Tornado Awareness and Risk Mitigation
February 15, 2022
Housekeeping

• This session is being recorded
• Materials from today’s webinar, including the presentations, will be posted to the Code Council web site
• Participants will receive a follow up email and link in the coming days
• We encourage you to participate in the Q&A!
• We will stay on for a short time following the scheduled end of the webinar
Today’s Panelists

Marc Levitan
NIST

Pataya Scott
FEMA

Donald Scott
PCS Structural Solutions

Larry Novak
International Code Council

Karl Fippinger
International Code Council
Background for Today’s Webinar

• FEMA Mitigation Assessment Team (MAT) concept
  – Observes building performance under severe hazard events
  – Provides design and construction strategic recommendations for reducing damage and protecting lives in hazard areas

• Pre-Mat - Kentucky Tornadoes - December 18-23, 2021
  – Visited over 600 individual sites in 4 days
  – Documented trends in building performance
  – Documented storm shelter construction and performance
Tornado Awareness and Risk Mitigation
I-Codes

Larry Novak, SE, F. SEI, F. ACI, CERT, LEED AP
Chief Structural Engineer
Codes and Standards Development
International Code Council
Outline

• Tornado Devastation

• 2022 I-Codes
  – IBC International Building Code
  – IRC International Residential Code
  – IEBC International Existing Building Code

• ICC 500-2020: Standard for the Design and Construction of Storm Shelters
Emergency Facilities
Large Structures
Single Family Residential
Single Family Residential
Shelters? Reinforced Concrete ‘vault’ in building
Example of a Modern ICC 500 Shelter
Example of a Modern ICC 500 Shelter
I-Codes
Complete Load Path Required:

Example: IRC Section R301.1:
... The construction of buildings and structures in accordance with the provisions of this code shall result in a system that provides a complete load path that meets the requirements for the transfer of loads from their point of origin through the load-resisting elements to the foundation. ...
When is a **Storm Shelter Required**, Per the IBC Section 423:

- Storm shelters constructed in accordance w/ IBC & ICC 500
- Can be Independent or Within Host Buildings
- Required for (in areas of ICC 500 design wind speed 250 mph):
  - **Critical Emergency Operations**
    - 911 Call Stations, Emergency Operation Centers, Fire, Rescue, Ambulance & Police Stations
  - **Group E Occupancies (Educational thru 12 grade)**
    - Except: day care facilities, accessory to places of religious worship, buildings meeting the requirements for shelter design in ICC 500

Note: IEBC requires storm shelters to be added in schools with additions that hold greater than 50 occupants (Section 303.2)
Group E Required Occupant Capacity of Storm Shelters, Per the IBC Section 423:

Occupant Capacity shall include all of the Buildings on the Site and shall be the greater of the following:

- Total occupant load of classrooms, vocational rooms and offices in Group E
- Occupant load of the largest indoor assembly space associated with Group E w/Exceptions (see Section 423.5.1)
Requirements in the IRC Section R323;
If Storm Shelter is constructed:

• Storm Shelters Shall be Constructed in Accordance w/ ICC 500:
  • Constructed as Detached Buildings or
  • Constructed as Safe Rooms within building

• Permit Required, Construction Documents prepared and sealed by *Registered Design Professional* indicating meets ICC 500
  • Except: components listed and labeled compliance with ICC 500
ICC 500-2020:

- Standard for the Design and Construction of Storm Shelters
- Establish minimum requirements to safeguard the public health, safety and general welfare relative to the design, construction and installation of storm shelters constructed for protection from tornadoes, hurricanes and other severe windstorms.
- Standard under continuous maintenance
ICC 500-2020: Design Wind Speeds, VT, for Tornadoes

Wind Speeds

- 130 MPH
- 160 MPH
- 200 MPH
- 250 MPH

Notes:
1. Values are nominal three-second gust wind speeds in miles per hour at 33 feet above ground for Exposure Category C.
2. Multiply miles per hour by 0.447 to obtain meters per second.
3. Location-specific storm shelter design wind speeds shall be permitted to be determined using the ATC Hazards by Location web site: https://hazards.atcouncil.org/
Tornado Awareness and Risk Mitigation
I-Codes

Larry Novak, SE, F. SEI, F. ACI, CERT, LEED AP
Chief Structural Engineer
Codes and Standards Development
International Code Council
FEMA Building Science Activities
Tornado Shelter and Safe Room Observations

FEMA Mitigation Assessment Team (MAT) & Formal Observation Reports

1999
Oklahoma and Kansas
(FEMA 342)

2011
Alabama and Missouri
(FEMA P-908)

2013
Moore, Oklahoma
(FEMA P-1020)
Bremen, KY

- Shelters very likely saved lives
  - 12 confirmed deaths in Bremen
  - 24 people took shelter in these two
    - Underground (8) installed early 2010s
    - Aboveground (16) constructed late 1970s or 80s
Tornado Shelter and Safe Room Observations

Gibson County, TN – Kenton Elementary School Safe Room

Good morning,

I just wanted to pass along a big THANK YOU! As I am sure you are aware, one of our schools who received a FEMA Safe Room Grant was able to open up on Friday Night during the tornadic activity. The storm shelter was full of community members from Kenton, TN. Kenton took a direct hit and over 50 homes were destroyed but no lives lost. I believe the shelter played a key role in no lives lost. I just wanted to pass this along and let you know how important your work is to saving lives!

