C&C zones (NTS)

Table 4.5 MWFRS Base Shear Comparison Power Plant

Load Direction	Exposure	Wind Base Shear, V_w, (Kips)	Tornado Base Shear, V_T, (Kips)	Change (Kips)	% Change
N-S	C	2512.3	2190.3	-321.9	-12.8
E-W	C	2512.3	2190.3	-321.9	-12.8

For the power plant example, the base shears for wind and tornado from the MWFRS loads are shown in Table 4.5 and the wind pressures for C&C are shown in Table 4.6. The results indicate that wind load is controlling over tornado load, which contrasts to the preconceived notion that tornado provisions would cause a dramatic increase in design loads. This example illustrates that it may not always be the case. The only two differences in the calculations are wind speed vs. tornado speed, and the velocity pressure exposure coefficients K_z vs. K_{zTor} when it comes to the lateral forces. The roof loads have an added 1.1 K_{vT} factor, increasing the uplift loads.

Table 4.6 C&C Exposure C Comparison Powerplant

Zones	Wind (psf)	Tornado (psf)	Change (psf)	% Change
-4	-53.4	-48.3	5.0	-9.4
-5	-58.6	-52.5	6.0	-10.3
Positive Wall	49.8	45.5	-4.3	-8.7
-1’	-46.4	-52.2	-5.8	12.5
-1	-61.2	-51.3	-0.2	0.3
-2	-77.1	-69.8	7.3	-9.5
-3	-84.7	-76.2	8.5	-10.0
Positive Roof	26.1	26.9	0.1	0.4
Parapet				
Windward				
-2	87.7	70.7	-19.1	-19.9
-3	95.2	76.8	-22.3	-19.9
Leeward				
-4	63.9	51.6	-12.8	-19.9
-5	69.1	55.8	-13.8	-19.9

The results comparing wind and tornado C&C design are shown above in Table 4.6. The wind design calculations were based on Exposure Category C parameters. Because of this, we see similar results to what we saw in the previous example where the wind loads controlled over the tornado loads for most zones. However, in this example we see that Zones 1' and 1 as well as the positive roof zones are controlled by tornado loads. This reinforces the conclusion from the previous example of the roof zones controlling due to the K_{dT} and K_{vT} being greater in the middle zones. We also see that the positive roof pressure is also controlled by tornados. This is due to using the K_{dT} value of 0.9 since this region includes the 1' roof zone and the K_{vT} is 1 compared to the uplift value of 1.05 or 1.2. This trend can also be noticed in the previous example by how the percent change in the positive roof pressure is smaller than some uplift zones. Overall, when tornadoes do control it is by a small percentage.

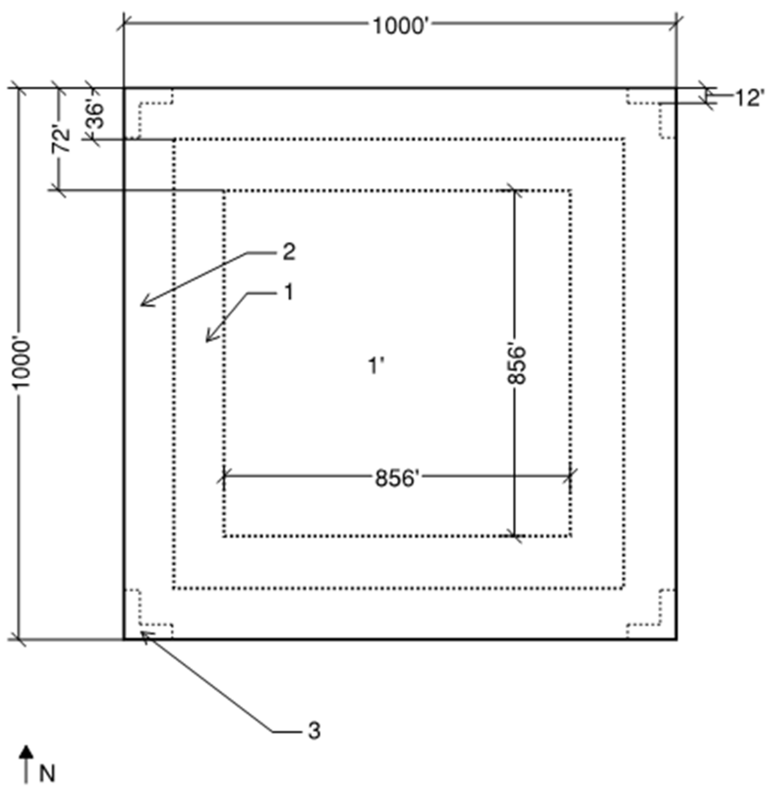


Figure 4.2 Plan View of Power Plant with C&C Zones (NTS)

As shown in this example, tornado loads may not control over wind loads. There are some important factors that could lead to tornadoes controlling. The one most apparent from these examples is the exposure category. The location of the building could also be another factor. Finally, the height of the building could play a role. For exposure category B buildings, tornado is more likely to govern, while for Exposure Category C buildings, it's less likely to govern. The height could be impactful due to the higher K_z values at higher elevations thus making the wind pressures larger. For tornados, K_{zT} has the highest value of 1 and decreases above 200 ft. There could be a correlation that the shorter the building, the more likely tornado loads would control.

