NIST Technical Note 2214

Economic Analysis of ASCE 7-22 Tornado Load Requirements

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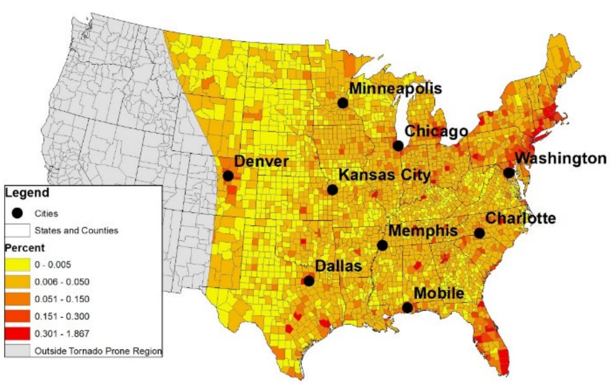

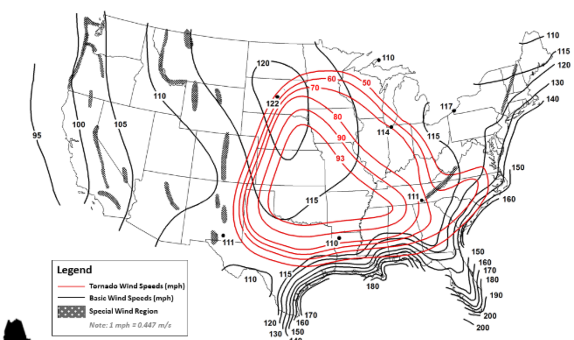

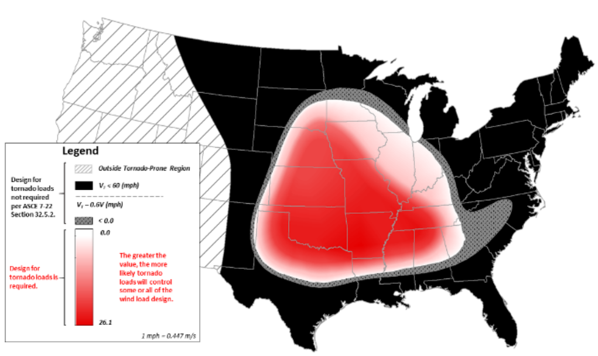

National Institute of Standards and Technology
U.S. Department of Commerce

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Gina M. Raimondo, Secretary

National Institute of Standards and Technology
James K. Olthoff, Performing the Non-Exclusive Functions and Duties of the Under Secretary of Commerce for Standards and Technology & Director, National Institute of Standards and Technology

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Preface

This study was jointly conducted by the Applied Economics Office (AEO) and the Structures Group of the Materials and Structural Systems Division in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST), in collaboration with the Building Science Branch in the Federal Insurance and Mitigation Administration at the Federal Emergency Management Agency (FEMA), as well as Huckabee, Inc. and TLSmith Consulting Inc. The study is to support NIST's overall effort to implement recommendations NIST made as a result of the National Construction Safety Team Act technical investigation of the May 22, 2011 tornado in Joplin, Missouri [1]. It is designed to identify the potential impacts on the commercial building and institutional building sectors associated with adoption of the new tornado load requirements in the ASCE 7-22 Standard: Minimum Design Loads and Associated Criteria for Buildings and Other Structures [2]. The intended audience is standards and codes development organizations, all levels of government that might adopt the International Building Code (IBC) and/or directly adopt ASCE 7, policy makers in the commercial and institutional building sectors, building owners and designers, researchers, and others interested in building resiliency.

Disclaimers

The policy of the National Institute of Standards and Technology is to use metric units in all of its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical and less confusing to include U.S. customary units as well as metric units. Measurement values in this report are therefore stated in U.S. customary units first, followed by the corresponding values in metric units within parentheses.

Abstract

This study analyzes the potential economic impacts from implementation of the new tornado load requirements in the ASCE 7-22 Standard: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, by incorporation into the International Building Code (Proposal S63-22 in Ref. [3]) and/or direct adoption by Federal, state, and local governments. The Standard requires that Risk Category III and IV buildings located in the tornado-prone region (approximately equal to the area of the conterminous U.S. east of the Continental Divide) be designed to resist tornado loads in addition to wind loads from other types of storms. Risk Category III includes buildings that represent a substantial hazard to human life in the event of failure (e.g., theaters and other assembly occupancies, schools, nursing homes), while Risk Category IV is for essential facilities (e.g., hospitals, fire and police stations, emergency operations centers).

The approach in this study is to (1) identify the potential numbers of buildings that may be impacted, (2) compare tornado loads with existing wind load requirements to understand when and where tornado loads will control design, (3) determine what building elements will require changes in construction design when tornado loads control, and (4) estimate the cost of these changes in construction design.

The adoption of the new tornado load requirements in the ASCE 7-22 standard will impact a small fraction of new buildings in the United States. When excluding residential occupancies with less than 50 units, the building stock occupancy types for Risk Category III and IV buildings in the tornado-prone region represents 15.0 % of the entire U.S. building stock and 18.3 % of the building stock in the tornado-prone region. These results are effectively upper bound estimates as tornado loads will not control over wind loads for all Risk Category III and IV buildings in the tornado-prone region. Whether tornado loads control any aspect of the building design over wind loads depends on many different climatological and building characteristics. Geospatial analyses are used identify the impacts of several of these variables. In general, the tornado design requirements will have the most impact in the central and southeast U.S.

Case studies are used to estimate the relative magnitude of the potential cost impacts of five building elements (roof systems, roof diaphragm, roof joists and wide flange beams and girders, exterior wall framing, and foundation anchorages) for two building types (elementary school and high school) for wind Exposure Categories B and C baseline building designs across nine locations to provide a range of potential load requirements and resulting cost implications. The results of the case studies show that tornado loads can vary significantly, from less than wind loads to more than double the wind loads. Tornado loads will not control for many locations and building types, particularly those on the periphery of the tornado-prone region. For scenarios in which the tornado loads do control, the construction design is often not influenced. Of the nine cities considered in this study, three realize cost increases for at least one exposure category for the elementary school and six for the high school. Of all the building type – location – exposure combinations (36), only six (three for each building type) realize cost impacts greater than 0.07 % of the project budget.

Key words

Building economics; tornadoes; tornado loads; atmospheric pressure change; ASCE 7; economic analysis; commercial buildings; institutional buildings; essential facilities; building codes; building standards

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1. Introduction

Tornadoes are one of the most impactful natural hazards in the United States in terms of lives lost and property damage. Perhaps this is because the word "tornado" did not appear in any of the model building codes from the 20th century, and is only a recent addition to the International Building Code (related to requirements for tornado shelters) [4]. If the design of the built environment is conducted without explicit consideration of tornado hazards, is the poor life safety and property protection performance of buildings in tornadoes any surprise?

The American Society of Civil Engineers (ASCE) took a major step forward towards addressing this problem with the publication of the ASCE 7-22 Standard for Minimum Design Loads and Associated Criteria for Buildings and Other Structures [2], which for the first time includes tornado load requirements. These new requirements are based on a decade of research and development by the National Institute of Standards and Technology and others. It followed the EF-5 tornado that destroyed a third of Joplin, Missouri on May 22, 2011, which was the single deadliest (161 fatalities) and costliest (≈ \$3 billion) tornado in the US since 1950 when official tornado records begin [1].

1.1. Tornado Impacts

The United States experiences more tornadoes and more violent tornadoes than any other country in the world [5]. Tornadoes cause more fatalities in the U.S. than earthquakes and hurricanes combined [6, 7], and most of these fatalities occur inside buildings (e.g., Ref. [1, 8, 9]). Tornadoes and tornadic storms cause more U.S. insured catastrophe losses than hurricanes and tropical storms combined [10] (Fig. 1). According to the Insurance Information Institute [10], "events including tornadoes" were the biggest source of insured catastrophe losses during the 20-year period from 1997 to 2016.

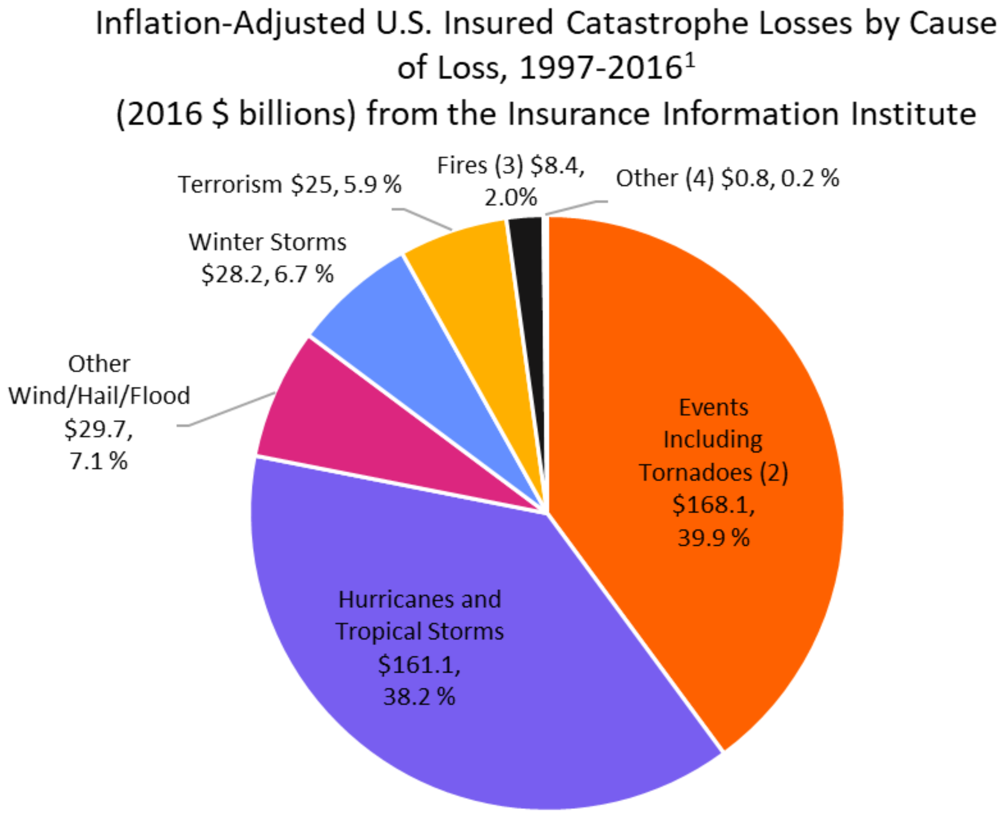


Fig. 1. Inflation-Adjusted U.S. Insured Catastrophe Losses by Cause[1,2,3,4,5]

Although it is the largest and most violent tornadoes that usually make the headlines, much of the total amount of property losses is caused by the less intense tornadoes (red curve in Fig. 2) because they are far more common. Of all recorded tornadoes from 1995 to 2016, 97.1 % were rated F/EF-2 or lower, as shown in Fig. 3. This histogram shows that the highest intensity tornadoes (F/EF-4 and F/EF- 5) make up only a fraction of a percent of all recorded tornadoes.

[1] Adjusted for inflation through 2016 by ISO using the GDP implicit price deflator. Excludes catastrophes causing direct losses less than $25 million in 1997 dollars. Excludes flood damage covered by the federally administered National Flood Insurance Program

[2] Includes other wind, hail, and/or flood losses associated with catastrophes involving tornadoes

[3] Includes wildland fires

[4] Includes losses from civil disorders, water damage, utility service disruptions, and any workers compensation catastrophes generating losses in excess of PCS's threshold after adjusting for inflation.[11]III , PCS (2022) Inflation-Adjusted U.S. Insured Catastrophe Losses By Cause Of Loss, 1997-2016 (2016 $ billions). (Insurance Information Institute and The Property Claim Services® (PCS®) unit of ISO®, a Verisk Analytics® company, https://www.iii.org/graph-archive/96104).

[5] Certain commercial entities, equipment, or materials may be identified in this document to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

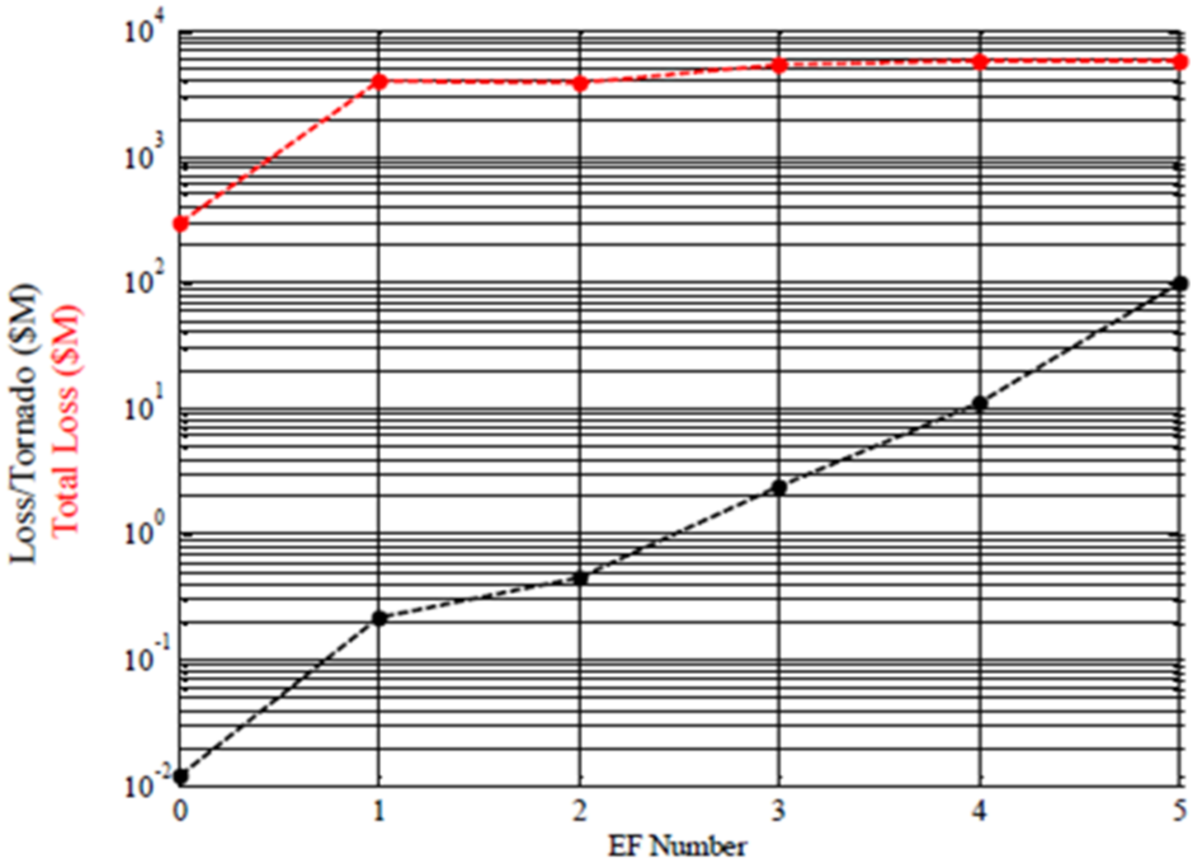
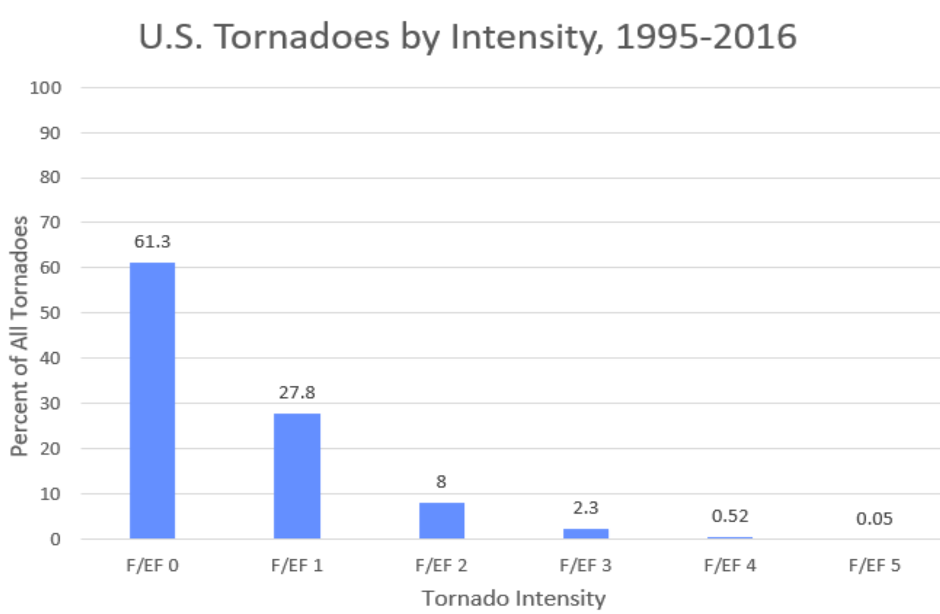


Fig. 2. Average loss per tornado and total loss by F/EF number for U.S. tornadoes from 1950-2011 (in 2011 $) [1]



Furthermore, even for the strongest tornadoes, most of the area impacted by a tornado does not experience the maximum winds speeds on which the tornado is rated. For example, in the 2013 EF-5 Newcastle-Moore Tornado in Oklahoma, EF-0 through EF-3 damage comprised the spatial majority of damage (Fig. 4) [13]. Even though this devastating tornado was rated as an EF-5, Fig. 4 demonstrates that most of the damage (spatially) was EF-3 and lower (blue, green, yellow, and orange areas). Another example is the 2011 EF-5 tornado that damaged or destroyed approximately 8000 buildings in Joplin, Missouri, where an estimated 72 % of the area swept by the tornado experienced EF-0 to EF-2 winds, while just 28 % experienced EF-3 and greater winds [1].

While design for life safety protection to resist EF-5 tornadoes is possible and not uncommon using ICC 500 storm shelters [14] and FEMA safe rooms [15], the vast majority of all tornadoes and much of the total tornado damage comes from EF-2 and lower intensity tornadoes, with wind speeds of 135 mph (60.4 m/s) and less. Design for tornadoes of this intensity is possible at much lower cost and impact than required for storm shelters and safe rooms, which are designed for 250 mph (111.8 m/s) across much of the central and southeast U.S.