Local Correspondence sent to TEMA, 12/15/21
FEMA P-320 (2021) Overview

- Safe room guidance is primarily intended for homeowners, builders, and contractors
- Updated scope addresses safe rooms for 1- and 2-family dwellings only
- Expanded consumer guidance and information on prefabricated safe rooms
- Prescriptive safe room design plans
How to Determine if You Need a Safe Room

Tornado Zones
- Zone I
- Zone II
- Zone III
- Zone IV

Coastal Wind Regions
- Hurricane-Prone Regions
- Coastal high winds

AMERICAN SAMOA, GUAM, NORTHERN MARIANA ISLANDS
PUERTO RICO, VIRGIN ISLANDS
FEMA P-361 (2021) Overview

- Covers community and residential safe rooms
- Planning, and operations and maintenance considerations
- Detailed design and construction criteria for hurricane, tornado, and combined safe rooms

NOTE
FEMA P-361 (2021) UPDATES

FEMA P-361 (2021) features clarified and updated guidance and revised guidance to reflect another 6 years of post-damage assessments and lessons learned following hurricanes and tornadoes, as well as research in the ever-growing field of wind engineering and safe rooms and storm shelters.
Both safe rooms and storm shelters provide life-safety protection from hurricanes and tornadoes.

Storm shelters must comply with ICC 500 (most recent edition is 2020).

FEMA-funded safe rooms must comply with the latest editions of ICC 500 and FEMA Funding Criteria provided in FEMA P-361.

The latest FEMA Funding Criteria is slightly more conservative for select flood siting and fire safety criteria.

Because safe rooms comply with ICC 500, they also qualify as storm shelters.

- **NOT all storm shelters are safe rooms**
- **All safe rooms are storm shelters**
As of February 2020, FEMA grant programs have provided approximately $1.2 billion in federal funds for safe rooms

- Nearly 26,300 residential safe rooms
- Over 2,200 community safe rooms
- 26 states and territories

**HMA Unified Guidance:** [www.fema.gov/hazard-mitigation-assistance](http://www.fema.gov/hazard-mitigation-assistance)

**State Hazard Mitigation Officer (SHMO):** [https://www.fema.gov/state-hazard-mitigation-officers](https://www.fema.gov/state-hazard-mitigation-officers)
Safe Room Resources

FEMA Safe Room Resources Webpage
https://www.fema.gov/emergency-managers/risk-management/safe-rooms/resources

Additional Resources

- Community Tornado Safe Room Doors Installation and Maintenance Fact Sheet
- Best Available Refuge Area Checklist
- Residential Tornado Safe Room Doors Fact Sheet
- Foundation and Anchoring Criteria for Safe Rooms Fact Sheet
- Flood Hazard Elevation and Siting Criteria for Community Safe Rooms
- Flood Hazard Elevation and Siting Criteria for Residential Safe Rooms
- Additional One-Page Safe Room Resources
Design of Buildings for Tornadoes

Marc L. Levitan, Ph.D.
Lead Research Engineer, National Windstorm Impact Reduction Program

ICC Tornado Awareness and Risk Mitigation Webinar
Feb. 15, 2022
Why Haven’t We Considered Tornadoes in Conventional Engineering Design?

Common Misperceptions

• Too rare
• Losses from tornadoes are small compared to other hazards
• Nothing we can do about them
• Inadequate knowledge
• Buildings would all have to be concrete bunkers
• Too expensive

Perceptions may be shaped by the few violent tornadoes per year that make the headlines
How Rare are Tornadoes?

This plot shows the number of *reported* tornadoes per year. Many tornadoes go unreported.
Tornadoes occur at many places across the globe, on all continents except Antarctica.


Source: NIST, from NOAA data
Tornadoes kill more people per year in the U.S. than hurricanes and earthquakes combined.

Tornado fatalities overwhelmingly occur inside buildings.

High Tornado Death Toll
5,600 killed (1950 – 2011)

Average deaths/year:
- Tornadoes: 91.6
- Hurricanes: 50.8
- Earthquakes: 7.5

Moore OK Tornado – 2013. Damage to the hallway and classrooms of the new main classroom building (complete loss of roof and many walls) where the 7 fatalities occurred (most of the debris has already been removed). This hallway area was a “designated area of safety.” NIST SP 1164 (2013)
We can design for mother nature’s worst
FEMA Safe Rooms are designed for ‘near-absolute’ life safety protection, ICC 500 Storm Shelters have almost identical requirements

- 250 mph tornado winds
- Impact of 15-pound 2x4 traveling at 100 mph
- No reported failures of safe rooms or shelters constructed to FEMA or ICC 500 requirements
Over the 20-year period, 1997 to 2016, events involving tornadoes, including other wind, hail and flood losses associated with tornadoes made up 39.9% of total catastrophe insured losses, adjusted for inflation.