In the cases where the tornado loads control the design, there is only a small increase in the loading. For the MWFRS the increases were only 10-15%, and for the C&C that same range of increase is seen for most zones excluding some roof zones in which the largest increase is 28.3%. This large increase of roof loads is noteworthy as it pertains to the roof, and it's stated in the NIST economic analysis (Kneifel, et al., 2022) that the roof connections is one of the areas where an increase in design strength and costs can occur. While there are many factors that play a role in tornado design, the process is still very similar to wind design. The chances that tornado loads govern the design are very conditional and so knowing those conditions is important. However, the cases that the tornado loads control appear to be limited.

Chapter 5: Conclusion

Tornadoes have been shown to be a destructive force that are not to be taken lightly, as tornadoes are responsible for a lot of fatalities and property damage every year. The impacts of these natural disasters led the ASCE to develop code provisions to limit the destruction in the regions affected by tornadoes. As has been shown from the Joplin Tornado and others, there are ways to improve building design that can have a meaningful impact and can be done with little interference on the current design and building practices. The ASCE 7-22 Chapter 32 Tornado Loads provides the means and methods to do that.

In Chapter Two of this report the characteristics of tornadoes, the damage they cause and the cost of reducing the damage are discussed. Tornadoes are a violent cyclone of swirling winds and this cyclone, while smaller in size than a hurricane, produces similar wind speeds. Due to the nature of tornadoes, they create a much larger suction force causing more wind-borne debris and greater uplift forces on buildings. The uplift force could lift roofs off buildings. In cases where the roof was an essential part of the MWFRS, it was observed that roof failure would result in complete building failure. This was the case in many box type structures, such as those warehouse and store buildings. The large amount of wind-borne debris was shown to break down building envelopes and allow for the penetration of storm water and debris into buildings. This intrusion makes buildings inoperable and unoccupiable (NIST, 2014). These reports from the Joplin Tornado provided some goals and direction for what would eventually become the tornado provisions in ASCE 7-22. Finally, a cost analysis by NIST provides the cost impact of the proposed provisions, showing that for a small cost increase one could offer greater protection for building occupants.

Chapter Three provides an overview of the research into some new parameters and modified coefficients of the tornado provisions, as well as the design procedure. These provisions introduced the first ever tornado wind speed maps that also include the consideration of the effective plan area, A_e. Another major contribution to the provisions was research where 5,000 small scale tornado simulations were studied (ASCE, 2021). This research led to the development of the tornado pressure coefficient adjustment factors, K_{vT}, brought about new values for the directionality factor, K_{dT}, and the internal pressure coefficients, GC_{piT}. This research looked further into the atmospheric pressure changes (APC) induced by tornadoes. It was discovered that the APC causes an increase in uplift forces that led to the K_{vT} factor. APC occurs rapidly, so the building internal pressure can't transfer through the envelope fast enough, causing an increase in internal pressure. The swirling winds of the tornado also create some interesting conditions when it comes to the directionality of the winds. This brought adjustments to the directionality factor for tornadoes. Multiple sources have done research on the topographic effects on tornado speeds, and inconsistent results led to this factor not being included in the provisions. The exposure category was also left out of the provisions due to its low impact on tornado speed.

Finally, in Chapter Four the results of two different design examples are presented. The first example is based on a single-story elementary school located in Branson, MO. The purpose of this calculation is to investigate the impact of tornado loads on different exposure categories. It was discovered that for Exposure Category B, tornado loads are more likely to govern over wind loads, while for Exposure Category C, wind loads are more likely to govern. This example was also located in an area with low wind speed and high tornado speed. The second example is a power plant located in Manhattan, KS, and is loosely based on a nearby power plant. This calculation was to provide an example of a large-scale risk category IV building to see what the impact would be. The result was a little surprising as intuitively one would think that a building of this magnitude would be greatly impacted by tornado loads. The tornado loads did not govern in most cases in this example, which is due to multiple reasons. The first factor is that the building has Exposure Category C which has been shown to make tornado loads less likely to control. The second factor is the height of the building. The K_z factor for wind design was 1.13 compared to K_{zT} value of 1. The zones where tornado loads did control where due to the tornado speed being greater than the wind speed, the K_{dT} and K_{vT} factors. The height factor showed that tornado loads have less impact for taller buildings.