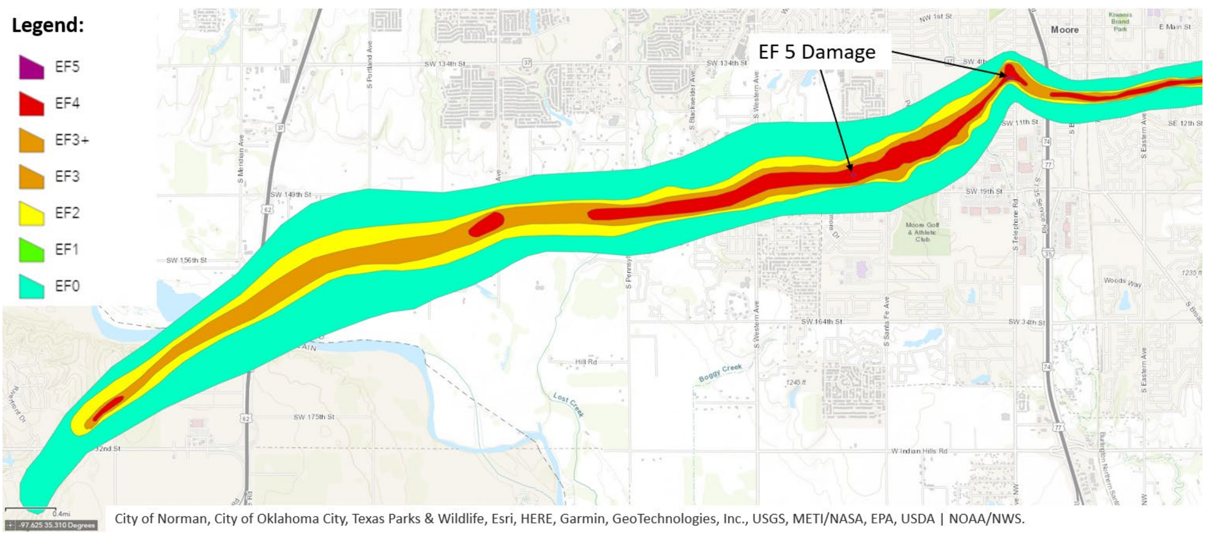


Fig. 4. 2013 Newcastle-Moore (Oklahoma) EF-5 Tornado Damage

1.2. ASCE 7-22 Tornado Load Requirements

While tornadoes are a type of windstorm, there are many and significant differences between tornadoes and other windstorms in terms of meteorology, climatology, wind, and wind-building and other structure interaction characteristics. Tornado loads are therefore treated completely separately from wind loads, hence their inclusion in a new chapter in ASCE 7-22 instead of as a subset of wind loads.

Tornado Load Procedures. The tornado load procedures are based on the overall framework of the ASCE 7 wind load procedures. Tornado velocity pressure and design pressure/design load equations are like those found in Chapters 26-31 (exclusive of Chapter 28 Envelope

Procedure, where the underlying methodology is incompatible with the tornado load approach). However, most of the terms used in the tornado load equations have some differences compared to their wind load counterparts, reflecting the unique characteristics of tornadic winds and wind-building or other structure interaction in contrast to straight-line winds. Several wind load parameters are not used in the tornado load chapter, while Chapter 32 also introduces a few new and significantly revised parameters.

Tornado Hazard Maps. A new generation of tornado hazard maps was developed taking spatial effects into account (since larger buildings are more likely to be struck by a tornado, tornado wind speeds increase with increasing plan (i.e., footprint) area of the building). These probabilistic tornado hazard maps identify tornado design wind speeds for a wide range of return periods and target building plan area sizes, enabling tornado-resistant design of conventional buildings and infrastructure, including essential facilities. Design tornado speed maps are provided for eight effective plan area (A_e) sizes, ranging from A_e = 1 ft2 (0.1 m^2) and 4 000 000 ft2 (371 612 m^2).

The mapped tornado speeds represent the maximum 3-s gust produced by the translating tornado at a height of 33 ft (10 m) anywhere within the plan area of the target building. The design tornado speeds for Risk Category III and IV buildings (for 1700- and 3000-year return periods, respectively) typically range from EF0-EF2 intensity, depending on geographic location, risk category, and plan size and shape (see Section 1.4 for information on risk category). For protection from more violent tornadoes, performance-based design is explicitly allowed, and commentary on additional design requirements for storm shelters is provided. At return periods of 300 and 700 years, tornado speeds are generally so low that tornado loads will not control over Chapter 26 wind loads, hence design for tornadoes is not required for Risk Category I and II buildings and other structures.

Tornado Velocity Pressure. While the effects of terrain and topography on tornado wind speed profiles are not yet well understood, a review of near-surface tornadic wind measurements from mobile research radar platforms plus numerical and experimental simulations consistently showed wind speed profiles with greater horizontal wind speeds closer to the ground than aloft. The tornado velocity pressure profile (K_zT_{or}) used has a uniform value of 1.0 from the ground up to a height of 200 ft (61 m), with a slightly smaller value at greater heights. In comparison, wind loads are based on an assumed boundary layer profile, where wind speeds are slower near the ground because of surface roughness.

Tornado Design Pressures. Atmospheric pressure change (APC) was found to have significant contributions to the tornado loads, particularly for large buildings with low permeability. The internal pressure coefficient was modified to also include the effects of APC. Since APC-related loads are not directionally dependent, the directionality factor was removed from the velocity pressure equation and added to the external pressure term in the design pressure/load equations. The directionality factor (K_d) was modified through analysis of tornado load simulations on building Main Wind Force Resisting Systems (MWFRS) and components and cladding (C&C) systems. The resulting tornado directionality factor K_{dT} has values slightly less than the corresponding wind K_d values, with the exception of roof zone 1' (in the field of the roof), which increased. External pressure and force coefficients for both the MWFRS and C&C remain unchanged, but a modifier (K_{vT}) was added to account for experimentally determinized increases to uplift loads on roofs caused by updrafts in the core of the tornado.

Reliability. A reliability analysis was conducted to evaluate the tornado load provisions for the purpose of identifying appropriate return periods for the tornado hazard maps. This effort was conducted by a working group composed of members from both the ASCE 7-22 Load Combinations and Wind Load Subcommittees. Monte Carlo analyses (adapted from the ASCE 7-16 wind speed map return period analysis) were used, in which significant uncertainties for system demands and capacity were identified and quantified in the form of random variables with defined probability distributions. The results of this series of risk-informed analyses showed that the tornadic load criteria of Chapter 32 provided reasonable consistency with the reliability delivered by the existing criteria in Chapters 26 and 27 for MWFRS; therefore, confirming that the 1700-year and 3000-year return periods used for Risk Category III and IV wind hazard maps (respectively) in Chapter 26 were also suitable return periods to use for the tornado hazard maps.

1.3. Defining Tornado-Prone Region

Although tornadoes occur in all 50 states, the over overwhelming majority and the most intense tornadoes occur east of the Continental Divide. ASCE 7-22 [2] defines the tornado-prone region as "The area of the conterminous United States most vulnerable to tornadoes", shown in Fig. 5. The tornado load provisions of ASCE 7-22 only apply to Risk Category III and IV buildings and other structures located in the tornado-prone region (see commentary Chapter C32 in [2] for more information).

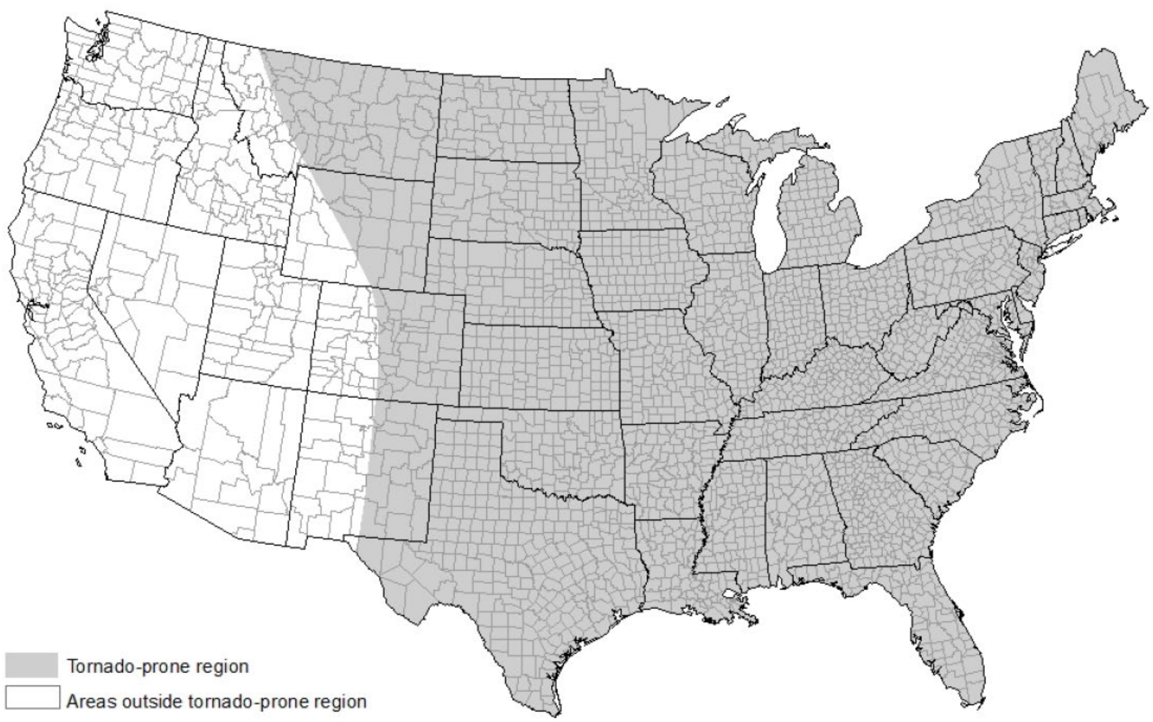


Fig. 5. Tornado-Prone Region

1.4. Applicable Risk Category of Structures

For design purposes, IBC (Table 1604.5) classifies buildings into four risk categories according to their occupancy type [16]. The building types associated with each of the four Building Risk Categories can be seen in Table 1 from Ref. [16]. This study focuses on Risk Category III and IV buildings, which are the subject of the adoption of the new tornado load requirements in the ASCE 7-22 standard [2].

Table 1. Structure Risk Categories[6]

Risk Category	Nature of Occupancy
I	**Buildings and other structures that represent a low hazard to human life in the event of failure, including but not limited to:** ● Agricultural facilities. ● Certain temporary facilities. ● Minor storage facilities.
II	**Buildings and other structures except those listed in Risk Categories I, III and IV.**
III	**Buildings and other structures that represent a substantial hazard to human life in the event of failure, including but not limited to:** ● Buildings and other structures whose primary occupancy is public assembly with an occupant load greater than 300. ● Buildings and other structures containing one or more public assembly spaces, each having an occupant load greater than 300 and a cumulative occupant load of these public assembly spaces of greater than 2500. ● Buildings and other structures containing Group E or Group I-4 occupancies or combination thereof, with an occupant load greater than 250. ● Buildings and other structures containing educational occupancies for student above the 12th grade with an occupant load greater than 500 ● Group I-2, Condition 1 occupancies with 50 or more care recipients. ● Group I-2, Condition 2 occupancies not having emergency surgery or emergency treatment facilities. ● Group I-3 occupancies. ● Any other occupancy with an occupant load greater than 5000. ● Power-generating stations, water treatment facilities for potable water, waste water treatment facilities and other public utility facilities not included in Risk Category IV. ● Buildings and other structures not included in Risk Category IV containing quantities of toxic or explosive materials that: ○ Exceed maximum allowable quantities per control area given in Table 307.1(1) or 307.1(2) or per outdoor control area in accordance with the *International Fire Code*; and ○ Are sufficient to pose a threat to the public if released.

[6] ICC (2021) Table 1604.5 Risk Category of Buildings and Other Structures

IV	**Buildings & other structures designated as essential facilities, including but not limited to:** ● Group I-2, Condition 2 occupancies having emergency surgery or emergency treatment facilities. ● Fire, rescue, ambulance and police stations and emergency vehicle garages. ● Designated earthquake, hurricane or other emergency shelters. ● Designated emergency preparedness, communications and operations centers and other facilities required for emergency response. ● Power-generating stations and other public utility facilities required as emergency backup facilities for Risk Category IV structures. ● Buildings and other structures containing quantities of highly toxic materials that: ○ Exceed maximum allowable quantities per control area as given in Table 307.1(2) or per outdoor control area in accordance with the *International Fire Code*; and ○ Are sufficient to pose a threat to the public if released. ● Aviation control towers, air traffic control centers and emergency aircraft hangars. ● Buildings and other structures having critical national defense functions. ● Water storage facilities and pump structures required to maintain water pressure for fire suppression.

1.5. Purpose and Approach

The purpose of this study is to analyze the potential economic impacts from implementation of the ASCE 7-22 tornado load requirements, by incorporation into the IBC (Proposal S63-22 in Ref. [3]) and/or direct adoption by Federal, state, and local governments. The approach in this study is based on four key steps to estimate the economic impact of the code change proposal.

First, identify where in the U.S. (within the tornado-prone region) and what building types may be impacted from inclusion of tornado load requirements into ASCE 7-22. This step immediately limits the need to consider tornado loads in design because the code change proposal only applies to specific building types (Risk Category III and IV) and locations in which expected tornado wind loads are sufficient to create concerns for building resilience.

Second, for the locations and building types that may be impacted, calculate the design wind pressures and design tornado pressures per ASCE 7-22 and determine whether the tornado loads control design. This step further narrows the potential impact because in many cases, the wind load requirements as defined in ASCE 7-22 are greater than those for tornado loads.

Third, for locations and building types for which tornado loads do control design, determine what building elements will require changes in construction design. This step accounts for the fact that current construction design practices may handle higher loads than the current load requirements. Therefore, even if tornado loads control an element of the design, the construction design for that element may not need to change.

Fourth, estimate the cost of these changes in construction design. This step calculates the estimated increase in construction costs resulting from any change in construction design to meet tornado loads relative to current ASCE 7-22 load requirements, both in total dollars and percent of total project construction budget.

Case studies are used to estimate the relative magnitude of the potential cost impacts for two building types (elementary school and high school) for wind Exposure Categories B and C baseline building designs across nine locations, to provide a range of potential load requirements and resulting cost implications.

2. Estimating Potentially Impacted Buildings and Structures

The adoption of the new tornado load requirements in the ASCE 7-22 standard will only impact a small fraction of new buildings in the United States. The only buildings that are eligible to be impacted are new buildings that meet or exceed the following requirements: (1) located within the tornado-prone region, (2) classified as Risk Category III or IV buildings, (3) located within an area where tornado speeds meet or exceed 60 mph (26.8 m/s), and (4) located within an area where the tornado speeds are greater than a specified fraction of the basic (non-tornado) design wind speeds. Requirements 3 and 4 represent approximate lower bounds on where tornado loads can begin to start controlling over wind loads for any element of a specific building or other structure.

This section of the report uses HAZUS building stock and building occupancy type data to estimate the percentage of existing buildings meeting requirements 1 and 2. Due to data limitations, inclusion of requirements 3 and 4, above, are not considered in estimating the percent of building stock impacted. This limitation will lead to an overestimation of potential impacts. Therefore, the results presented here are effectively upper bounds; the anticipated impacts of the code change are expected to be smaller, and perhaps substantially so. Section 3 provides several examples of the application of requirements 3 and 4, which are dependent on risk category, geographic location, the effective plan area of the building or facility, and the terrain exposure (e.g., roughness of the upwind terrain – which affects the non-tornadic wind loads).

2.1. HAZUS Building Stock Data

HAZUS provides a standardized methodology to assess losses from earthquakes, hurricane winds, and floods [17]. It leverages data from the Census Bureau, among other sources, to inventory the building stock for the U.S. and provides the data at the census tract level. For this study, the census tract data is aggregated to calculate a building count by occupancy type at the county level using data in HAZUS-MH MR4 Version 1.4 [18].

2.2. Building Stock in Tornado-Prone Region

Of the 3219 counties in the HAZUS database, 2820 counties are at least partially within the tornado-prone region Fig. 5. The following analysis assumes the building stock for the tornado-zone region includes the building stock data for these 2820 counties. The full number of buildings is included even for counties that are only partially in the tornado-prone region. Therefore, building stock counts are overestimates that will slightly bias the impacts reported as a percentage of the U.S. market, but should not have much effect on estimated regional impacts.

HAZUS occupancy types likely to be designated as Risk Category III or IV buildings in Table 2 were mapped against the IBC definitions (Table 1). Note that these selections are an approximation, as the occupancy categories in HAZUS and the Risk Categories in the IBC do not directly correspond, and no information is available on the occupant load of the building stock, which is a factor in the IBC table. (See Ref. [19] for a detailed description of a similar selection process.)

Table 2. HAZUS Occupancy Types and Assignment of Risk Categories

Occupancy Type		Risk Category III or IV
Code	**Description**	
RES1I	Residential Single-Family	
RES2I	Residential Manufactured Housing	
RES3AI	Residential Duplex	
RES3BI	Residential 3-4 Units	
RES3CI	Residential 5-9 Units	
RES3DI	Residential 10-19 Units	
RES3EI	Residential 20-49 Units	
RES3FI	Residential 50+ Units	
RES4I	Residential Temp Lodging	
RES5I	**Residential Institutional**	**X**
RES6I	**Residential Nursing Home**	**X**
COM1I	Retail Trade	
COM2I	Wholesale Trade	
COM3I	Personal Service	
COM4I	Professional	
COM5I	Banking	

Occupancy Type		Risk Category III or IV
Code	**Description**	
COM6I	**Hospital**	**X**
COM7I	**Medical Office**	**X**
COM8I	**Entertainment**	**X**
COM9I	**Theaters**	**X**
COM10I	Parking	
IND1I	Heavy Industrial	
IND2I	Light Industrial	
IND3I	Food/Drug	
IND4I	Metals	
IND5I	High Tech	
IND6I	Construction	
AGR1I	Agriculture	
REL1I	Religious	
GOV1I	**General Services**	**X**
GOV2I	**Emergency Center**	**X**
EDU1I	**Schools**	**X**
EDU2I	**Colleges**	**X**

Fig. 6 shows the estimated percentage of existing Risk Category III and IV buildings in the tornado-prone region based on the definition of building stock and applicable building occupancy types from Table 2. The percent of Risk Category III and IV buildings varies significantly, from 0 % to 1.9 %, depending on the county, with “hotspots” in and around the metropolitan areas.