In conclusion, the tornado provisions in the ASCE 7-22 provide a good start to limiting the impact of tornadoes on a community. The purpose of these provisions is not to make every building a storm shelter and in no way does a building designed with this provision alone meet the requirements of a storm shelter. It aims to keep buildings critical to survival in an emergency and buildings posing significant risk to human life from having a catastrophic failure, and to keep essential facilities operational. While the provisions do not intend for extreme tornados due to the ultra-low probability, they will protect these buildings against tornados to achieve the reliability corresponding to their risk category. These provisions provide a good methodology and time will tell if they are successful in their endeavor.

References

ASCE. (2021). *ASCE/SEI 7-22 Standard: Minimum Design Loads and Associated Criteria for Buildings and Other Strucutres.* American Society of Civil Engineers (ASCE).

CDC (Centers for Diesease Control and Prevention). (2012). *Tornado Related Fatalities: Five States, Southeastern United States, April 25-28, 2011.* U.S. Department of Health and Human Services.

Davies-Jones, R., Trapp, R. J., & Bluestein, H. B. (2001). *Tornadoes and Tornadic Storms.* Meteorological Monographs.

Insurance Information Institute. (2023, March 15). *Facts + Statistics: Tornadoes and thunderstroms*. Retrieved from Insurance Information Institute: https://www.iii.org/fact-statistic/facts-statistics-tornadoes-and-thunderstorms#:~:text=In%20an%20average%20year%2C%20about,and%20type%20of%20wind%20damage.

Insurance Information Institute. (2023, January 16). Spotlight on: Catastophes: Insurance Issues.

Kneifel, J., Levitan, M., Harris, B., Haney, B., Smith, T., Butry, D., . . . Tohmas, D. (2022). *Economic analysis of ASCE 7-22 Tornado Load Requirments.* National Institute of Standards and Technology.

McDonald, J. R., & Mehta, K. C. (2012). *Development, Implementation and Implications of the Enhanced Fujita Scale* . Lubbock: Texas Tech University.

Merriam-Webster. (2023, Feburary 18). Retrieved from merriam-webster.com: https://www.merriam-webster.com/dictionary/tornado

NIST. (2014). *Final Report: NIST Technical Investigation of the May 22, 2011, Tornado in Joplin Missouri.*

Prevatt, D. O., van De Lindt, J. W., Back, E. W., Graettinger, A. J., Pei, S., Coulbourne, W., . . . James, D. (2012). *Making the Case for Improved Strucutral Design: Tornado Outbreaks of 2011.* Leadership Managment Engineering.

Refan, M., & Hangan, H. (2018). Near surface experimental exploration of tornado vortices. *Journal of Wind Engineering and Industrial Aerodynamics*, 120-135. Retrieved from https://doi.org/10.1016/j.jweia.2018.01.042.

Texas Tech University. (2006). *A reccomondation for an enhanced Fujita scale.* Lubbock, TX: Wind Science and Engineering Center.

Appendix A: Building Loading Examples

Design Wind Pressures for Elementary School in Branson, Mo. Using ASCE 7-22

Step	Calculations					Ref.
1	Design Parameters					
	Basic Wind Speed V=	114	MPH (3s gust)			ASCE haz
	Exposure category =	B				sec 26.7
	Building Parameters					
	Roof Height=	15	ft			
	Parapet Height=	2	ft			
	plan area					
	(N-S) Dim	500	ft			
	(E-W) Dim	300	ft	Ae(sf)=	150000	
	EW/NS=	0.6	used for EW wind			
	NS/EW=	1.666667	used for NS wind			
	Gust Effect Factor=	0.85				sec 26.11
	Enclosure Partially Enclosed			Gcpi=	0.55	26.13-1
	Topographic factor (Kzt) =	1	(Flat Terrain)			26.8.2
	Directionality Factor (kd)=	0.85				26.6-1
	Elevation Factor (Ke)=	0.969	(780 ft)			26.9-1

Eq. 26.10.2

$$q_z = 0.00256 K_z K_{zt} K_e V^2$$

Eq. 27.3-1

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

Eq. 27.3-3

$$p_p = q_p K_d (GC_{pn})$$

Step	Calculations	Ref.