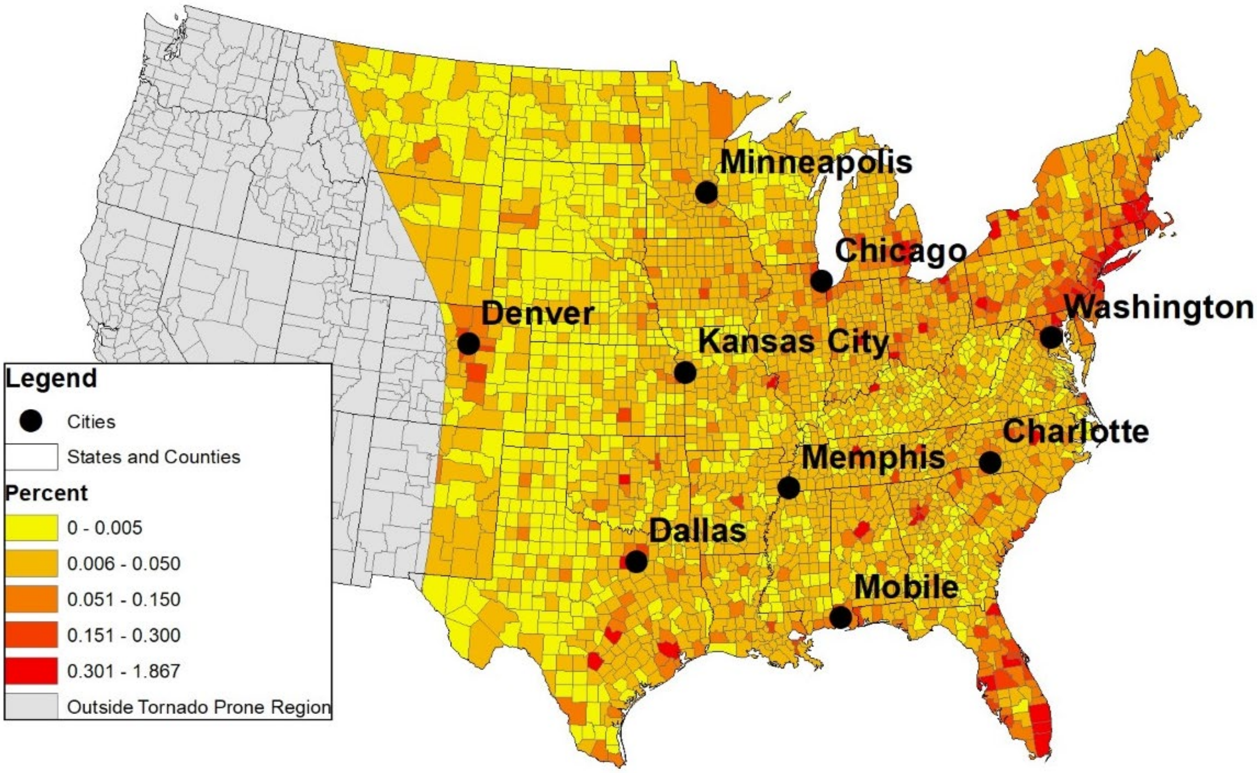


Fig. 6. Estimated Percentage of Risk Category III and IV Buildings, By State and County

Aggregation of the building stock for the tornado-prone region compared to the U.S. building stock is shown in Table 3. The tornado-prone region accounts for 81 % of the building stock, ranging from 69 % to 88 % depending on the occupancy type. Of the occupancy types identified as Risk Category III and IV buildings, the tornado-prone region accounts for 80 % to 88 % depending on the occupancy type, with an overall average of 81 %. The Risk Category III and IV buildings are estimated to comprise 1.4 % of the entire U.S. building stock and 1.7 % of the building stock in the tornado-prone region.

When excluding residential occupancies with less than 50 units, the building stock occupancy types for Risk Category III and IV buildings in the tornado-prone region becomes 15.0 % of the entire U.S. building stock and 18.3 % of the building stock in the tornado-prone region.

These results are effectively upper bound estimates; the actual values would be smaller, perhaps substantially so. This is due to limitations of the data and assumptions made in the analysis, all of which tend to bias the results towards overestimation of the impacts of the adoption of the new tornado load requirements in the ASCE 7-22 standard.

Table 3. Building Count by Occupancy Type and Count and Fraction Located in Tornado-Prone Region

Occupancy Type		Building Count		
Code	**Description**	**Total US**	**Tornado – Prone Region**	**Fraction of US in Tornado – Prone Region**
RES1I	Residential Single-Family	77 341 549	61 968 809	80 %
RES2I	Residential Manufactured Housing	8 585 222	7 077 132	82 %
RES3AI	Residential Duplex	4 701 077	4 092 341	87 %
RES3BI	Residential 3-4 Units	3 693 939	3 072 738	83 %
RES3CI	Residential 5-9 Units	2 649 603	2 208 626	83 %
RES3DI	Residential 10-19 Units	1 838 264	1 507 694	82 %
RES3EI	Residential 20-49 Units	1 389 157	1 123 895	81 %
RES3FI	Residential 50+ Units	1 059 443	845 988	80 %
RES4I	Temp Lodging	86 318	67 302	78 %
RES5I	**Institutional**	**205 116**	**163 536**	**80 %**
RES6I	**Nursing Home**	**40 295**	**33 489**	**83 %**
COM1I	Retail Trade	983 783	811 328	82 %
COM2I	Wholesale Trade	707 373	578 097	82 %
COM3I	Personal Service	1 039 452	856 493	82 %
COM4I	Professional	1 565 278	1 260 153	81 %
COM5I	Banking	141 214	119 220	84 %
COM6I	**Hospital**	**27 440**	**23 269**	**85 %**
COM7I	**Medical Office**	**404 628**	**330 495**	**82 %**
COM8I	**Entertainment**	**763 363**	**623 890**	**82 %**
COM9I	**Theaters**	**25 326**	**20495**	**81 %**
IND1I	Heavy Industrial	278 759	233 042	84 %
IND2I	Light Industrial	307 080	245 586	80 %
IND3I	Food/Drug	73 066	57 688	79 %
IND4I	Metals	43 899	38 255	87 %
IND5I	High Tech	8706	6039	69 %
IND6I	Construction	931 380	769 888	83 %
AGR1I	Agriculture	503 485	426 558	85 %
REL1I	Religious	504 437	429 596	85 %
GOV1I	**General Services**	**154 613**	**131 419**	**85 %**
GOV2I	**Emergency Center**	**30 576**	**26 946**	**88 %**
EDU1I	**Schools**	**176 226**	**142 313**	**81 %**
EDU2I	**Colleges**	**19 987**	**17 219**	**86 %**
TOTAL		**110 280 054**	**89 309 539**	**81 %**
TOTAL (Exclud. Resident. < 50 units)		**10 081 243**	**8 258 304**	**82 %**
TOTAL (Impacted Occupancy Types i.e., Risk Category III and IV)		**1 847 570**	**1 513 071**	**81 %**

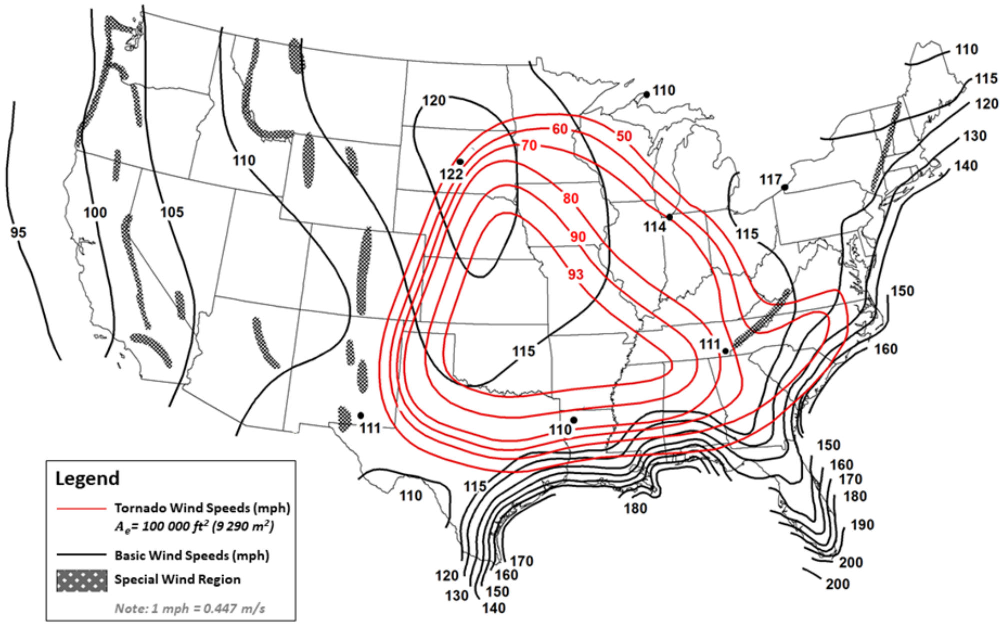
3. Where Design for Tornado Loads is Not Required

The ASCE 7-22 tornado load provisions (Section 32.5.2) include tools to help identify many of the situations where tornado loads will not control any aspects of the design and are therefore not required. This section describes those provisions and provides examples of their application.

3.1. Comparing Design Tornado and Design Wind Speed

Areas outside of the tornado-prone region do not require design for tornado loads. Even within the tornado-prone region, design for tornado loads is not always required. If the design tornado speed (V_T) is less than 60 mph (26.8 m/s) tornado loads will generally not control over wind loads. Additionally, if the tornado speed is less than a certain percentage of the basic (non-tornado) wind speed, V, tornado loads will not control. For buildings located in wind Exposure Category B or C, design for tornado loads is not required where $V_T < 0.5V$ or $V_T < 0.6V$, respectively (in this context, Exposure B means that the building is surrounded by urban, suburban, or wooded terrain, Exposure C is flat, open terrain). The exposure category does not change the tornado loads, but wind loads in Exposure B are less than those in Exposure C. Subsequently, a building located in Exposure B is more likely to have tornado loads control over wind loads, compared to the same building in Exposure C.

To understand the spatial differences between basic wind speed and tornado wind speed hazard maps, Fig. 7 shows overlays of wind speed contours for the two hazards for Risk Category III buildings and other structures (top) and Risk Category IV buildings and other structures (bottom). As described in Section 1.2, the design tornado speed is a strong function of effective plan area in addition to risk category and geographic location. The tornado speeds shown in the top and bottom plots are for A_e = 100 000 ft^2 (929 m^2) and 1 000 000 ft^2 (92 903 m^2), respectively. In both maps, the tornado speed contours are greatest in the central Great Plains region and extending into the Southeast of the U.S. and taper off in the west and northeast of the county as well as in the hurricane-prone regions of the Atlantic and Gulf Coasts. The greatest values for basic wind speed in the interior of the country are also located in the central US but are further north and west of the region of maximum tornado speeds. Basic wind speeds increase in the hurricane-prone region of the country, especially along the Gulf Coast and portions of the Atlantic Coast. The difference between the two design speeds for a specified location greatly influences whether tornado loads will control over wind loads.



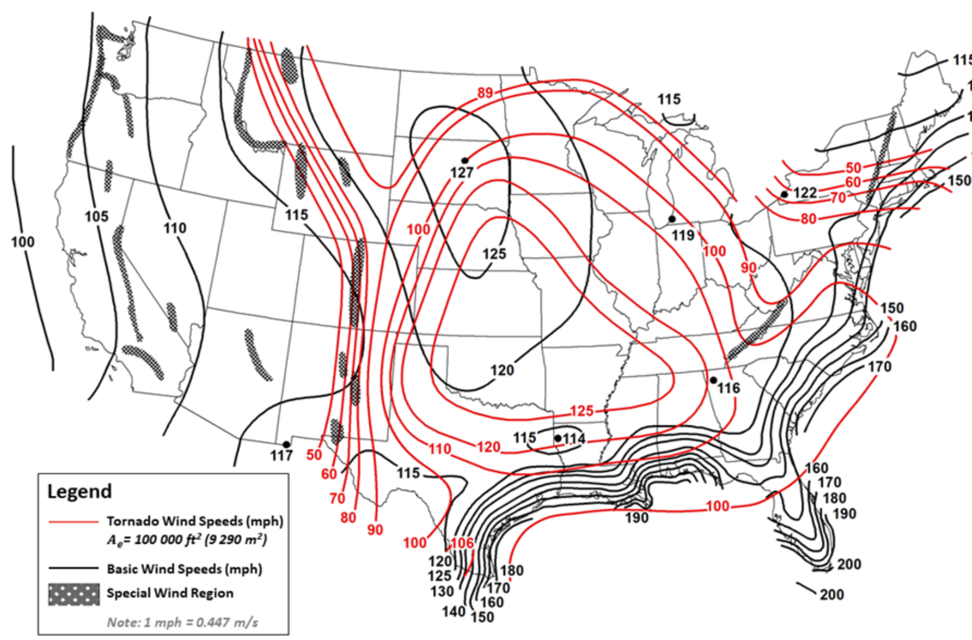


Fig. 7. Tornado speed and basic wind speed contours for Risk Category III buildings (top) and Risk Category IV buildings (bottom)

3.2. Example Maps Showing Where Design for Tornado Loads is Not Required

Maps were created to show where design for tornado loads is not required based on the risk category, exposure category, and design speeds for a specified location. Examples for a medium size (A_e = 100 000 ft^2 (929 m^2)) Risk Category III building and a large (A_e = 1 000 000 ft^2 (92 903 m^2)) Risk Category IV facility are shown in Fig. 8 and Fig. 9, for Exposures B and C. These maps were created using the Environmental Systems Research Institute ArcGIS Desktop 10.8 [20] software package and tools offered in the Spatial Analyst extension of the software. Underlaying basic and tornado wind speed data layers were collected in raster file format from the ASCE 7 Hazard Tool REST services website [21, 22] and the ArcGIS Desktop raster calculator tool [20] was used to perform the calculations required for each of the analyses described herein.

For the medium-sized Risk Category III building the tornado speeds are less than 60 mph (26.8 m/s) across much of the tornado prone region, as shown in black (Fig. 8). Locations where tornado speeds are less than the specified percentages of basic wind speeds, depending on exposure, are shown in grey. Tornado loads are only required in the areas shaded in the white-to-red spectrum which spans roughly between north Texas, central Minnesota, and the central Carolinas. In contrast, design for tornado loads is required across most of the tornado-prone region for very large Risk Category IV facilities, except for New England and small areas of south Florida and south Louisiana for Exposure C (Fig. 9). In both figures the darker reds indicate areas that tornado loads are more likely to exceed wind loads in the design of building elements. Section 4.4 will discuss the comparison of tornado versus wind pressures on different building elements in in more detail.

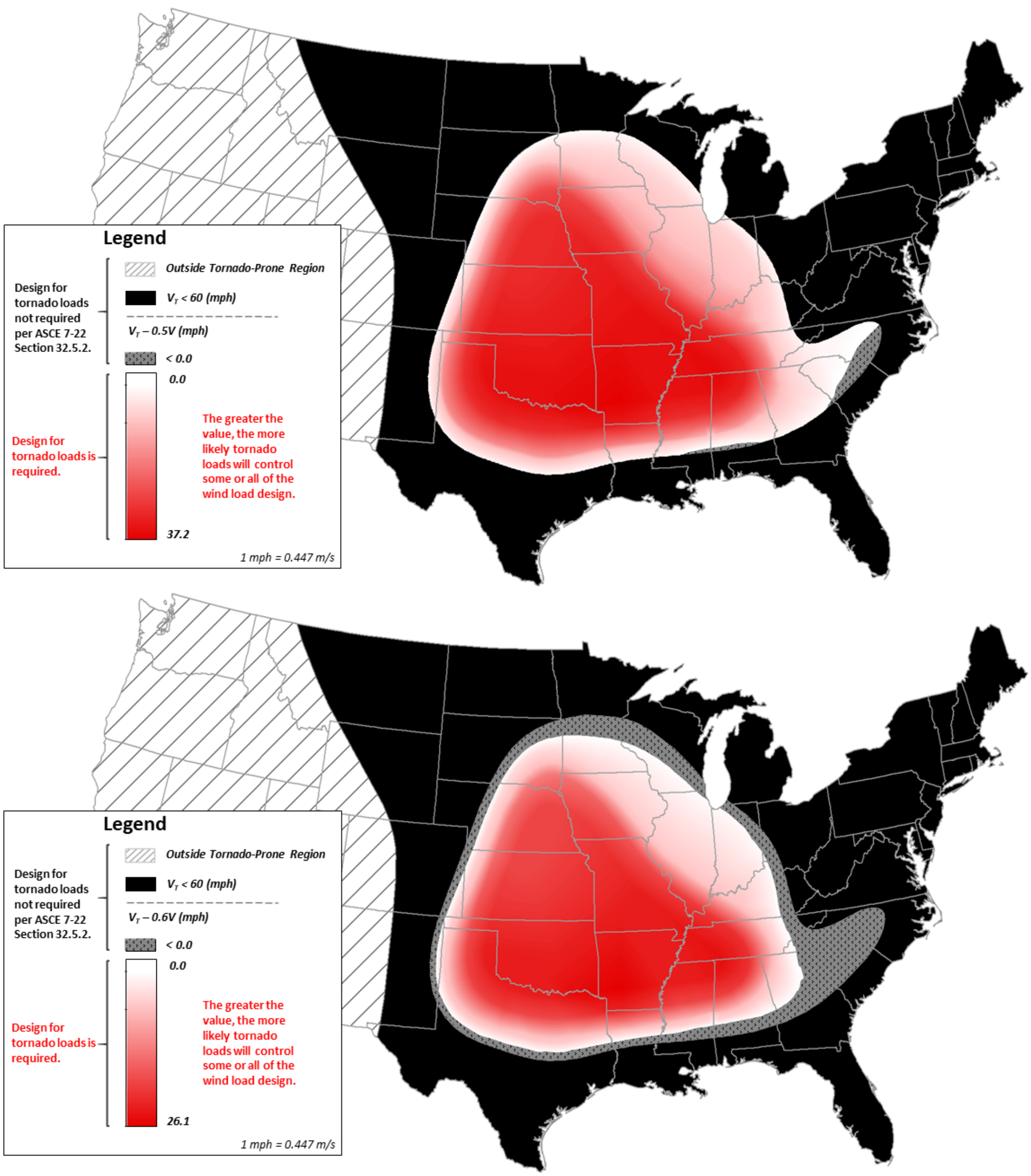


Fig. 8. Map of likelihood that design for tornado loads is required for a Risk Category III A_e = 100 000 ft^2 (9290 m^2) building or other structure in Exposure B (top) and Exposure C (bottom)

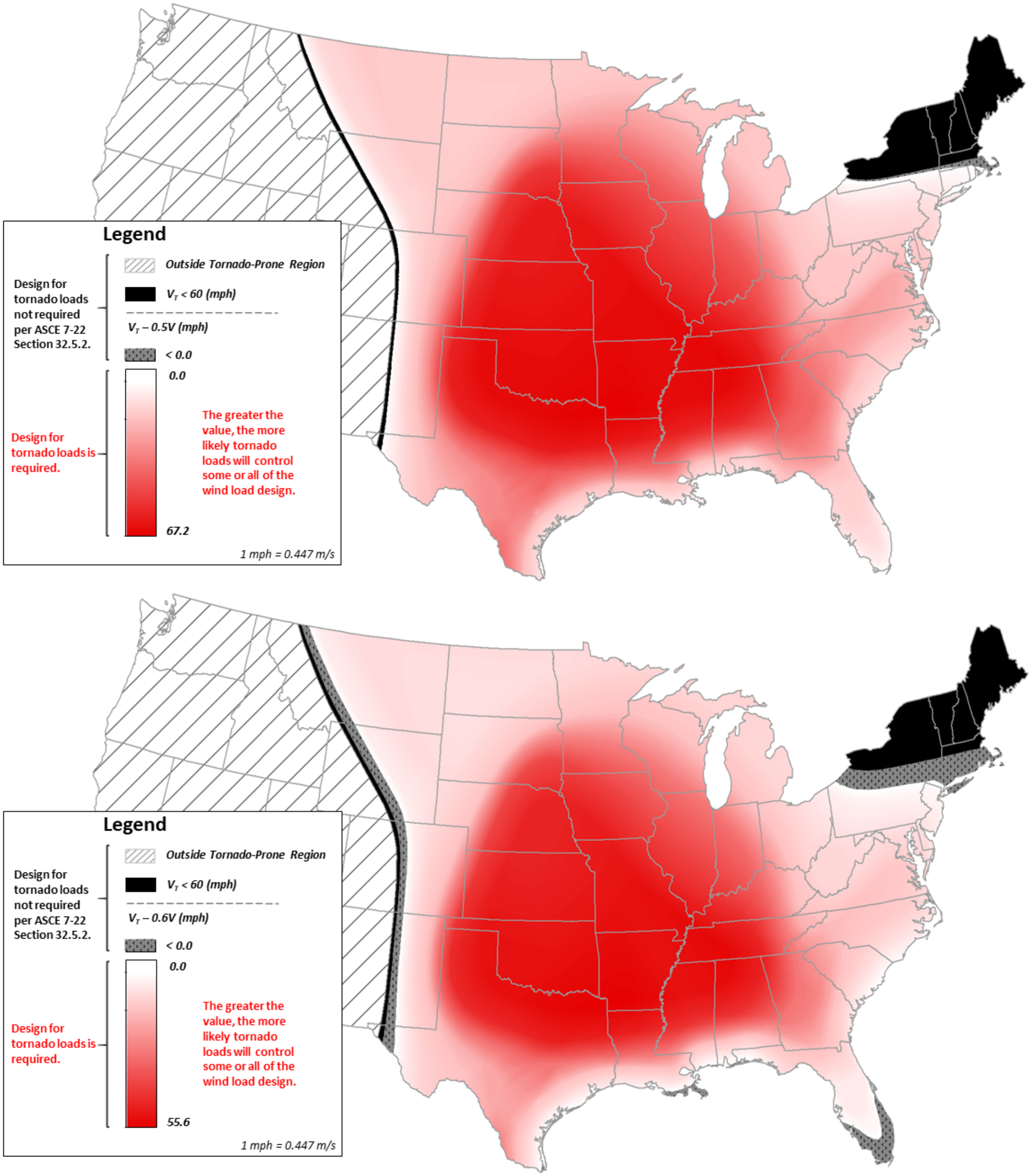


Fig. 9. Map of likelihood that design for tornado loads is required for a Risk Category IV A_e = 1 000 000 ft^2 (92 903 m^2) building or other structure in Exposure B (top) and Exposure C (bottom)

4. Impacts on Building Loads

The new ASCE 7-22 tornado provisions have a wide range of potential impacts to loads on buildings and other structures, compared to the basic wind load provisions already required by the standard. Depending on many variables related to tornado climatology and building characteristics, tornado loads can be smaller in magnitude than wind loads or more than double the wind loads – and sometimes both extremes apply to different elements of the same building. To demonstrate the range of impacts and trends, this section provides comparisons of wind and tornado loads on several building types, using three approaches with different combinations of spatial and analytical detail.

The complex interplay of the differences between the tornado load and wind load procedures makes it less than obvious which hazard will ultimately control the design. In many instances, tornado loads will control some, but not all, elements of the main wind force resisting system and/or components and cladding design. For example, outward-acting leeward wall pressures and uplift pressures in the field of the roof for enclosed buildings are comparatively greater in magnitude for tornado loads than for wind loads, due to the stronger influence of the effective internal pressure in tornadoes caused by atmospheric pressure change.

Whether or not tornado loads will ultimately control any aspects of the design for a particular building or structure is dependent on many factors. The relative hazard intensity (design speed) for both tornado and wind are obviously critical; however, many other parameters also come into play including, but not limited to:

- tornado speed, which is a function of
  - geographic location
  - risk category
  - effective plan area, which depends on footprint size and shape
- basic wind speed, which is a function of
  - geographic location
  - risk category
- wind exposure category
- designation as an essential facility or not
- building or other structure (and specific type of other structure)

For buildings, the following additional factors are also important:

- building plan shape
- roof geometry
- roof height
- enclosure classification

4.1. Building Types

Four different building types were used in this study – an elementary school, a high school, a fire station, and a hospital. Examples of actual buildings of these types in the Dallas-Ft. Worth (DFW) area were reviewed to develop typical dimensions for each. The elementary school and high school are two-story buildings. The fire station has one story, and the hospital has five stories. All buildings have low-slope roofs. The schools are considered Risk Category III and the fire station and hospital are Risk Category IV.

Other key building characteristics are summarized in **Table 4**, along with parameters used for each to calculate wind and tornado loads (for symbols and terms not previously defined in this report, see ASCE 7-22 [2]). The effective plan area, A_e, (similar to footprint area) assumed for each facility is shown in the first row of the table. This parameter is used in determination of the design tornado speed V_T. For the hospital, the effective plan area encompasses multiple buildings[7] on the hospital campus that are required to maintain functionality of the facility following an extreme environmental hazard. The design tornado speeds and basic (non-tornado) wind speeds shown are for the DFW area. The tornado speeds come from ASCE 7-22, while the basic wind speeds are from ASCE 7-16 [23] and used in Section 4.2 of this report only. Basic wind speeds used in Section 4.3 and later in the report are from ASCE 7-22. Per the minimum requirements of ASCE 7-22, the fire station and hospital are assumed to have either impact-resistant glazing (e.g., laminated glass) or impact protective systems (e.g., shutters or screens). The schools do not have impact-resistant or impact protected glazing.

Table 4. Building Characteristics, and Wind and Tornado Load Parameters[8]

SCHOOLS

Variable	ASCE 7-16 (Basic Wind)		Tornado: *Elem. School*	Tornado: *High School*
A_e (SF)	N/A		100,000	500,000
V or V_T (MPH)	112		90	102
Exposure	B	C	N/A for pressure calcs	
Mean Roof Height, h (ft)	33			
K_d or K_{dT}	0.85		Varies 0.75 to 0.9	
K_{zt}	1		N/A	
K_e	1			
K_z or K_{zTor}	0.72	1	1	
G or G_T	0.85			
Enclosure	Enclosed		Partially Enclosed	
GC_{pi} or GC_{piT}	+/-0.18		+/-0.55	
K_{vT}	N/A		Varies 1.05 to 1.3	

ESSENTIAL FACILITIES

Variable	ASCE 7-16 (Basic Wind)		Tornado: *Fire Station*	Tornado: *Hospital*
A_e (SF)	N/A		15,000	1,000,000
V or V_T (MPH)	115		97	123
Exposure	B	C	N/A for pressure calcs	
Mean Roof Height, h (ft)	20/80		20	80
K_d or K_{dT}	0.85		0.8 MWFRS, 1.0 C&C	
K_{zt}	1		N/A	
K_e	1			
K_z or K_{zTor}	0.62/0.93	0.9/1.21	1	
G or G_T	0.85			
Enclosure	Enclosed			
GC_{pi} or GC_{piT}	+/-0.18		+0.55/-0.18	
K_{vT}	N/A		Varies 1.05 to 1.3	

4.2. DFW-Area Comparisons of Wind and Tornado Loads

Wind and tornado pressures were computed for different elements of the main wind force resisting system (MWFRS) and component and cladding (C&C) on each of the four building types described in the previous section. This analysis was conducted during the development of the ASCE 7-22 load provisions and used to inform the committee regarding the impacts of the proposed addition of tornado loads to the standard. Since the revisions to the wind load provisions for ASCE 7-22 were not yet completed, the comparison was made between ASCE 7-22 tornado loads and ASCE 7-16 wind loads. All later sections of this report use ASCE 7-22 to determine both wind and tornado loads. The change to wind loads between 7-16 and 7-22 as related to the four example buildings in the region studied were very modest (a few percent).

[7] The heights of the various buildings are not needed for determination of A_e, just their size and location on the hospital campus.

[8] Unit Conversions: 1 mph = 0.44704 m/s; 1 ft = 2.54 cm; 1 m^2 = 10.7639 ft^2

This initial study was limited to the prototype buildings located in the DFW area. It should be noted that the DFW region is one of the most heavily impacted parts of the country with respect to increases in loads for tornadoes. DFW is situated close to the area of most intense tornado activity, so has relatively large tornado speeds compared to much of the rest of the country, but far enough away from the coast that the basic wind speed is not impacted by hurricanes, and it is located south of the greater wind speeds on the high plains (see Fig. 7 through Fig. 9).

Fig. 10 through Fig. 12 demonstrate that tornado loads are often greater than wind loads on the same building elements for the four building types in the DFW area. Wind loads in these figures are shown in solid bars, while tornado loads have hatched bars, with all bars color-coded by building type. Tornado design pressures on the MWFRS exceed wind design pressures in all cases shown (windward and leeward walls, uplift on the windward edge and in the field (middle) of the roof), for the buildings with Exposure B (urban, suburban, and/or wooded areas, which reduces the wind load), as shown in the top of Fig. 10. Increases range from 14 % to 184 %. Since wind loads increase by approximately 1/3 when moving from Exposure B to Exposure C, the relative differences are lower between tornado and wind loads in Exposure C. This is demonstrated in the bottom half of Fig. 10, where wind loads now control over tornado loads in a few instances, and the maximum increase of tornado to wind load is reduced to 118 %.

The middle block of comparison bars on Fig. 10 shows the effects on the net lateral force (i.e., base shear) on the building for one wind direction. The net lateral force from tornado loads was less than from wind loads in Exposure C for all buildings, and increased modestly for 3 of the 4 buildings for wind Exposure B.

Comparisons of tornado and wind loads for C&C on the roof (Fig. 11) and wall (Fig. 12) show similar trends. Tornado loads generally control over wind loads in Exposure B for the locations and effective wind areas shown, although the increases are somewhat less than for the MWFRS. For Exposure C, wind loads sometimes control over tornado loads, and when tornado loads control, it is by a smaller margin.

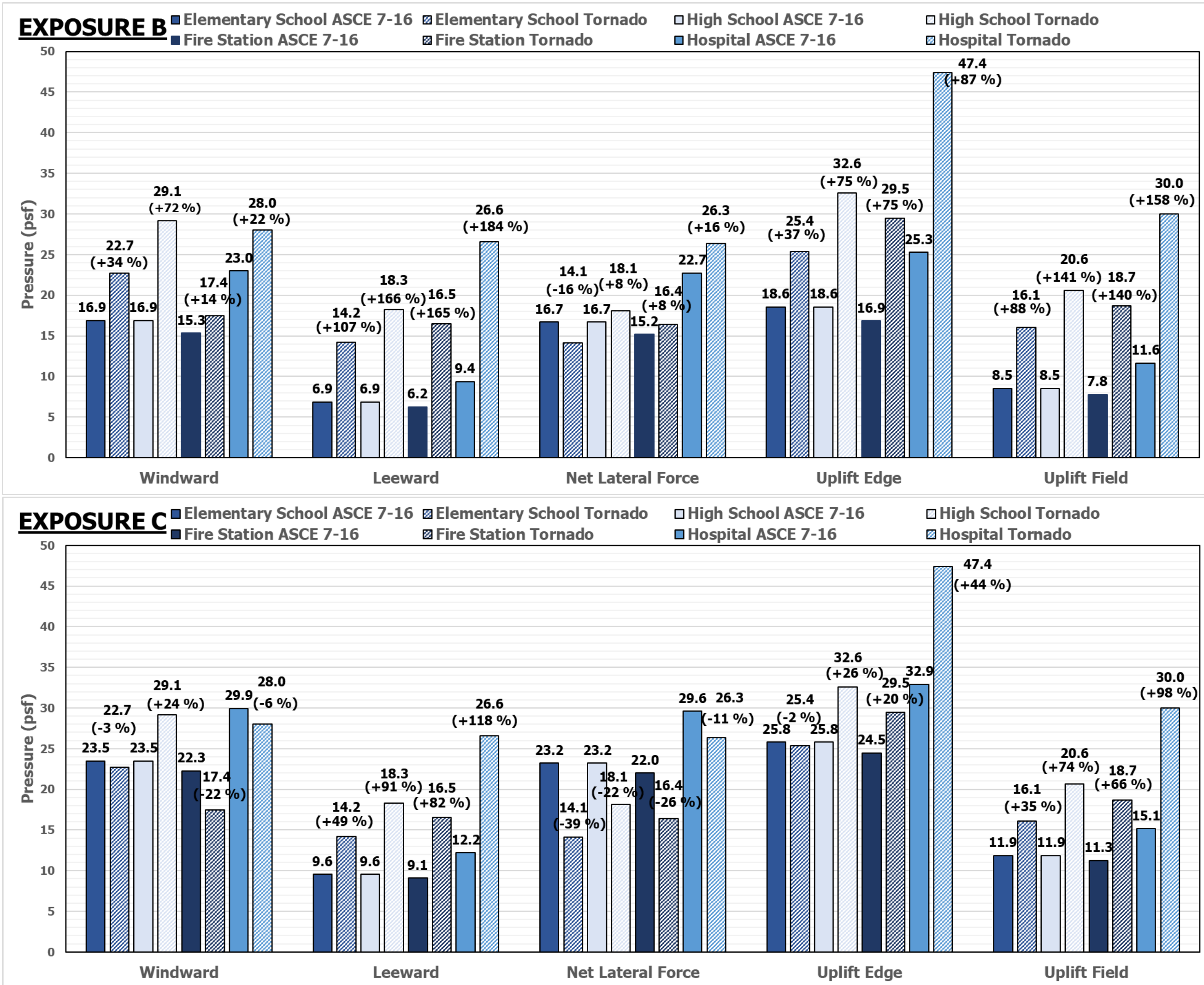


Fig. 10. Main Wind Force Resisting System (MWFRS) Load Comparisons, for DFW Area

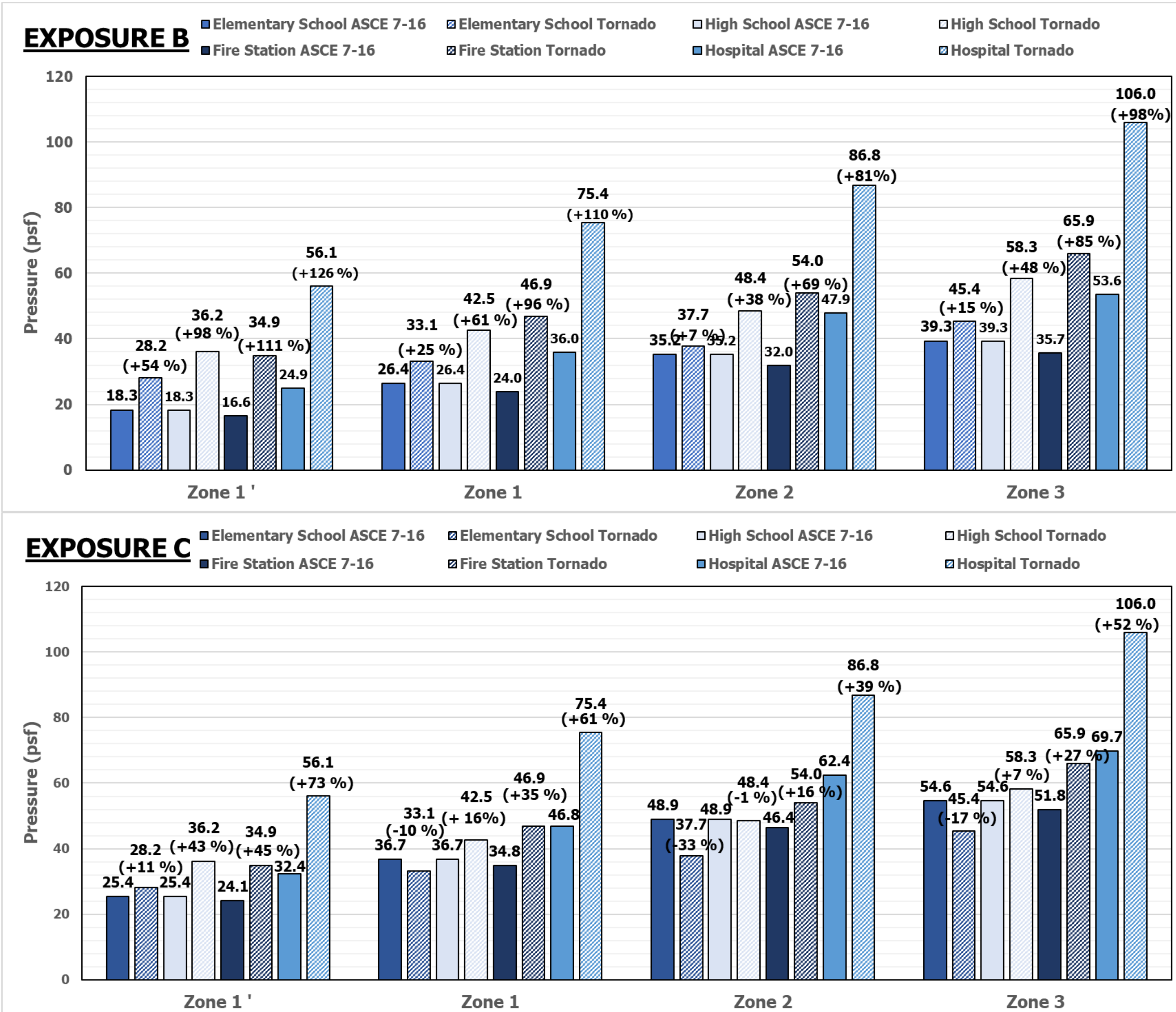


Fig. 11. C&C Roof Load Comparisons for Effective Wind Area = 200 ft^2 (18.6 m^2), for DFW Area