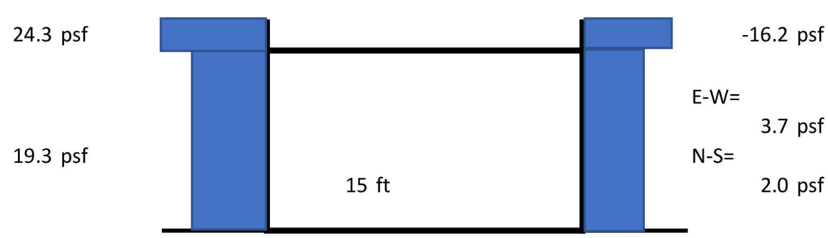
2 Surface Pressures MWFRS (CH 27)

Surface	Z (ft)	q(psf)	Cp	qKdGCp (psf)	Net Pressure (psf) +GCpi	Net Pressure (psf) -Gcpi
Windward	15	18.5	0.8	10.7	2.0	19.3
Leeward	All	18.5	-0.367	-4.9	-13.5	3.7
		18.5	-0.5	-6.7	-15.3	2.0
Sidewall	All	18.5	-0.7	-9.3	-18.0	-0.7
Roof	0-21.3	18.5	-0.9	-12.0	-20.6	-3.4
	21.3-42.6	18.5	-0.5	-6.7	-15.3	2.0
	42.6-290	18.5	-0.3	-4.0	-12.6	4.6
Parapet			Gcpn			
windward	17	19.1	1.5		24.3	
Leeward	17	19.1	-1.0			-16.2

ASCE 7-16
27.3.4
Eq. 27.3-1

27.3.4
Eq. 27.3-3

3 Base shear



	N-S=		E-W=	
15-17	600 sf	24.3 k	1000 sf	40.6 k
0-15	4500 sf	78.1 k	7500 sf	116.8 k

N-S= 102.4 k E-W= 157.4 K

Step	Calculations	Ref.
		ASCE 7-16
4	Componets and cladding Calculations (CH 30)	Ch 30
	q= 18.5 psf	Eq 26.10-1
	qp= 19.1 psf	

Structural Componet	Zone	Surface Area (sf)	GCp	qGCp(psf)	Net Pressure (psf) +GCpi	Net Pressure (psf) -Gcpi	Ref.
							Eq 30.3-1
Wall	-4	75	-0.95	-14.8	-23.5	-6.2	Fig 30.3-1
	-5	75	-1.09	-17.1	-25.8	-8.5	
	4 & 5	75	0.85	13.3	4.6	21.9	
Roof	-1'	200	-0.75	-11.8	-20.4	-3.1	Fig 30.3-2A
	-1	200	-1.16	-18.3	-26.9	-9.6	
	-2	200	-1.61	-25.3	-33.9	-16.7	
	-3	200	-1.82	-28.6	-37.2	-20.0	
	1', 1, 2 & 3	200	0.20	3.1	-5.5	11.8	
Parapet					Windward	Leeward	
	4&5	75	0.85	16.1			
	-4	75	-0.95	-18.1		29.1	
	-5	75	-1.09	-20.8		31.4	
	-2	75	-1.84	-35.1	43.5		
	-3	75	-2.27	-43.4	50.6		

eq 30.3-1

$$p = q_h K_d\left[\left(GC_p\right) - \left(GC_{pi}\right)\right]$$

Design Wind Pressures for Elementary School in Branson, Mo. Using ASCE 7-22

Step	Calculations					Ref.
1	Design Parameters					
	Basic Wind Speed V=		114	MPH (3s gust)		ASCE haz
	Exposure category =	C				sec 26.7
	Building Parameters					
	Roof Height=		15	ft		
	Parapet Height=		2	ft		
	plan area					
	(N-S) Dim		500	ft		
	(E-W) Dim		300	ft	Ae(sf)= 150000	
	EW/NS=	0.6		used for EW wind		
	NS/EW=	1.666667		used for NS wind		
	Gust Effect Factor=		0.85			sec 26.11
	Enclosure	Partially Enclosed		Gcpi=	0.55	26.13-1
	Topographic factor (Kzt) =		1	(Flat Terrain)		26.8.2
	Directionality Factor (kd)=		0.85			26.6-1
	Elevation Factor (Ke)=		0.969	(780 ft)		26.9-1

Eq. 26.10.2

$$q_z = 0.00256 K_z K_{zt} K_e V^2$$

Eq. 27.3-1

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

Eq. 27.3-3

$$p_p = q_p K_d (GC_{pn})$$

Step	Calculations	Ref.