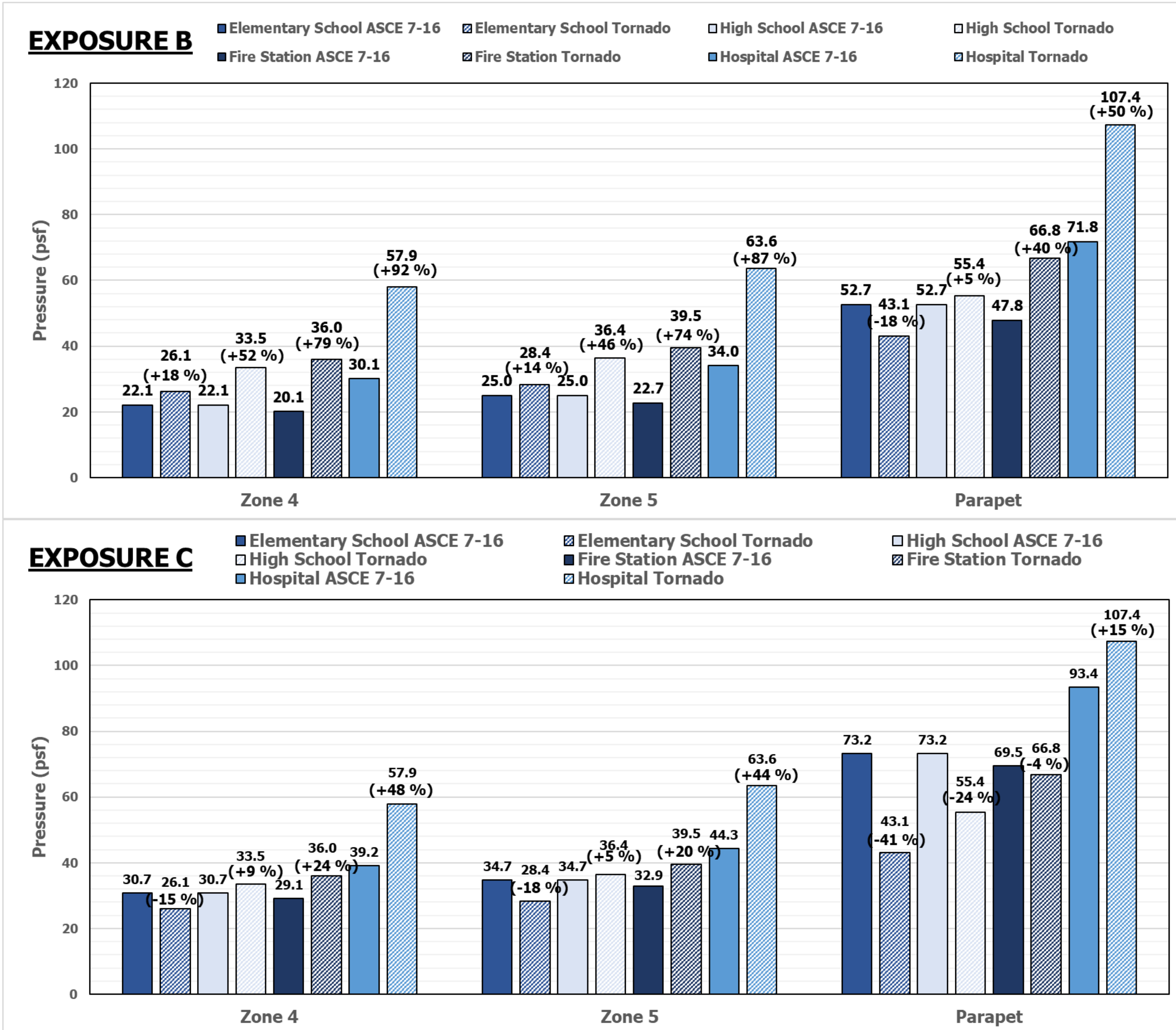


Fig. 12. C&C Wall Load Comparisons for Effective Wind Area = 75 ft^2 (7.0 m^2), for DFW Area

4.3. Extending the DFW-Area Case Study to Additional Cities

A subset of the DFW-area comparison study was extended to other parts of the country for the elementary school and the hospital. Table 5 displays tornado and wind pressures[9] on the same elements of the MWFRS shown in Fig. 10, for the DFW area and the eight other cities shown in Fig. 6. Where cells in Table 5 are shaded in black or dark grey, tornado loads are either not required or do not control over wind loads. The light gray and white shaded cells show where tornado pressures exceed the corresponding wind pressures. For cities located on the periphery of the tornado-prone region (Denver, Mobile, Charlotte, Washington DC), tornado loads do not control the design of any elementary school elements in either exposure

[9] Note that the wind pressures in this section were computed using ASCE 7-22. The basic (non-tornado) wind speeds for DFW increased by approximately 2 % compared to ASCE 7-16 basic wind speeds, so the wind pressures shown here are slightly different than those in **Fig. 9**. The tornado pressures are unchanged.

category. In the remaining cities, tornado loads will control at least some element of the design, especially if the school is located in Exposure B. By contrast, tornado loads will control at least some aspect of the design of the hospital in all nine cities if the building is in Exposure B, and 7 of the 9 cities when the building is in Exposure C.

Table 6 shows similar comparisons for C&C roof uplift pressures on the elementary school and hospital for a small effective wind area, as would be used to design the roof covering (see Section 5). Tornado loads have a relatively smaller impact on these C&C design pressures compared to MWFRS pressures, only controlling some roof zones on the elementary school in three selected cities (DFW, Kansas City, and Memphis). Tornado controlling cases for the hospital are reduced as well.

Table 5. Comparison of MWFRS Wind and Tornado Design Pressures

Elementary School

Surface	Location	Charlotte		Chicago		DFW		Denver		Kansas City		Memphis		Minneap.		Mobile		Wash. DC	
	Exposure	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C
Wwrd Wall	Wind Pr	18	25	17	24	18	24			18	25	18	25	18	25				
	Tor Pr	10	-	13	13	**22**	22			**23**	23	**24**	24	13	-				
Lwrd Wall	Wind Pr	7	10	7	10	7	10			7	10	7	10	7	10				
	Tor Pr	6	-	**8**	8	**14**	**14**			**15**	**15**	**15**	**15**	**8**	-				
Wwrd Roof	Wind Pr	20	27	19	26	19	27			20	27	19	27	20	27				
	Tor Pr	11	-	15	15	**25**	25			**26**	26	**27**	27	15	-				
Lwrd Roof	Wind Pr	9	13	9	12	9	12			9	13	9	12	9	13				
	Tor Pr	7	-	**10**	10	**16**	**16**			**17**	**17**	**17**	**17**	**9**	-				

Hospital

Surface	Location	Charlotte		Chicago		DFW		Denver		Kansas City		Memphis		Minneap.		Mobile		Wash. DC	
	Exposure	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C
Wwrd Wall	Wind Pr	24	33	23	31	23	31	19	26	24	33	24	32	24	32	48	64	26	35
	Tor Pr	18	18	21	21	**28**	28	10	10	**28**	28	**29**	29	21	21	22	22	16	16
Lwrd Wall	Wind Pr	10	13	9	13	9	12	8	10	10	13	10	13	10	13	19	26	11	14
	Tor Pr	**17**	**17**	**20**	**20**	**27**	**27**	**10**	10	**27**	**27**	**27**	**27**	**20**	**20**	**20**	20	**16**	**16**
Wwrd Roof	Wind Pr	27	**36**	26	34	25	34	21	28	27	36	26	36	26	35	52	70	29	39
	Tor Pr	**31**	31	**36**	**36**	**47**	**47**	17	17	**47**	**47**	**49**	**49**	**35**	**35**	37	37	28	28
Lwrd Roof	Wind Pr	12	17	12	16	11	15	10	13	12	17	12	16	12	16	24	32	13	18
	Tor Pr	**19**	**19**	**23**	**23**	**30**	**30**	**11**	11	**30**	**30**	**31**	**31**	**22**	**22**	23	23	**18**	18

Legend

Legend	
Tornado Speed < 60 mph	Design for tornado loads not required
Tornado Speed <0.5V for Exp. B or 0.6V for Exp. C	Design for tornado loads not required
Tornado Pressure < Wind Pressure	Design for tornado loads required but does not control
Tornado Pressure > Wind Pressure for Exposure B	Design for tornado loads is required and controls over wind loads
Tornado Pressure > Wind Pressure for Exposure C	Design for tornado loads is required and controls over wind loads

Note 1: Pressures shown in psf

Note 2: 1 psf = 47.88 N/m^2

Table 6. Comparison of C&C Wind and Tornado Design Roof Uplift Pressures, for Effective Wind Areas =10 ft^2 (0.93 m^2)

Elementary School

Roof Zone	Location	Charlotte		Chicago		Dallas		Denver		Kansas City		Memphis		Minneap.		Mobile		Wash. DC	
	Exposure	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C
1'	Wind Pr	23	31	22	30	22	31			23	31	22	31	23	31				
	Tor Pr	14	-	19	19	**31**	**31**			**33**	33	**33**	**33**	19	-				
1	Wind Pr	39	55	38	52	38	53			39	54	39	54	39	54				
	Tor Pr	19	-	26	26	**42**	42			**45**	45	**46**	46	25	-				
2	Wind Pr	52	72	49	69	51	70			52	72	51	71	52	72				
	Tor Pr	21	-	29	29	48	48			51	51	**52**	52	72	-				
3	Wind Pr	71	98	67	94	69	96			70	98	69.5	97	70	98				
	Tor Pr	28	-	38	38	63	63			66	66	67	67	37	-				

Hospital

Roof Zone	Location	Charlotte		Chicago		Dallas		Denver		Kansas City		Memphis		Minneap.		Mobile		Wash. DC	
	Exposure	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C
1'	Wind Pr	31	41	29	39	28	38	24	32	31	41	30	41	30	40	51	69	33	44
	Tor Pr	**41**	41	**48**	**48**	**63**	**63**	23	23	**63**	**63**	**65**	**65**	**47**	**47**	43	43	**37**	37
1	Wind Pr	53	72	51	69	50	67	42	56	53	71	53	71	52	70	74	100	57	77
	Tor Pr	**65**	65	**76**	**76**	**100**	**100**	36	36	**100**	**100**	**103**	**103**	**75**	**75**	58	58	**59**	59
2	Wind Pr	70	95	67	90	65	88	55	74	70	94	69	93	69	93	99	133	76	102
	Tor Pr	**74**	74	**87**	87	**115**	**115**	41	41	**115**	**115**	**118**	**118**	**86**	86	67	67	67	67
3	Wind Pr	96	129	92	123	89	120	75	101	96	128	95	127	94	126	111	149	103	139
	Tor Pr	**98**	98	**114**	114	**151**	**151**	54	54	**152**	**152**	**155**	**155**	**113**	113	74	74	88	88

Legend

- Tornado Speed < 60 mph
- Tornado Speed <0.5V for Exp. B or 0.6V for Exp. C

} Design for tornado loads not required

- Tornado Pressure < Wind Pressure

Design for tornado loads required but does not control

- Tornado Pressure > Wind Pressure for Exposure B
- Tornado Pressure > Wind Pressure for Exposure C

} Design for tornado loads is required and controls over wind loads

Note 1: Pressures shown in psf

Note 2: 1 psf = 47.88 N/m^2

4.4. National Comparisons of Wind and Tornado Loads

Although it would not be feasible to expand the design examples to all areas of the tornado-prone region, maps are provided here to illustrate nationwide load comparisons for the school and hospital examples. These maps show where tornado loads will control for select building elements for the elementary school and hospital examples described earlier.

Fig. 13 shows the ratio of design tornado pressure, p_T, to design wind pressure, p, for the elementary school when considering uplift loads on the leeward roof for design of the MWFRS for Exposure B (top) and Exposure C (bottom). For reference, see the 1st set of bars under "leeward" in Fig. 10 for the corollary of the DFW example for this building element. The ratio of tornado pressure to wind pressure p_T/p is increasingly larger in areas depicted by increasingly deeper shades of red. The spatial comparison for this design element is similar to that observed in Fig. 8, where the tornado design controls for the central Great Plains region and extending into the southeast. The maximum ratio of tornado pressure to wind pressure for the leeward roof is 2.02 for buildings in Exposure B and 1.5 for buildings in Exposure C. Tornado design is not required or does not control in the black and grey shaded areas, respectively.

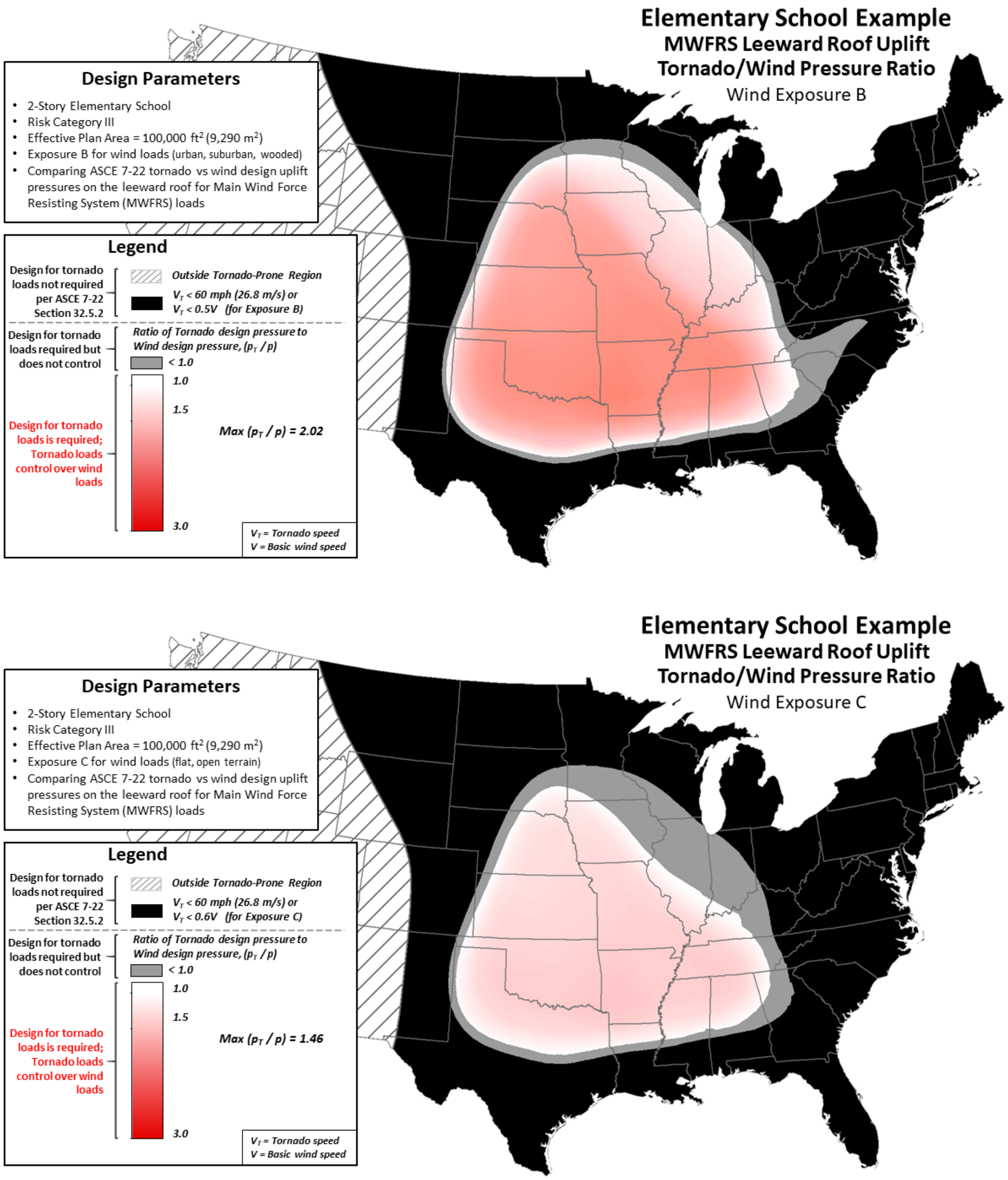
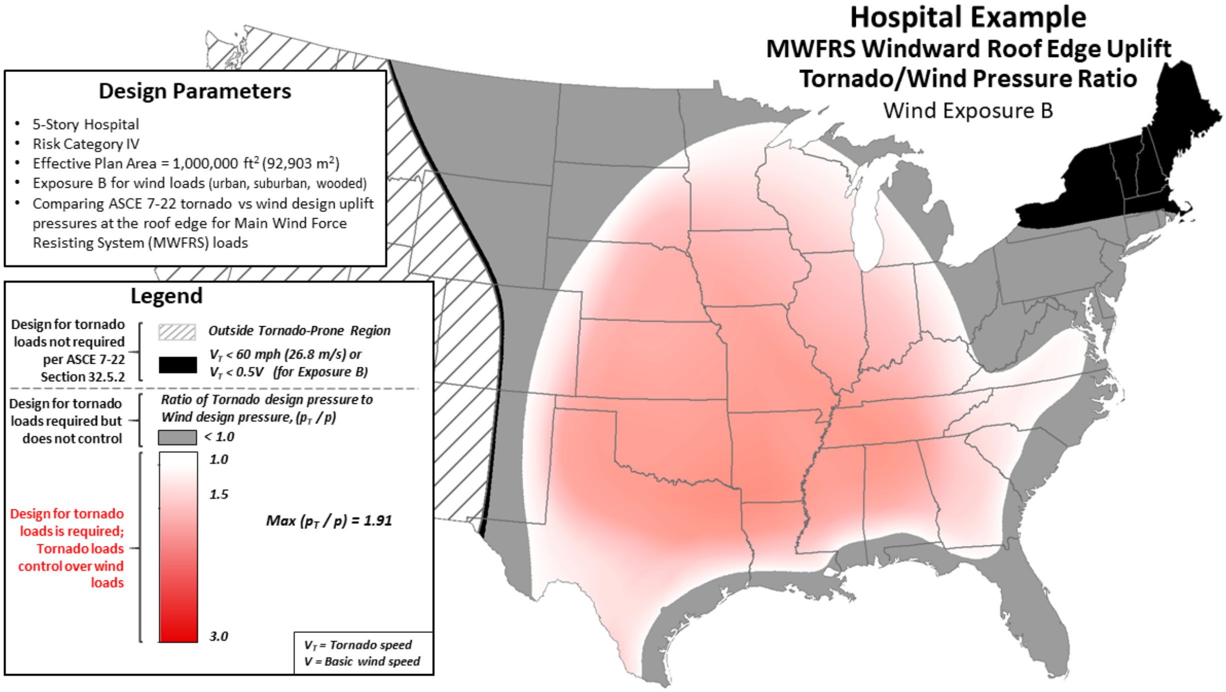


Fig. 13. Comparison of design tornado and wind pressures for leeward roof uplift on the MWFRS of the elementary school in Exposure B (top) and Exposure C (bottom)

Fig. 14 shows the pressure comparison for the hospital example, considering the MWFRS windward roof edge uplift design for Exposure Category B (top) and Exposure Category C (bottom). For reference, see the 4th set of bars under "windward" in Fig. 10 for the corollary of the DFW example for this building element. Due mostly to the larger effective area of the hospital compared to that of the elementary school and the change from Risk Category III for the elementary school to Risk Category IV for the hospital, tornado load design for this building element is required for a much larger area of the country and the tornado load design controls in more of the country compared to the elementary school example. The maximum ratio of design tornado pressure to wind pressure is 1.91 for buildings in Exposure Category B and 1.47 for buildings in Exposure Category C.