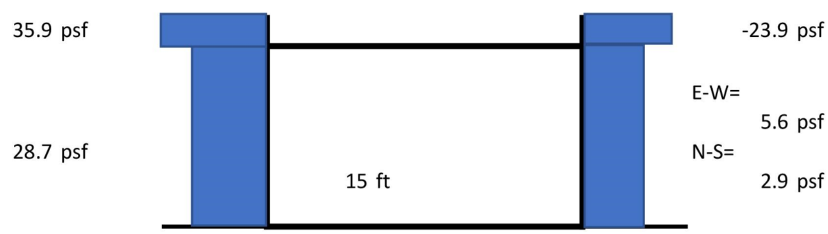
2 Surface Pressures MWFRS (CH 27)

Surface	Z (ft)	q(psf)	Cp	qKdGCp (psf)	Net Pressure (psf) +GCpi	Net Pressure (psf) -Gcpi
Windward	15	27.4	0.8	15.9	3.0	28.7
Leeward	All	27.4	-0.367	-7.3	-20.1	5.6
		27.4	-0.5	-9.9	-22.7	2.9
Sidewall	All	27.4	-0.7	-13.9	-26.7	-1.0
Roof	0-21.3	27.4	-0.9	-17.8	-30.7	-5.0
	21.3-42.6	27.4	-0.5	-9.9	-22.7	2.9
	42.6+	27.4	-0.3	-5.9	-18.8	6.9
Parapet			Gcpn			
windward	17	28.1	1.5		35.9	
Leeward	17	28.1	-1.0			-23.9

ASCE 7-16
27.3.4
Eq. 27.3-1

27.3.4
Eq. 27.3-3

3 Base shear



	N-S=		E-W=	
15-17	600 sf	35.9 k	1000 sf	59.8 k
0-15	4500 sf	116.0 k	7500 sf	173.5 k

N-S= 151.9 k E-W= 233.3 K

Step	Calculations	Ref.
		ASCE 7-16
4	Componets and cladding Calculations (CH 30)	Ch 30
	q= 27.4 psf	Eq 26.10-1
	qp= 28.1 psf	

Structural Componet	Zone	Surface Area (sf)	GCp	qGCp(psf)	Net Pressure (psf)	
					+GCpi	-Gcpi
Wall	-4	75	-0.95	-22.1	-34.9	-9.2
	-5	75	-1.09	-25.4	-38.3	-12.6
	4 & 5	75	0.85	19.7	6.9	32.5
Roof	-1'	200	-0.75	-17.5	-30.3	-4.7
	-1	200	-1.16	-27.1	-40.0	-14.3
	-2	200	-1.61	-37.6	-50.4	-24.7
	-3	200	-1.82	-42.5	-55.3	-29.7
	1', 1, 2 & 3	200	0.20	4.7	-8.2	17.5
Parapet					Windward	Leeward
	4&5	75	0.85	20.2		
	-4	75	-0.95	-22.6		42.9
	-5	75	-1.09	-26.1		46.3
	-2	75	-1.84	-43.9	64.2	
	-3	75	-2.27	-54.4	74.6	

Eq 30.3-1
Fig 30.3-1
Fig 30.3-2A

eq 30.3-1

$$p = q_h K_d[(GC_p) - (GC_p)]$$

Design Tornado Pressures for Elementary School in Branson, Mo. Using ASCE 7-22

Step	Calculations	Ref.
1	Design Parameters	ASCE 7-22
	Basic Wind Speed V_T= 95 MPH	Fig 32.5-1
	Exposure category = N/A	
	Building Parameters	
	Roof Height= 15 ft	
	Parapet Height= 2 ft	
	plan area	
	(N-S) Dim 500 ft	
	(E-W) Dim 300 ft Plan Area 150000	
	EW/NS= 0.6 used for EW wind	
	NS/EW= 1.666667 used for NS wind	
	Gust Effect Factor (G_T) 0.85	
	Enclosure Partially Enclosed GC_{piT}= 0.55	
	Directionality Factor (k_{dT})= MWFRS= 0.8	
	C&C	
	Roof zone 1' = 0.9	
	All other= 0.75	
	Elevation Factor (K_e)= 0.969 (1000 ft)	
	Tornado Pressure Coefficent Adjustment factor (Kvt)	
	Uplift on roofs	
	MWFRS Roof= 1.1 Positive roof= 1	
	C&C Wall Pressure= 1	
	Zone 1= 1.2	
	all other cases= 1	
	Zone 2&3= 1.05	

Step	Calculations	Ref.

Eq. 32.10-1

$$q_{zT} = 0.00256 K_{zTor} K_e V_T^2$$

Eq. 32.10-1

$$p_T = qG_T K_{dT} K_{vT} C_p - q_i (GC_{piT})$$

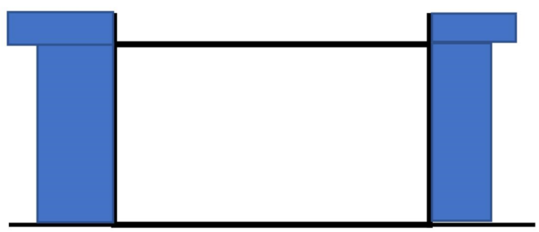
2 Tornado Surface pressures (CH 32)