Fig. 15 shows another pressure comparison for the hospital example, considering the MWFRS of the leeward part of the roof, for Exposure Category B (top) and Exposure Category C (bottom). For reference, see the 4th set of bars under "windward" in Fig. 10 for the corollary of the DFW example for this building element. The areas where design for tornado loads is not required is the same as for the MWFRS windward roof edge uplift shown in Fig. 14, but tornado loads control for a much larger portion of the country for the leeward roof uplift due to the smaller magnitude of the pressures and the greater relative contribution of internal pressure and atmospheric pressure change. The maximum ratio of design tornado pressure to design wind pressure is 2.63 for buildings in Exposure Category B and 2.02 for buildings in Exposure Category C.

These example maps show the spatial implications of the introduction of the ASCE 7-22 tornado pressures on overall building design for specific building elements. Comparison of the maps for different building elements shows that the magnitude of the difference between design tornado and wind pressures is also a strong function of the design element being considered.



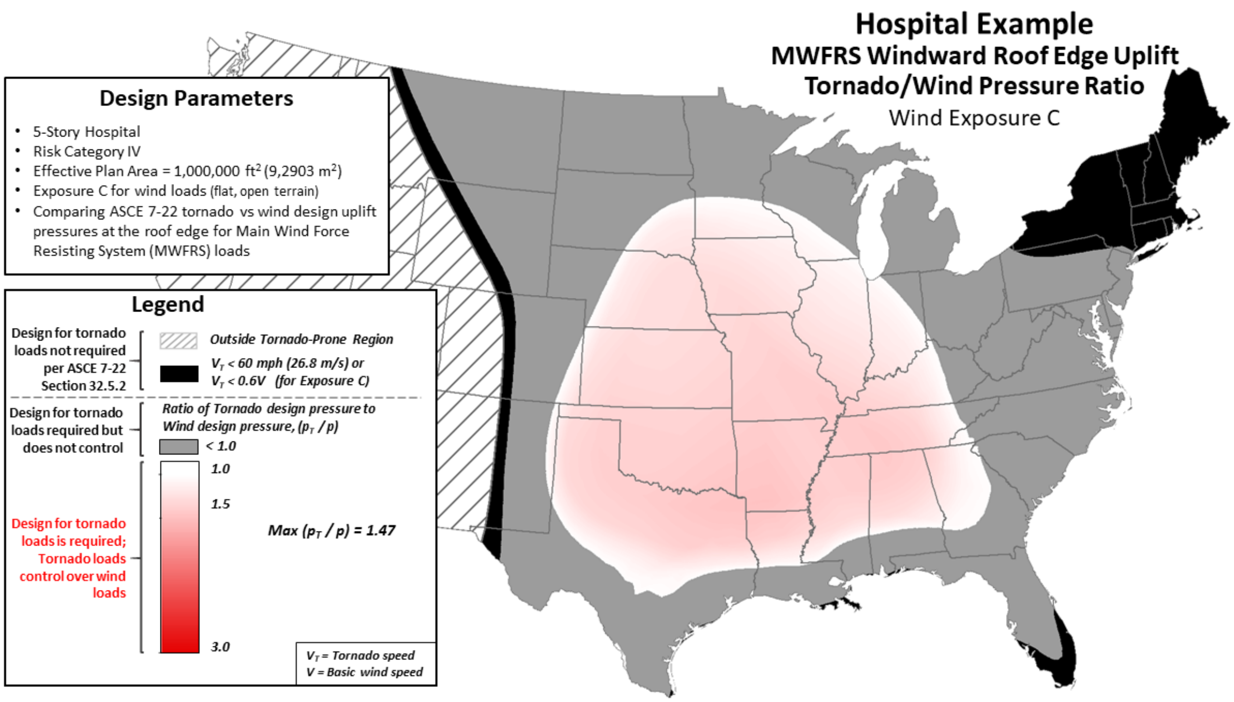
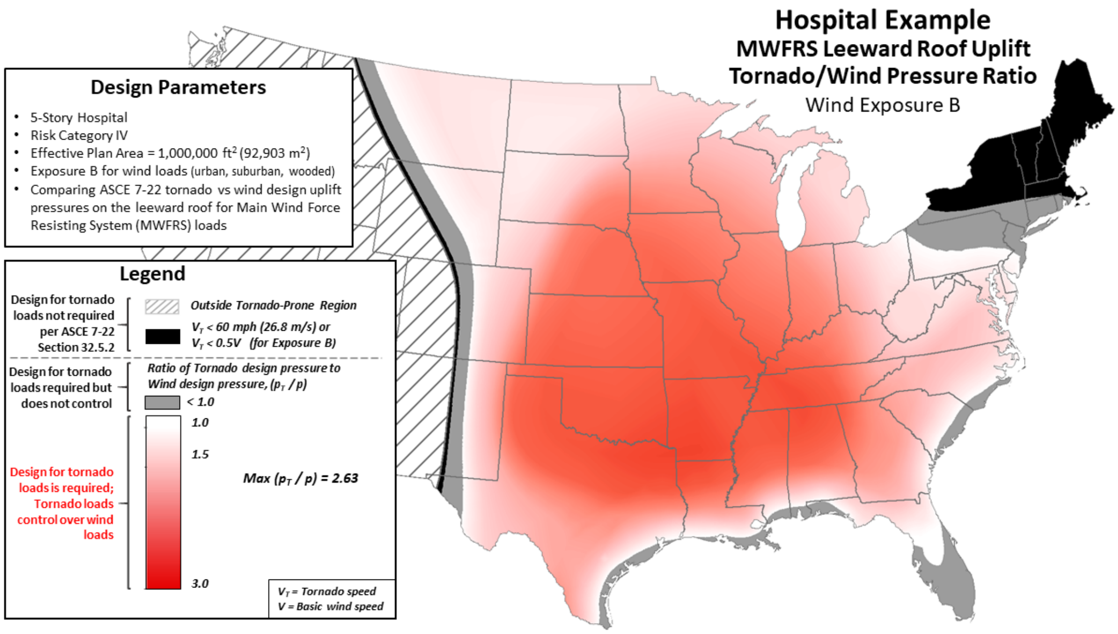


Fig. 14. Comparison of design tornado and wind pressures for windward roof edge uplift on the hospital in Exposure B (top) and Exposure C (bottom)



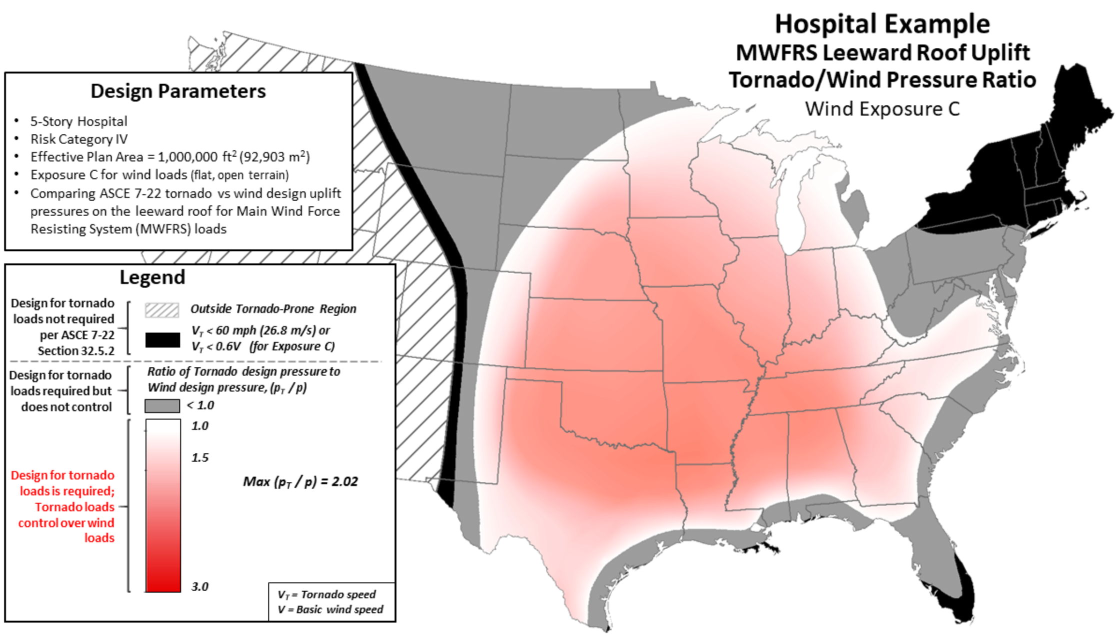


Fig. 15. Comparison of design tornado and wind pressures for the leeward roof uplift on the hospital in Exposure B (top) and Exposure C (bottom)

5. Impacts on Roof Systems

This section discusses potential impacts on roof systems with adoption of the new tornado load requirements in ASCE 7-22. Four different systems were studied, applied to the example buildings described in Section 4.1. Each system was evaluated at the nine cities shown in Fig. 6. The studied roof systems are as follows:

Elementary school: Fully adhered membrane over steel roof deck:,

- Adhered membrane (either modified bitumen or single-ply)
- Cover board, set in foam ribbon adhesive
- Polyisocyanurate roof insulation, 4 ft x 4 ft (1.2 m x 1.2 m), set in foam ribbon adhesive
- Polyisocyanurate roof insulation, 4 ft x 8 ft (1.2 m x 2.4 m), mechanically attached
- Steel roof deck

High school: Mechanically attached membrane over steel roof deck:,

- Mechanically attached single-ply membrane
- Cover board, 4 ft x 8 ft (1.2 m x 2.4 m), mechanically attached
- 2 layers of polyisocyanurate roof insulation, 4 ft x 8 ft (1.2 m x 2.4 m), loose-laid
- Steel roof deck

Fire station: Structural standing seam metal panel system

- Structural standing seam metal panel system, concealed clips
- Steel roof deck or steel purlins

Hospital – Roof System 1: Fully adhered membrane over steel roof deck – same as elementary school roof system.

Hospital – Roof System 2: Fully adhered membrane over concrete roof deck:,

- Adhered membrane (either modified bitumen or single-ply)
- Cover board, set in foam ribbon adhesive
- 2 layers of polyisocyanurate roof insulation, 4 ft x 4 ft (1.2 m x 1.2 m), set in foam ribbon adhesive
- Modified bitumen membrane, torched to primed concrete roof deck
- Normal weight concrete roof deck

All studied roof systems are commonly used throughout the U.S. on commercial buildings and essential facilities.

5.1. Evaluation Process

A six-step process was used to evaluate the potential impact on the roof system for each of studied roof systems at each city, as follows:

(1) The ultimate design uplift load was calculated for each roof zone (i.e. zones 1’, 1, 2 and 3), in accordance with ASCE 7-22 Chapter 30 for design pressures on low-slope roofs, for an effective wind area of 10 ft^2 (0.93 m^2). Tornado loads were calculated along with wind loads for Exposure B and C.

(2) The ultimate design uplift load was converted to an allowable stress design (ASD) uplift load per ASCE 7 (i.e., ultimate design load x 0.6 equals the ASD load).
(3) A 2.0 safety factor was applied to the ASD load to determine the minimum required laboratory test pressure.
(4) The minimum uplift resistance Class was determined. The Class was based on testing in accordance with ANSI/FM 4474 (one of the test standards listed in Section 1504.4.1 of IBC 2021) [24]. The lowest Class is 60. A Class 60 roof assembly passed the test at a pressure of 60 pounds per square foot (psf) (2872 N/m^2). A Class 60 assembly is suitable for ASD uplift loads less than or equal to 30 psf (1436 N/m^2). Classes are stepped by 15 psf (718 N/m^2) increments (e.g., Class 60, 75, 90, 105, 120, …).
(5) After determining the minimum required Class, a database of tested assemblies was searched to find a studied system that had the minimum required Class. Key characteristics of the system that affected costs were identified (e.g., the number of fasteners per insulation board and spacing of foam ribbon adhesive).
(6) The system's key characteristic requirements for Exposure B, C, and tornado were compared to determine if tornado design impacted the Exposure B or C requirements. The impacts are summarized in Section 5.2. Section 6 identifies the cost impacts for the elementary school and high school.

Table 7 illustrates this process for the high school in Memphis (mechanically attached single-ply membrane roof system on top of a steel deck).

Table 7. High School – Memphis – Roof Assembly Loads and Construction Example

Wind Exposure B						
Zone	Ult design uplift load (psf)	ASD uplift load (psf) (Ult x 0.6)	Min. test pressure (psf) (ASD load x 2.0 safety factor)	Min. uplift resistance Class (psf)	Row spacing, fasteners along row,	Fasteners per 4 ft x 8 ft board
1’	22.2	13.32	26.64	60	9.5 ft x 12 in oc	4
1	38.6	23.16	46.32	60	9.5 ft x 12 in oc	4
2	51	30.60	61.20	75	9.5 ft x 12 in oc	4
3	69.5	41.7	83.40	90	7.5 ft x 12 in oc	4

Wind Exposure C						
Zone	Ult design uplift load (psf)	ASD uplift load (Ult x 0.6)	Min. test pressure (ASD load x 2.0 safety factor)	Min. uplift resistance Class	Row spacing, fasteners along row	Fasteners per 4 ft x 8 ft board
1’	30.8	18.48	36.96	60	9.5 ft x 12 in oc	4
1	53.7	32.22	64.44	75	9.5 ft x 12 in oc	4
2	70.8	42.48	84.96	90	7.5 ft x 12 in oc	4
3	96.5	57.90	115.80	120	9.38 ft x 6 in oc	4

Tornado						
Zone	Ult design uplift load (psf)	ASD uplift load (Ult x 0.6)	Min. test pressure (ASD load x 2.0 safety factor)	Min. uplift resistance Class	Row spacing, fasteners along row	Fasteners per 4 ft x 8 ft board
1’	42.6	25.56	51.12	60	9.5 ft x 12 in oc	4
1	58.2	34.92	69.84	75	9.5 ft x 12 in oc	4
2	66.1	39.66	79.32	90	7.5 ft x 12 in oc	4
3	85.9	51.54	103.08	105	9.58 ft x 6 in oc	4

Note 1: Tornado pressure controls for zones 1’ and 1 for Exposure B and C. Tornado pressure controls for zone 2 and 3 for Exposure B
Note 2: The tornado minimum resistance Class is not changed for zone 1’ compared with Exposure B and C. For zones 1 – 3, the Class is increased compared with Exposure B, but the membrane fastener spacing is the same at zone 1**.** Hence, tornado increases the roof system cost for zones 2 and 3 verses Exposure B.
Note 3: Tornado does not increase the roof system cost compared with Exposure C.
Note 4: Unit Conversions: 1 in = 2.54 cm; 1 m = 3.28084 ft; 1 psf = 47.88 N/m^2

5.2. Summary of Tornado Impacts on Roof Systems

Tornado load impacts on the roof design as a function of building type, roof system, and city are shown in Table 8. Despite the sometimes significant (more than double) increases in uplift pressures, in no case did the tornado designs require the use of a different type of roof system or different roof system components than needed to resist the wind loads. There were no net impacts on the design of the elementary school roof or the hospital roof with the steel deck in any of the cities for either wind exposure. Where tornado loads had an impact on the studied roof systems, the impact consisted of requiring additional foam ribbon adhesive and/or additional fasteners. Given that buildings in Exposure C (flat, open terrain) have greater wind loads than the buildings with the same characteristics located in Exposure B (urban, suburban, or wooded areas), the relative impact of tornado loads on buildings in Exposure C were less than for Exposure B. Note that the under no scenario did roof deck design change.

Table 8. Tornado Load Impacts on Studied Roofing System Construction, by Location and Exposure

Building Type	Roof Construction	Cities	Exposure (Zones)	Construction Design Change
High School	steel roof deck, mechanically attached membrane	Memphis, Kansas City	B (2 & 3)	Additional membrane fasteners
		DFW	B	Additional membrane fasteners
Fire Station	structural standing seam metal panel system	Memphis, Kansas City, & DFW	B (all zones)	panel rib spacing is reduced
Hospital	steel roof deck, adhered roof system	Memphis, Kansas City, & DFW	B (all zones)	Additional insulation board fasteners
			B (1, 2)	Additional foam ribbon adhesive
			C (all zones)	Additional insulation board fasteners
			C (Zone 1)	Additional foam ribbon adhesive
		Chicago	B (Zone 1-3)	Additional insulation board fasteners
			B (Zone 1 & 2)	additional foam ribbon adhesive
			C (zone 1)	Additional insulation board fasteners & foam ribbon adhesive
		Minneapolis	B (Zone 1-3)	Additional insulation board fasteners
			B (Zone 2)	additional foam ribbon adhesive
		Charlotte	B (zone 1)	Additional insulation board fasteners & foam ribbon adhesive
Note 1: No impact for any location or exposure for elementary school (fully adhered membrane over steel roof deck) or hospital with concrete roof deck (adhered roof system). Note 2: No impact for all other locations, exposures, and zones for high school, fire station or hospital with steel roof deck.				

Wind-borne debris is another consideration in the design of roofs. Information on this hazard and design strategies to minimize the consequences of debris impacts is presented in the Appendix.

6. Construction Cost Analysis

The construction cost analysis of the ASCE 7-22 tornado load requirements is discussed in detail in this section, including an explanation of the general methodology, construction design options considered to meet the design pressures, cost data collection and development for these construction design options across locations, and cost comparison approach. This study updates and expands on previous analysis completed by Huckabee, Inc. for two building types (elementary school and high school) and two wind exposures (B and C) for the DFW area and replicates the process for eight other locations to provide examples of cost impacts under different tornado load conditions.