Surface	Z (ft)	q(psf)	Cp	qGCp(psf)	Net Pressure (psf)	
					+GCpi	-Gcpi
Windward	33	22.4	0.8	15.2	-0.1	24.5
Leeward	33	22.4	-0.367	-7.0	-17.9	6.7
	33	22.4	-0.5	-9.5	-19.9	4.7
Sidewall	33	22.4	-0.7	-13.3	-23.0	1.7
Roof	0-33	22.4	-0.9	-17.1	-27.4	-2.8
	33-66	22.4	-0.5	-9.5	-20.7	4.7
	66-1000	22.4	-0.3	-5.7	-17.3	7.7
Parapet			Gcpn			
windward	17	22.4	1.5		26.9	
Leeward	17	22.4	-1.0			-17.9

3 Base Shear

26.9 psf

24.5 psf



-17.9 psf

E-W=

6.7 psf

N-S=

4.7 psf

Max base shear

	N-S			E-W	
15-17	600 sf	26.9 k		1000 sf	44.8 k
0-15	4500 sf	89.1 k		7500 sf	133.2 k

VT= 115.9 k VT= 178.0 k

4 Comparison to Wind loads

Direction	Exposure	Vw (k)	VT (k)	Change	% change
N-S	B	102.4	115.9	13.5	13.2
	C	151.9		-35.9	-23.7
E-W	B	157.4	178.0	20.6	13.1
	C	233.3		-55.3	-23.7

Step	Calculations	Ref.
5	Componets and Cladding (CH 32)	

qht= 22.4 psf
qpT= 22.4 psf

Structural Componet	Zone	Surface Area (sf)	GCp	Net Pressure (psf)	
				+GCpi	-Gcpi
Wall	-4	75	-0.95	-28.2	-3.6
	-5	75	-1.09	-30.6	-6.0
	4 & 5	75	0.85	1.9	26.5
Roof	-1'	200	-0.75	-30.4	-5.8
	-1	200	-1.16	-35.8	-11.1
	-2	200	-1.61	-40.7	-16.1
	-3	200	-1.82	-44.4	-19.8
	1', 1, 2 & 3	200	0.20	-8.3	16.3
Parapet				Windward	Leeward
	4&5	75	0.85		
	-4	75	-0.95		30.1
	-5	75	-1.09		32.5
	-2	75	-1.84	45.0	
	-3	75	-2.27	52.4	

5 Comparison to wind loads

Zones	Wind (B)	Wind (C)	Tornado	change (B)	% change	change (C)	% change
-4	-23.5	-34.9	-28.2	-4.7	20.1	6.7	-19.2
-5	-25.8	-38.3	-30.6	-4.9	18.9	7.6	-20.0
4 & 5	21.9	32.5	26.5	4.6	21.0	-6.0	-18.6
-1'	-20.4	-30.3	-30.4	-10.0	49.2	-0.1	0.4
-1	-26.9	-40.0	-35.8	-8.9	32.9	4.2	-10.5
-2	-33.9	-50.4	-40.7	-6.8	20.0	9.7	-19.2
-3	-37.2	-55.3	-44.4	-7.2	19.3	10.9	-19.7
1', 1, 2 & 3	11.8	17.5	16.3	4.6	38.8	-1.1	-6.6
Parapet windward							
-2	43.5	64.2	45.0	1.5	3.4	-19.1	-29.8
-3	50.6	74.6	52.4	1.7	3.4	-22.3	-29.8
Leeward							
-4	29.1	42.9	30.1	1.0	3.4	-12.8	-29.8
-5	31.4	46.3	32.5	1.1	3.4	-13.8	-29.8

Design Wind Pressures for Powerplant in Manhattan, KS. Using ASCE 7-22

Step	Calculations					Ref.
1	Design Parameters					
	Basic Wind Speed V=		123	MPH (3s gust)		ASCE haz
	Exposure category =	C				sec 26.7
	Building Parameters					
	Roof Height=		60	ft		
	Parapet Height=		2	ft		
	plan area					
	(N-S) Dim		1000	ft		
	(E-W) Dim		1000	ft	Ae(sf)= 1000000	
	EW/NS=	1		used for EW wind		
	NS/EW=	1		used for NS wind		
	Gust Effect Factor=		0.85			sec 26.11
	Enclosure Partially Enclosed			Gcpi=	0.55	26.13-1
	Topographic factor (Kzt) =		1	(Flat Terrain)		26.8.2
	Directionality Factor (kd)=		0.85			26.6-1
	Elevation Factor (Ke)=		0.96	(1000 ft)		26.9-1