6.1. Methodology

The general methodology to estimate the construction cost impacts of ASCE 7-22 tornado loads for a given building type in a specific location is defined in the following steps:

1) Calculate the design wind pressures for Exposure B, Exposure C, and design tornado pressure as defined by ASCE 7-22
2) Estimate construction costs for building elements for each of the three cases in step 1
3) Calculate the difference in costs for each building element
4) Sum costs for all building elements for which costs increase to meet the tornado loads
5) Replicate Steps (1) to (4) for other locations
6) Replicate Steps (1) to (5) for other building types

These calculations require the following information for each building type and location:

- Initial project budget for the building
- Design wind and tornado pressure the building is required to withstand
- Building element design options to meet the different pressures
- Construction costs of these building element design options

The design wind and tornado pressures are calculated as described in Section 4. Whether design tornado pressure loads control over wind pressure loads varies by building type, location, and exposure category. Below are the four design loads used for selection and cost estimation of the building element constructions and the range of design tornado loads as a percentage of wind load:

- MWFRS Roof Field: -79 % to +144 %
- Zone 2 Roof Uplift C&C pressure, EWA 10 ft^2 (0.93 m^2): -89 % to +30 %
- Zone 1' Roof Net Uplift[10]: -92 % to +137 %
- Zone 4 C&C Pressure, EWA 75 ft^2 (6.97 m^2): -87 % to +52 %

Clearly, design tornado loads will not control in some cases while in other cases there are large load increases. In general, the tornado loads have a greater percentage increase relative to the existing load requirements for the high school (i.e., larger building footprint), buildings with Exposure B, and locations in the central and southern United States.

[10] Zone 1' Roof Net Uplift is a function of Roof Uplift C&C pressure, EWA 200 ft^2 (18.58 m^2) = 0.6* Uplift - 3

The initial project budget, building element design options, and construction cost data were collected by Huckabee for a single location (DFW area). City cost indexes for construction costs are applied to adjust the cost data for other locations. The exception to this process is roofing, which was not provided by Huckabee and is calculated using location-specific cost data.

6.1.1. Building Element Options and Maximum Loads

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. For each of the five considered building elements there is an associated wind load requirement. Table 9 provides the maximum load value for a given building element construction design option.

The diaphragm construction must meet calculated Zone 2 uplift for Effective Wind Area (EWA) 10 ft^2 (0.93 m^2) load thresholds. The construction options developed by Huckabee are based on a conventional design using ⅝ in (1.6 cm) arc puddle welds (PW) support fastener, 36/4 support pattern, #12 TEK screw sidelap fasteners. The design options are based on the number of sidelap fasteners per span (3 to 8) based on maximum load requirement thresholds (42 psf to 116 psf or 2011 N/m^2 to 5554 N/m^2). Diaphragm attachments were designed for concurrent uplift and diaphragm shear. Expert judgement determined typical design will meet MWFRS diaphragm shear of 600 pounds per linear foot (plf) or 813 N-m, which remains constant across all designs considered for diaphragm connectors.

The roof joists and wide flange beams and girders construction must meet calculated Zone 1' Net Uplift (assuming 5 psf (239 N/m^2) deadload) load thresholds factored using the ASD combination $0.6D + 0.6W$, where D is the deadload and W is the wind load, or in this case the wine or tornado load, as appropriate. The assumed minimum construction is a 25 ft x 25 ft (7.6 m x 7.6 m) framing bay with joists spaced at 6 ft 6 in (2 m) on-center (OC). Wide flange girders span 25 ft (7.6 m) between columns perpendicular to the joists. The wide flange girders' bottom flange is assumed to be unbraced for lateral torsional buckling under net uplift loading. The joist construction options were developed by a joist manufacturer engineer with minimal changes to the design. The construction options for the wide flange beams were developed by Huckabee and cover a range of beams as shown in Table 5. The combined construction design options cover uplift values for up to 33 psf (1580 N/m^2).

The foundation anchorage construction requirements (concrete, rebar, and steel) developed by Huckabee are based on the fraction increase in the calculated MWFRS Roof Field load. Increases in the maximum load values are limited to between 30 % and 75 %. Any increase of less than 30 % or greater than 75 % is assumed to be 30 % or 75 %, respectively. Additional anchorage includes additional concrete, rebar, and/or steel to meet the higher loads. This will be discussed further in Section 6.1.2.

The wall framing selection is based on calculated Zone 4 C&C Pressure load thresholds. Per Huckabee's assessment, a maximum load value less than 31.8 psf (1523 N/m^2) can be met using typical 18 gauge (ga) metal stud construction while any value between 31.8 psf (1523 N/m^2) and 39.8 psf (1906 N/m^2) is met by switching to 16 ga metal studs. The flange width on the stud was assumed to be 1-5/8 in (4.1 cm). The loads are not expected to be greater than 39.8 psf (1906 N/m^2) for any scenario in this analysis. These values assume a typical stud span of 15 ft (4.6 m) and the wall studs are backing masonry veneer.

As discussed in Section 5.1, the roofing construction is based on minimum test pressure (ASD uplift load x 2.0 safety factor) and are categorized into minimum uplift resistance classes ranging from 60 psf (2873 N/m^2) to 120 psf (5746 N/m^2) based on testing in accordance with ANSI/FM 4474. The assumed high school roof assembly (per Section 5) is a mechanically attached single-ply membrane with mechanically attached cover board (4 ft x 8 ft (1.2 m x 2.4 m)), polyisocyanurate insulation (2 layers of loose-laid 4 ft x 8 ft (1.2 m x 2.4 m) sheets), and a steel roof deck. No change is necessary for the steel deck properties or attachment. The only change in construction is the number of fasteners required for the membrane installation to meet the minimum uplift load. The required number of fasteners vary based on loads for each roof zone.

Table 9. Load Values for Construction Assembly Design Options

Building Assembly, Material and Load Categories		**Construction Description**	**Max Load Value (psf)**
Roof	Diaphragm Zone 2 Uplift EWA 10 ft^2	Convent, 5/8 in PW, 36/4, #12 TEK, 3	42
		Convent, 5/8 in PW, 36/4, #12 TEK, 4	72
		Convent, 5/8 in PW, 36/4, #12 TEK, 5	91.5
		Convent, 5/8 in PW, 36/4, #12 TEK, 6	103.5
		Convent, 5/8 in PW, 36/4, #12 TEK, 7	111
		Convent, 5/8 in PW, 36/4, #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
		Maximum 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
Unit Conversions: 5/8 in = 1.6 cm; 1 m = 3.28084 ft; 1 m^2 = 10.7639 ft^2; \$1.00/ft^2 = \$10.7639/m^2; 1 psf = 47.88 N/m^2			

6.1.2. Converting Load Requirements to Cost Estimates

Initial cost data was developed by Huckabee for an elementary school and high school in the DFW area in 2019. The assumed budget for construction in DFW was $20 million for the elementary school and $200 million for the high school. The cost estimates per unit of roof or wall area are completed for each of the construction options defined in Section 6.1.1 and provided in Table 10.

The diaphragm costs are estimated for a 200 ft x 200 ft (61 m x 61 m) roof area and then converted to a cost per unit of area, which ranges from $0.1834/ft^2 to $0.1928/ft^2 ($1.97/m^2 to $2.08/m^2) of roof area based on costs from the manufacturer.

The joist and wide flange costs are estimated and combined for a cost per unit of roof area, which range from $3.28/ft^2 to $4.45/ft^2 ($35.31/m^2 to $47.90/m^2). The joist cost data was provided by the joist manufacturer's engineer based on cost data in 2019. For wide flange beams and girders, Huckabee estimated the costs based on a quantity of steel at $4000/ton unit price (2019). The combined costs are converted to a cost per unit of area. The fraction of the costs associated with the joists range from 29.1 % to 36.6 % with the share decreasing as the maximum load value increases. Therefore, the wide flanges account for most of the costs with their share increasing from 63.4 % to 70.9 % as the load value increases. Joist cost data was provided to Huckabee by a joist manufacturer.

Foundation anchorage costs are also costs per unit of roof area, and are based on the fraction increase in MWFRS Roof Field loads. Based on expert judgement by Huckabee, an increase of less than 30 % is assumed to not require a change in construction and, therefore, add no additional costs. An increase of greater than 75 % is assumed to lead to the highest potential additional construction costs. The per unit cost estimate was developed by Huckabee based on the total cost of approximately $20 000 for additional anchorage for a high school with 386 126 ft^2 (35 872 m^2) of roof area ($0.0518/ft^2 or $0.558/m^2). Based on their expert judgment, the cost of an increase in MWFRS Roof Field loads between 30 % and 75% is interpolated between these two cost values.

Exterior wall framing costs are estimated per unit of exterior wall area. The two cost estimates are for two gauges (18 ga and 16 ga) of 6 in wall cold-formed metal studs. The 18 ga steel studs are used until loads are greater than 31.8 psf (1523 N/m^2), at which time costs increase by $0.44/ft^2 ($4.74/m^2) of exterior wall area based on the quantity of steel, estimated by Huckabee at a $4000/ton unit price (2019).

The roofing construction costs are based on the per square foot of roof area impacted. The change in construction is based on the number of fasteners required for the membrane installation. The cost of fasteners is assumed to be minimal and is excluded from the cost estimate. The labor costs are assumed to be linear based on the number of fasteners installed, ranging from $0.48/ft^2 to $0.97/ft^2 ($5.17/m^2 to $10.44/m^2) for DFW assuming "open shop" labor type in RSMeans Commercial New Construction Assembly database (Year 2019 Q1) [25]. The uplift resistance class requirements are calculated for each roof zone with varying uplift load by roof zone and, therefore, could have different roofing installation cost impacts for each zone.

Table 10. Cost Per Unit (ft^2) by Maximum Load Value for Schools in DFW, TX

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
Unit Conversions: 1 psf = 47.88 N/m^2; 1 m^2 = 10.7639 ft^2; $\$1.00/ft^2 = \$10.7639/m^2$				

6.1.3. City Cost Indexing

The cost data in Section 6.1.2 was developed for the DFW area. Two approaches could be used to replicate the cost estimates in other locations: (1) replicate the "bottom-up" cost estimate approach used for DFW or (2) use city cost indexes to account for relative differences in costs by building element. Option 1 may be more accurate but is labor-intensive and requires access to cost data and expertise in cost estimating in each location. Option 2 may be less accurate but can be completed quickly with no additional expertise. Based on limited funding, time, and the resulting magnitude of the incremental cost impacts, Option 2 was determined to be the most appropriate for this study. The only exception is roofing, which uses Option 1 based on expert guidance from TLSmith Consulting. If deemed beneficial, future analysis could adopt Option 1 for a more rigorous, detailed analysis.

The DFW cost data is adjusted using RSMeans City Cost Indexes to control for cost variation across locations [26]. Indexes for Quarter 1 (Q1) of 2019 were selected to match the cost data provided by Huckabee as well as exclude any pandemic-related effects. Each building construction element is mapped to the appropriate Level 2 building element using the standards classification standard UNIFORMAT II [27], and then matched to that Level 2 group element cost index as shown in **Table 11**. The total project budget is mapped to the weighted average cost index for each location.

Table 11. City Cost Indexes (RSMeans 2019 Q1)

UNIFORMAT	Diaphragm	Joists	Wide Flange	Wall Frame	Foundation Anchorage	Weighted Average
Level 2	**Superstructure**			**Exterior Closure**	**Substructure**	**Baseline Building Cost**
Level 3	**Roof**			**Exterior Walls**	**Foundations**	
DFW	79.3	79.3	79.3	83.9	82.2	88.0
Charlotte	85.1	85.1	85.1	75.4	86.1	90.4
Kansas City	105.3	105.3	105.3	97.7	98.2	101
Chicago	125.7	125.7	125.7	130.4	136.4	123.5
Mobile	98.3	98.3	98.3	77.8	80.8	87.4
Memphis	90.1	90.1	90.1	80.2	85.9	88.2
Washington	100.6	100.6	100.6	97.2	95.7	98.0
Minneapolis	109.3	109.3	109.3	114.8	109.5	109.4
Denver	95.7	95.7	95.7	86.8	93.8	93.2

The city cost indexes are normalized to the DFW City Cost Index and then the cost data are adjusted using that normalized city cost index adjustment factor, creating the data in **Table 12**. The only building element not implementing the city cost index adjustment approach is roofing because it was not included in Huckabee's initial analysis, and instead uses city-specific labor cost data for installing single-ply ethylene propylene diene terpolymer (EPDM) membrane from the RSMeans 2019 Q1 assembly database as is used for DFW. These per unit costs are used for completing the cost estimates for each location.

Table 12. Cost Per Unit ($/ft^2) by Load Requirement and Location

Area Unit	Load Unit	Value	DFW	Charlotte	Kansas City	Chicago	Mobile	Memphis	Washing.	Minn.	Denver
Roof Area	Zone 2 Uplift EWA 10 ft^2	42	$0.18	$0.16	$0.19	$0.23	$0.18	$0.17	$0.18	$0.20	$0.18
		72	$0.19	$0.16	$0.20	$0.23	$0.18	$0.17	$0.19	$0.20	$0.18
		91.5	$0.19	$0.16	$0.20	$0.24	$0.18	$0.17	$0.19	$0.20	$0.18
		103.5	$0.19	$0.16	$0.20	$0.24	$0.19	$0.17	$0.19	$0.21	$0.18
		111	$0.19	$0.16	$0.20	$0.24	$0.19	$0.17	$0.19	$0.21	$0.18
		116	$0.19	$0.16	$0.20	$0.24	$0.19	$0.17	$0.19	$0.21	$0.18
	Zone 1' Net Uplift	12	$3.28	$2.79	$3.45	$4.12	$3.22	$2.96	$3.30	$3.59	$3.14
		14	$3.62	$3.08	$3.81	$4.55	$3.56	$3.26	$3.64	$3.96	$3.46
		21	$3.64	$3.10	$3.84	$4.58	$3.58	$3.28	$3.66	$3.98	$3.49
		25	$3.97	$3.38	$4.18	$4.99	$3.90	$3.58	$3.99	$4.34	$3.80
		31	$4.29	$3.65	$4.52	$5.39	$4.22	$3.87	$4.32	$4.69	$4.11
		33	$4.45	$3.79	$4.69	$5.59	$4.37	$4.01	$4.48	$4.86	$4.26
	MWFRS Roof Field	0.3	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
		0.75	$0.05	$0.05	$0.05	$0.07	$0.04	$0.04	$0.05	$0.06	$0.05
Ext Wall Area	Zone 4 C&C Pressure	31.8	$3.47	$2.62	$3.39	$4.53	$2.70	$2.78	$3.37	$3.98	$3.01
		39.8	$3.83	$2.89	$3.74	$4.99	$2.98	$3.07	$3.72	$4.40	$3.32
Roof Area Impacted	Min. Uplift Class	60	$0.48	$0.47	$0.72	$1.02	$0.48	$0.50	$0.61	$0.81	$0.52
		75	$0.48	$0.47	$0.72	$1.02	$0.48	$0.50	$0.61	$0.81	$0.52
		90	$0.61	$0.60	$0.91	$1.29	$0.61	$0.63	$0.77	$1.03	$0.66
		105	$0.95	$0.93	$1.43	$2.02	$0.95	$0.99	$1.21	$1.61	$1.03
		120	$0.97	$0.95	$1.46	$2.07	$0.97	$1.01	$1.24	$1.64	$1.05
Unit Conversion: 1 m^2 = 10.7639 ft^2; $1.00/ft^2 = $10.7639/m^2											

6.1.4. Calculating Construction Cost Impacts

The cost data is used to estimate the costs of meeting the maximum wind pressure loads for each building element based on the current requirements for Exposure B, Exposure C, and tornado loads. The cost estimates for both the Exposure B and Exposure C designs are compared to the cost estimates for the tornado loads. There are three potential outcomes for each building element where $C_{c,e}$ is the cost of meeting the code (*c*) for a given exposure (*e*) and C_T is the cost of meeting the tornado loads:

(1) Design option to meet tornado loads costs less than the design option to meet current code requirements ($C_T < C_{c,e}$)
(2) Design option to meet tornado loads is the same as the design option to meet current code requirements ($C_T = C_{c,e}$)
(3) Design option to meet tornado loads costs more than the design option to meet current code requirements ($C_T > C_{c,e}$)

For outcome (1) and (2), the cost impact is assumed to be zero because the building element must be constructed to meet the current code requirements. For outcome (3), the cost impact is simply the difference between the costs of the two building element design options $(C_T - C_{c,e})$. Alternatively, the cost impact for a building element can be expressed as $max\{0\,,(C_T - C_{c,e})\}$.

The cost impacts of each building element are aggregated to estimate the total cost impact from the code change for a given building type-location-exposure.

Alternatively, the aggregated cost impact for all building elements can be expressed as the following where i is the building element: $\sum_{i=1}^{5} max\{0, (C_{T,i} - C_{c,e,i})\}$.

6.2. Cost Impact Results

There are three general outcomes from estimating the impact of ASCE 7-22 tornado loads on the building construction costs. First, the tornado speed for a given location is below 60 mph (26.8 m/s) and does not need to be considered for any building design. Second, the construction design requirements based on the tornado loads do not control because the already required wind loads are greater. Third, the construction design requirements based on the tornado loads control for at least one construction element for at least one exposure type. In the first two cases, there is no impact on the construction and, therefore, no impact on construction costs. In the third case, the construction costs must be calculated to determine if there is and the magnitude of cost impacts.

6.2.1. Elementary School Example

For elementary schools, only three locations realize an impact on construction costs from meeting the tornado load requirements. In fact, four locations can be excluded from the cost analysis: Mobile, Washington, D.C., and Denver because the tornado wind speed is less than 60 mph (26.8 m/s) and Charlotte because the tornado loads do not control over wind load requirements. DFW, Kansas City, Chicago, Minneapolis, and Memphis have tornado loads control for at least one construction element for at least one exposure type. For Chicago and Minneapolis, the foundation anchorage tornado load controls for an elementary school with Exposure B. However, the increase in the load is less than 30 %, which is estimated to not have a cost impact. Therefore, cost analysis is only necessary for DFW, Kansas City, and Memphis. Results for which are provided in Table 13, both in total costs and fraction of the project construction budget.

For DFW, the tornado load controls for the foundation anchorage and roof joists and wide flange beams and girders for both Exposure B and Exposure C as well as wall framing for Exposure B. However, these only impact the design for the foundation anchorage and joist and wide flange for Exposure B, leading to an increase in construction costs of $27 933 or 0.16 % of the project budget.

For Kansas City, the tornado loads control for foundation anchorage and roof joists and wide flange beams and girders for both Exposure B and Exposure C and wall framing for Exposure B. However, these only impact the design for the foundation anchorage and roof joists and wide flange beams and girders for Exposure B and Exposure C, leading to an increase in construction costs of $28 354 (0.16 %) for Exposure B and $1658 (0.01 %) for Exposure C.

For Memphis, the tornado loads control for foundation anchorage and roof joist and wide flange beams and girders for both Exposure B and Exposure C and wall framing for Exposure B. However, construction for wall framing for Exposure B is not impacted. The impact on the design for the foundation anchorage and roof joists and wide flange beams and girders leading to an increase in construction costs of $29 498 (0.15 %) for Exposure B and $2135 (0.01 %) for Exposure C.