Eq. 26.10.2

$$q_z = 0.00256 K_z K_{zt} K_e V^2$$

Eq. 27.3-1

$$p = q K_d G C_p - q_i K_d (G C_{pi})$$

Eq. 27.3-3

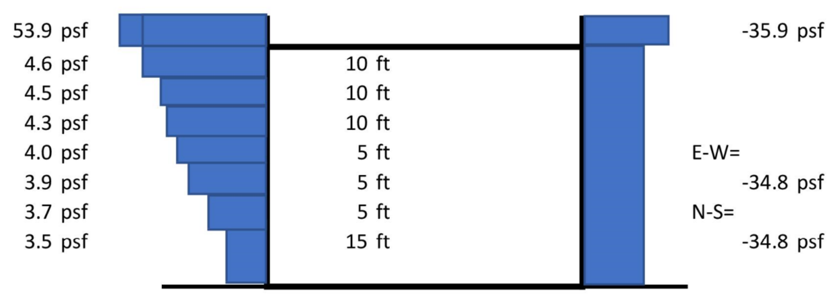
$$p_p = q_p K_d (G C_{pn})$$

Step	Calculations	Ref.

2 Surface Pressures MWFRS (CH 27)

Surface	Z (ft)	q(psf)	Cp	qGCp(psf)	Net Pressure (psf) +GCpi	-Gcpi	Ref.
Windward	15	31.6	0.8	18.3	3.5	33.1	ASCE 7-16 27.3.4
	20	33.6	0.8	19.4	3.7	35.1	Eq. 27.3-1
	25	35.1	0.8	20.3	3.9	36.7	
	30	36.5	0.8	21.1	4.0	38.1	
	40	38.7	0.8	22.3	4.3	40.4	
	50	40.5	0.8	23.4	4.5	42.3	
	60	42.0	0.8	24.3	4.6	43.9	
Leeward	All	42.0	-0.5	-15.2	-34.8	4.5	
		42.0	-0.5	-15.2	-34.8	4.5	
Sidewall	All	42.0	-0.7	-21.2	-40.9	-1.6	
Roof	0-60	42.0	-0.9	-27.3	-46.9	-7.7	
	60-120	42.0	-0.5	-15.2	-34.8	4.5	
	120-1000	42.0	-0.3	-9.1	-28.7	10.5	
Parapet			Gcpn				27.3.4
windward	62	42.3	1.5		53.9		Eq. 27.3-3
Leeward	62	42.3	-1.0			-35.9	

3 Base shear



	N-S=				E-W=			
0-15	15000	sf	574.5	k	15000	sf	574.5	k
20	5000	sf	192.6	k	5000	sf	192.6	k
25	5000	sf	193.4	k	5000	sf	193.4	k
30	5000	sf	194.2	k	5000	sf	194.2	k
40	10000	sf	390.8	k	10000	sf	390.8	k
50	10000	sf	392.7	k	10000	sf	392.7	k
60	10000	sf	394.4	k	10000	sf	394.4	k
60-62	2000	sf	179.7	k	2000	sf	179.7	k

N-S= 2512.3 k E-W= 2512.3 K

Step	Calculations	Ref.
		ASCE 7-16
4	Componets and cladding Calculations (CH 30)	Ch 30
	q= 42.0 psf	Eq 26.10-1
	qp= 42.3 psf	

Structural Componet	Zone	Surface Area (sf)	GCp	qGCp(psf)	Net Pressure (psf)		Ref.
					+GCpi	-Gcpi	Eq 30.3-1
Wall	-4	75	-0.95	-33.7	-53.4	-14.1	Fig 30.3-1
	-5	75	-1.09	-38.9	-58.6	-19.3	
	4 & 5	75	0.85	30.2	10.5	49.8	
Roof	-1'	200	-0.75	-26.8	-46.4	-7.1	Fig 30.3-2A
	-1	200	-1.16	-41.5	-61.2	-21.9	
	-2	200	-1.61	-57.5	-77.1	-37.9	
	-3	200	-1.82	-65.0	-84.7	-45.4	
	1', 1, 2 & 3	200	0.20	7.1	-12.5	26.8	
Parapet					Windward	Leeward	
	4&5	75	0.85	30.4			
	-4	75	-0.95	-34.0		64.4	
	-5	75	-1.09	-39.2		69.6	
	-2	75	-1.84	-66.0	96.4		
	-3	75	-2.27	-81.7	112.1		

eq 30.3-1

$$p = q_h[(GC_p) - (GC_p)]$$

Design Tornado Pressures for Walmart in Joplin. Using ASCE 7-22 Chapter 32

Step	Calculations	Ref.
1	Design Parameters	ASCE 7-22
	Basic Wind Speed V_T= 125 MPH	Fig 32.5-1
	Exposure category = N/A	
	Building Parameters	
	Roof Height= 60 ft	
	Parapet Height= 2 ft	
	plan area (N-S) Dim 1000 ft	
	(E-W) Dim 1000 ft Plan Area 1000000	
	EW/NS= 1 used for EW wind	
	NS/EW= 1 used for NS wind	
	Gust Effect Factor (G_T): 0.85	
	Enclosure Partially Enclosed GC_{piT}= 0.55	
	Directionality Factor (k_{dT})= MWFRS= 0.8	
	C&C	
	Roof zone 1' = 0.9 All other= 0.75	
	Elevation Factor (K_e)= 0.96 (1000 ft)	
	Tornado Pressure Coefficent Adjustment factor (Kvt)	
	Uplift on roofs MWFRS Roof= 1.1 Positive roof= 1	
	C&C Wall Pressure= 1 Zone 1= 1.2	
	all other cases= 1	
	Zone 2&3= 1.05	

Step	Calculations	Ref.

Eq. 32.10-1

$$q_{zT} = 0.00256 K_{zTor} K_e V_T^2$$

Eq. 32.10-1

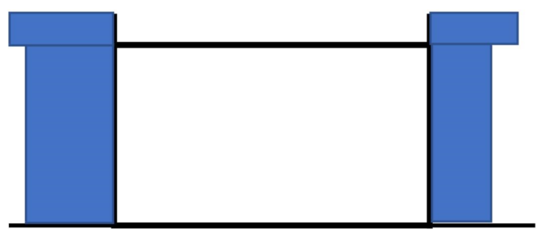
$$p_T = q G_T K_{dT} K_{vT} C_p - q_i (G C_{piT})$$

2 Tornado Surface pressures (CH 32)

					Net Pressure (psf)	
Surface	Z (ft)	q(psf)	Cp	qGCp(psf)	+GCpi	-Gcpi
Windward	60	38.4	0.8	26.1	-0.2	42.0
Leeward	60	38.4	-0.5	-16.3	-34.2	8.1
Sidewall	60	38.4	-0.7	-22.8	-39.4	2.8
Roof	0-60	38.4	-0.9	-29.4	-47.0	-4.7
	60-120	38.4	-0.5	-16.3	-35.5	8.1
	120-1000	38.4	-0.3	-9.8	-29.7	13.3
Parapet			Gcpn			
Windward	62	38.4	1.5		46.08	
Leeward	62	38.4	-1.0			-30.72

3 Base Shear

46.08 psf -30.72 psf



E-W=

42.0 psf 8.1 psf

Max base shear

	N-S			E-W	
60-62	2000 sf	153.6 k		2000 sf	153.6 k
0-60	60000 sf	2036.7 k		60000 sf	2036.7 k

VT= 2190.3 k VT= 2190.3 k

4 Comparison to Wind loads

Direction	Exposure	Vw (k)	VT(k)	Change	% change
N-S	C	2512.3	2190.3	-321.9	-12.8
E-W	C	2512.3	2190.3	-321.9	-12.8

Step	Calculations	Ref.
5	Componets and Cladding (CH 32)	

qhT= 38.4 psf
qpT= 38.4 psf

Structural Componet	Zone	Surface Area (sf)	GCp	Net Pressure (psf)	
				+GCpi	-Gcpi
Wall	-4	75	-0.95	-48.3	-6.1
	-5	75	-1.09	-52.5	-10.3
	4 & 5	75	0.85	3.2	45.5
Roof	-1'	200	-0.75	-52.2	-10.0
	-1	200	-1.16	-61.3	-19.1
	-2	200	-1.61	-69.8	-27.6
	-3	200	-1.82	-76.2	-34.0
	1', 1, 2 & 3	200	0.20	-15.4	26.9
Parapet				Windward	Leeward
	4&5	75	0.85		
	-4	75	-0.95		51.6
	-5	75	-1.09		55.8
	-2	75	-1.84	77.2	
	-3	75	-2.27	89.8	

5 Comparison to wind loads

Zones	Wind (psf)	Tornado (psf)	change	% change
-4	-53.4	-48.3	5.0	-9.4
-5	-58.6	-52.5	6.0	-10.3
4 & 5	49.8	45.5	-4.3	-8.7
-1'	-46.4	-52.2	-5.8	12.5
-1	-61.2	-61.3	-0.2	0.3
-2	-77.1	-69.8	7.3	-9.5
-3	-84.7	-76.2	8.5	-10.0
1', 1, 2 & 3	26.8	26.9	0.1	0.4
Parapet windward				
-2	96.4	77.2	-19.1	-19.9
-3	112.1	89.8	-22.3	-19.9
Leeward				
-4	64.4	51.6	-12.8	-19.9
-5	69.6	55.8	-13.8	-19.9