Table 13. Estimated Cost Impacts from Tornado Loads – Elementary School

Building Element	DFW		Kansas City		Memphis	
	B	C	B	C	B	C
Roofing Fasteners	$0	$0	$0	$0	$0	$0
Diaphragm	$0	$0	$0	$0	$0	$0
Joists & Wide Flange	$24 240	$0	$25 370	$1542	$25 964	$1578
Wall Frame	$0	$0	$0	$0	$0	$0
Found. Anchor.	$3693	$0	$2984	$116	$3534	$557
Total	**$27 933**	**$0**	**$28 354**	**$1658**	**$29 498**	**$2135**
Budget ($million)	$20.00	$20.00	$19.86	$19.86	$22.27	$22.27
Percent of Budget	**0.14 %**	**0.00 %**	**0.14 %**	**0.01 %**	**0.13 %**	**0.01 %**
Note: No cost impact from tornado loads for all other locations and exposures.						

6.2.2. High School Example

The design wind pressures are the same for high schools as those for elementary schools because both were assumed to be two-story buildings. The design tornado pressure is greater for the high school since it has a much larger building footprint than the elementary school and hence a larger design tornado speed. Therefore, the cost impact is expected to be greater for the same three locations and exposures as elementary schools, as well as potentially lead to cost increases in other locations not impacted for elementary schools.

For high schools, three locations can be excluded from the cost analysis: Mobile, Washington, D.C., and Denver because the tornado wind speed is less than 60 mph (26.8 m/s). The six other locations have tornado loads control for at least one construction element for at least one exposure type. Three locations realize an increase in costs for both Exposure B and Exposure C: DFW, Kansas City, and Memphis. Three locations realize an increase in costs for Exposure B only: Charlotte, Chicago, and Minneapolis. Results are provided in Table 14, both in total costs and fraction of the project construction budget.

For Charlotte, the foundation anchorage, roof joists and wide flange beams and girders, and roof fastener tornado load controls for a high school with Exposure B. However, these only impact the design for the foundation anchorage, leading to an increase in construction costs of $2391 or 0.001 % of the project budget.

For Chicago, the tornado load controls for the foundation anchorage for both Exposure B and Exposure C as well as roof joists and wide flange beams and girders, wall framing, and roof fasteners for Exposure B. However, these only impact the design for the foundation anchorage and roof joists and wide flange beams and girders for Exposure B, leading to an increase in construction costs of $185 857 or 0.08 % of the project budget.

For Minneapolis, the tornado load controls for the foundation anchorage for both Exposure B and Exposure C as well as roof joists and wide flange beams and girders, and wall framing for Exposure B. However, these only impact the design for the foundation anchorage for Exposure B, leading to an increase in construction costs of $12 675 or 0.006 % of the project budget.

For DFW, the tornado loads control for foundation anchorage, roof joists and wide flange beams and girders, and wall framing for both Exposure B and Exposure C and diaphragm and roof fasteners for Exposure B. However, these only impact the design for the foundation anchorage, roof joists and wide flange beams and girders for both Exposure B and Exposure C and wall framing and roof fasteners (Zone 3) for Exposure B, leading to an increase in construction costs of $250 077 (0.14 %) for Exposure B and $24 069 (0.01 %) for Exposure C.

For Kansas City, the tornado loads control for foundation anchorage, roof joists and wide flange beams and girders, and wall framing for both Exposure B and Exposure C and diaphragm for Exposure B. However, these only impact the design for the foundation anchorage and roof joists and wide flange beams and girders for both Exposure B and Exposure C and wall framing and roof fasteners (Zone 2 and Zone 3) for Exposure B, leading to an increase in construction costs of $223 582 (0.13 %) for Exposure B and $22 088 (0.01 %) for Exposure C.

For Memphis, tornado loads control for foundation anchorage, roof joists and wide flange beams and girders, and wall framing for both Exposure B and Exposure C and diaphragm for Exposure B. However, these only impact the design for the foundation anchorage and roof joists and wide flange beams and girders for both Exposure B and Exposure C and wall framing and roof fasteners (Zone 2 and Zone 3) for Exposure B, leading to an increase in construction costs of $247 236 (0.13 %) for Exposure B and $27 686 (0.01 %) for Exposure C.

Table 14. Estimated Cost Impacts from Tornado Loads – High School

Cost Item	Charl.	Chicago	Minn.	DFW		Kansas City		Memphis	
	B	B	B	B	C	B	C	B	C
Roof Fasteners	$0	$0	$0	$300	$0	$11 943	$0	$8294	$0
Diaph.	$0	$0	$0	$0	$0	$0	$0	$0	$0
Joists & WF	$0	$165 023	$0	$139 778	$8495	$137 401	$8350	$140 616	$8546
Wall Frame	$0	$0	$0	$90 000	$0	$70 020	$0	$87 480	$0
Found. Anchor.	$2391	$20 835	$12 675	$20 000	$15 574	$16 160	$13 738	$19 140	$19 140
Total	**$2391**	**$185 857**	**$12 675**	**$250 077**	**$24 069**	**$235 525**	**$22 088**	**$255 530**	**$27 686**
Budget ($million)	$200.45	$280.68	$248.64	$200.00	$200.00	$198.64	$198.64	$222.73	$222.73
Pct of Budget	**0.001 %**	**0.07 %**	**0.005 %**	**0.13 %**	**0.01 %**	**0.12 %**	**0.01 %**	**0.11 %**	**0.01 %**
Note: Exposures not displayed had zero cost impacts from tornado loads									

6.2.3. Results Summary

In summary, the new tornado load requirements in ASCE 7-22 have minimal initial construction cost impacts for schools regardless of location or wind exposure for the two example facilities considered in this study. For most of the U.S. the cost impact on similarly sized schools is zero because the tornado loads often do not control, and when tornado loads do control the building element designs are typically not impacted. Even in the most extreme scenarios for the two case studies where tornado loads control for multiple building elements, the cost impact is less than $30 000 for elementary schools and $256 000 for high schools, accounting for project budget increases of 0.14 % or less under all building type-location-exposure combinations. Of the nine cities considered in this study, three realize cost increases for at least one exposure category for the elementary school and six for high school. Additionally, of all the building type – location – exposure combinations, only six (three for each building type) realize cost impacts greater than 0.07 % of the project budget.

The cost study did not include the fire station or hospital examples. Risk Category IV facilities similar in size and shape would have greater relative increases in tornado loads compared to wind loads, which could lead to construction cost increases. Additionally, Risk Category IV facilities are required to have impact-resistant glazing or impact protective systems, which may also add to construction costs. The magnitude of these potential additional cost increases relative to the total construction budget is unclear. For example, the construction cost per unit of floor area for a hospital is greater than most other types of buildings, which may lead to similar or smaller percentage increases than for those estimated in the school case studies.

7. Summary

This study analyzes the potential economic impacts from implementation of the new tornado load requirements in the ASCE 7-22 Standard: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, by incorporation into the IBC (Proposal S63-22 in Ref. [3]) and/or direct adoption by Federal, state, and local governments. The Standard requires that Risk Category III and IV buildings and other structures located in the tornado-prone region (approximately equal to the area of the conterminous U.S. east of the Continental Divide) be designed to resist tornado loads in addition to wind loads from other types of storms. Risk Category III includes buildings that represent a substantial hazard to human life in the event of failure (e.g., theaters and other assembly occupancies, schools, nursing homes), while Risk Category IV is for essential facilities (e.g., hospitals, fire and police stations, emergency operations centers).

The approach in this study is based on four key steps to estimate the economic impact of the code change proposal. The first step identifies the potential numbers of buildings that may be impacted. This step limits the need to consider tornado loads for locations not in the tornado-prone region or Risk Category I and II building types. The second step compares tornado loads with existing wind load requirements to understand when and where tornado loads will control design. This step further narrows the potential impact because in many cases that existing wind load requirements are greater than those of the tornado loads. The third step determines what building elements will require changes in construction design when tornado loads control. Consideration of construction design includes five building elements (roof systems, roof diaphragm, roof joists and wide flange beams and girders, exterior wall framing, and foundation anchorages). This step accounts for the fact that current construction design practices can often handle much higher loads than the existing wind load requirements. Therefore, even if tornado loads control, the construction design may not need to change. The fourth step estimates the cost of these changes in construction design. This step calculates the estimated increase in construction costs resulting from any change in construction design to meet tornado loads relative to current ASCE 7-22 load requirements, both in total dollars and percent of total project construction budget.

Case studies are used to estimate the relative magnitude of the potential cost impacts of five building elements (roof systems, roof diaphragm, roof joists and wide flange beams and girders, exterior wall framing, and foundation anchorages) for two building types (elementary school and high school) for wind Exposure Categories B and C baseline building designs across nine locations to provide a range of potential load requirements and resulting cost implications.

7.1. Potential Impacts of Adopting ASCE 7-22

Section 2 shows the adoption of the new tornado load requirements in the ASCE 7-22 standard will impact a small fraction of new buildings in the United States. The only buildings that are eligible to be impacted are new buildings that meet the following requirements:

(1) located within the tornado-prone region
(2) classified as Risk Category III or IV buildings
(3) located within an area where tornado speeds meet or exceed 60 mph (26.8 m/s)

(4) located within an area where the tornado speeds are greater than a specified fraction of the basic (non-tornado) design wind speeds.

Requirements 3 and 4 represent approximate lower bounds on where tornado loads can begin to start controlling over wind loads for any element of a specific building or other structure.

When excluding residential occupancies with less than 50 units, the building stock occupancy types for Risk Category III and IV buildings in the tornado-prone region represents 15.0 % of the entire U.S. building stock and 18.3 % of the building stock in the tornado-prone region. These results are effectively upper bound estimates as tornado loads will not control over wind loads for all Risk Category III and IV buildings in the tornado-prone region. Whether tornado loads control any aspect of the building design over wind loads depends on many different climatological and building characteristics. Geospatial analyses are used identify the impacts of several of these variables. In general, the tornado design requirements will have the most impact in the central and southeast United States.

Section 3 through Section 5 explain how the tornado loads are calculated, which tornado loads to consider, when tornado loads control, and whether the tornado load impacts the construction design. Section 3 shows that the likelihood of tornado load controlling varies by building risk category, effective plan area, and exposure category. Additionally, the tornado load has the greatest probability of controlling in the central and southeast U.S. (excluding the hurricane-prone southern coastline). Section 4 provides additional detail on the factors that influence the likelihood of the tornado load controlling design, including relative hazard levels, tornado speed, basic wind speed, effective plan area, and wind exposure category as well as building characteristics (building plan shape, roof geometry, roof height, and enclosure classification). A range of impacts and trends are demonstrated through comparisons of wind and tornado loads on several building types using three approaches with different combinations of spatial and analytical detail. Section 5 provides a detailed assessment of the impact of ASCE 7-22 tornado load requirements on roof systems, providing an example of the analysis necessary to determine whether the tornado loads result in changes in construction design.

Section 6 completes a construction cost analysis of adopting ASCE 7-22 tornado load requirements, including an explanation of the methodology, construction design options for five building elements considered (roof systems, roof diaphragm, roof joists and wide flange beams and girders, exterior wall framing, and foundation anchorages), cost data collection and development for these construction design options across locations, and cost comparison approach. This study updates and expands on previous analysis completed by Huckabee, Inc. for two building types (elementary school and high school) and two wind exposures (B and C) for the DFW area and replicates the process for eight other locations to provide examples of cost impacts under different tornado load profiles. For each building type and location, the following process is implemented:

1) Calculate the design wind pressures for Exposure B, Exposure C, and design tornado pressure as defined by ASCE 7-22
2) Estimate the construction costs of each building element for each of the three cases in step 1
3) Calculate the difference in costs for each building element
4) Sum costs for all building elements for which costs increase to meet the tornado loads

The design wind and tornado pressures are calculated as described in Section 4. Whether design tornado pressure loads control over wind pressure loads varies by building type, location, and exposure category. Below are the four design loads used for selection and cost estimation of the building element constructions and the range of design tornado loads as a percentage of wind load:

- MWFRS Roof Field: -79 % to +144 %
- Zone 2 Roof Uplift C&C pressure, EWA 10 ft^2 (0.93 m^2): -89 % to +30 %
- Zone 1' Roof Net Uplift[11]: -92 % to +137 %
- Zone 4 C&C Pressure, EWA 75 ft^2 (6.97 m^2): -87 % to +52 %

Clearly, design tornado loads will not control in some cases while in other cases there are large load increases. In general, the tornado loads have a greater percentage increase relative to the existing load requirements for the high school, buildings with Exposure B, and locations in the central and southern United States.

The results of the school case studies suggest that tornado loads will not control for many locations and building types. Construction designs for both the elementary school and high school with either Exposure B and C located in Mobile, Washington D.C., and Denver remained unchanged. Additionally, the elementary school in Charlotte is unchanged with either Exposure B or C and the high school in Charlotte is unchanged with Exposure C. For those scenarios in which the tornado load does control, the construction design is often not influenced. For the elementary school, the construction design for Chicago and Minneapolis with either Exposure B or C and DFW with Exposure C are unchanged. For high school, the construction for Chicago, Minneapolis, and Charlotte with Exposure C are unchanged.

Even for the scenarios in which designing to meet the tornado load does control design, the incremental construction cost increase is minimal. For the elementary school, only three locations realize higher costs – Kansas City and Memphis with either Exposure B or C and DFW with Exposure B, ranging from approximately \$28 000 to \$29 500 (0.13 % to 0.14 % of project budget) with Exposure B and \$2135 (0.01 % of project budget) or less with Exposure C. For the high school, more cities realize higher costs for at least one exposure category because the high school has a larger building footprint. However, the cost impact relative to the project budget remains minimal. Charlotte, Chicago, and Minneapolis realize cost impacts with Exposure B while DFW, Kansas City, and Memphis realize cost impacts with either Exposure B or C. The cost impacts with Exposure C range from approximately \$22 000 to \$27 686 (0.01% of project budget) while the cost impacts with Exposure B range from \$2391 to \$255 530 (0.001 % to 0.13 % of project budget) or less with Exposure C.

The results of the case studies show that tornado loads can vary significantly, from less than wind loads to more than double the wind loads. Tornado loads will not control for many locations and building types, particularly those on the periphery of the tornado-prone region. For scenarios in which the tornado loads do control, the construction design is often not influenced. Of the nine cities considered in this study, three realize cost increases for at least one exposure category for the elementary school and six for high school. Of all the building

[11] Zone 1' Roof Net Uplift is a function of Roof Uplift C&C pressure, EWA 200 ft^2 (18.58 m^2) = 0.6* Uplift - 3

type – location – exposure combinations (36), only six (three for each building type) realize cost impacts greater than 0.07 % of the project budget.

7.2. Limitations

Determining how the tornado load provisions of ASCE 7-22 will impact construction costs across the entire U.S. is complicated because of the variability in building types, typical construction practices, and tornado and non-tornado related wind loads. Additionally, a lack of resources (data and labor) limited the scope of this study. Below is a non-exhaustive list of limitations identified for this study.

There is a lack of data necessary to quantify the share of new construction that may be impacted by the code change proposal with great precision. First, the data available for this study is the existing building stock data from HAZUS. Therefore, this study assumes that the existing building stock is representative of new construction. Second, the HAZUS data building type categories are not as precise as necessary to perfectly match language in ASCE 7-22 defining Risk Category III and IV buildings. For example, buildings labeled as "medical office and entertainment" in HAZUS are categorized as Risk Category III and IV although though many of these buildings may not meet the definitions of Risk Category III or IV (e.g., small dental office in a strip mall or a residence by be included in the HAZUS database as medical office). Therefore, this study overestimated (setting an upper bound on) the fraction of the building stock potentially impacted by the code change proposal.

There are several limitations on the cost analysis that should be highlighted. This study completes cost analysis for only two case studies (elementary school and high school). Huckabee specializes in school construction and could provide detailed cost data for the DFW area. Therefore, the focus of the cost analysis is on schools and leverages city cost indexes to adjust the estimated costs provided by Huckabee to apply to other cities. A more rigorous analysis using detailed cost data for each location, other building types, and different construction practices (e.g., typical school size and geometry) would provide more robust results that could provide a more holistic economic analysis of the total impacts across the U.S. of adopting the code change proposal. However, given limited resources and time, such an analysis was not feasible for this study.

Additionally, this cost study considered primary structural steel, foundation concrete and reinforcing, exterior wall stud costs, and roof deck and roofing assemblies. It does not include other building element costs that may be impacted by the proposal, including but not limited to rooftop equipment (including anchorages), or miscellaneous steel.

Glazing varies significantly across buildings, even within the same building type. However, to get a general magnitude estimate, Huckabee obtained information from a window manufacturer to ballpark the worst-case additional glazing cost for a high school. The cost of glass is not expected to increase while the aluminum mullion costs would rise slightly. Assuming a base case of 32.1 psf (1537 N/m^2) Exposure C pressure, the incremental cost increases would not exceed 0.36/ft^2 or \$10 852 due to more significant framing to meet the higher pressure (35.2 psf or 1685 N/m^2) for Memphis. Kansas City and DFW would realize even lower cost increases of \$8402 and \$2800, respectively. With general magnitudes of \$10 000 or less for a typical high school in DFW with a footprint of roughly 380 000 ft^2

(35 303 m^2), these additional costs would have negligible impacts on the construction costs of schools.

Another limitation of this study is that it excludes any economic benefits and avoided costs from adoption of ASCE 7-22. Avoided costs include the estimated repair costs and lost service time for the building from a potential future tornado strike. Projected benefits include improved life safety, resulting in avoided fatalities and injuries from potential future tornado strikes. Other benefits and avoided costs include those related to the additional building protection from potential non-tornadic windstorms.

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Appendix: Wind-borne Debris Impact on Roof Systems

Neither the IBC nor ASCE 7-22 have wind-borne debris (WBD) requirements for roof systems in either the hurricane Wind-borne Debris Region or tornado-prone region. However, WBD can penetrate most roof coverings (including all the coverings included in this study). To avoid water leaking into a building after the roof is penetrated by WBD, a secondary membrane is needed.

For example, the hospital with the concrete deck has a modified bitumen membrane over the deck. The purpose of this membrane is to protect the insulation from moisture migrating from the concrete. However, it also functions as a secondary membrane if the primary membrane is punctured by WBD. Secondary membranes are particularly important for buildings such as hospitals that need to remain functional after a storm, because without a secondary membrane, water leakage from a punctured roof membrane can preclude building occupancy.

A secondary membrane can be incorporated into a roof system that is over a steel deck. For example, a modified bitumen membrane could be applied to a cover board that is mechanically attached to the deck. The remainder of the roof system could then be adhered to the secondary membrane. WBD roof system design guidance is provided for hurricanes and tornadoes in Ref. [28, 29].