Hurricanes and tropical storms were a close second largest cause of catastrophe losses, accounting for 38.2% of losses.
Isn’t Most Damage Caused by the Big Tornadoes?

Property damage and resulting losses per individual tornado (black curve) increase dramatically with EF rating.

However, aggregate losses for all tornadoes per EF number (red curve) are of the same magnitude (except EF0)

- because there are so many more tornadoes with lower intensities

Source: NIST (2014)  
https://doi.org/10.6028/NIST.NCSTAR.3
We don’t *have* to design everything to withstand the most violent tornadoes in order to significantly reduce tornado damage.

From 1995-2016, of the over 1,200 tornadoes/year
* **89.1%** were EF0-EF1, **97.1%** were EF0-EF2

Most of the area impacted by a tornado does not experience the greatest winds, e.g., in the 2011 EF-5 Joplin Tornado (NIST, 2014)
* **72%** of area swept by tornado experienced EF0-EF2 winds
* **28%** experienced EF3-EF5 winds
Paradigm Shift Needed

Ignoring tornado hazards in the design of our built environment is not an appropriate response
The first tornado study to include storm characteristics, building performance, emergency communication and human behavior together - with assessment of the impact of each on fatalities

16 recommendations for improving:

• Tornado hazard characterization
  R3 - develop new tornado hazard maps considering spatial estimates of tornado hazard

• Design and construction of buildings and shelters in tornado–prone regions
  R5 - develop performance-based tornado-resistant design standards
  R6 - develop tornado design methodologies

• Emergency communications that warn of threats from tornadoes

NOTE: Summaries of the recommendations are provided in this presentation for context. The complete recommendations are available in the final report, available through the link shown at left.
Map Development Overview

- Tornado Risk Mapping Project Components
  - Six year effort, working with Applied Research Associates, Inc. (ARA) under contract to NIST, led by Dr. Larry Twisdale
  - The US Nuclear Regulatory Commission supplemented NIST funding to include the analysis of epistemic uncertainties

Tornado Hazard Maps

Primary Data Sources
- Databases:
  - SPC
  - Storm Data
  - DAT
  - Census, Hazus Data
- Literature
- Augmented Database

Regional Climatology
- Tornado Metrics
- Physiographic Metrics
- Develop Regions/Subregions

Models/Analytics
- Reporting Trends, Eras
- Bias Analysis
- Occurrence Rate
- EF System
- Random Encounter
- Tornado Path Variables

Tornado Data

Tornado Windfield
- Engineering Model
  - Single Cell Vertex
  - Probabilistic Parameters
    - Intensity, RMW
    - Velocities, Profiles
    - Swirl
- Swath Model
  - PUV
  - Path Width
  - RMW
  - Path Edge Wind Speeds
  - Spline Fitted PUV

Wind Field Hazard/Risk Models
- Stochastic Model
  - ARA TORRISK2
  - Single/Two Loop Simulations
  - Building/Facility Size Effects
  - Wind Speed Frequencies
  - Hazard Curves
- Hazard Curves

Wind Speeds
- Model Components
  - Tornado Strike
  - TORDAM (3D)
  - Prob. Load/Resistance
  - Progressive Failures
  - WBD
  - Internal Pressure
  - EF Scale, Dis, DODs
  - Building Stock Dist.

Epistemic Uncertainties
- Model/Parameter Uncertainties
- Derived Mean Frequencies

Tornado Hazard Maps
- Spatial Smoothing
- Return Period
Tornado risk and tornado speeds are a function of building or facility size and shape (effective plan area)

- Tornado strike probabilities increase with increasing plan area of the target building or structure (target size)
- For a given return period (i.e., mean recurrence interval), tornado speeds increase with increasing target size
### Tornado Hazard Maps - Examples

<table>
<thead>
<tr>
<th>Effective Plan Area, $A_e$ (ft$^2$)</th>
<th>Risk Category III (1,700 Year)</th>
<th>Risk Category IV (3,000 Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10K</td>
<td><img src="image1" alt="Map" /></td>
<td><img src="image2" alt="Map" /></td>
</tr>
<tr>
<td>111</td>
<td></td>
<td>99</td>
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<tr>
<td>1M</td>
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<td><img src="image4" alt="Map" /></td>
</tr>
<tr>
<td>111</td>
<td></td>
<td>125</td>
</tr>
</tbody>
</table>

- Tornado speeds are 3-s peak gusts in mph at 33 ft (10 m) height
- 8 mapped effective plan area sizes, $A_e$ (target sizes), from 1 to 4M sq ft
- Mapped tornado speeds also developed for longer return periods
  - 10,000 years
  - 100,000 years
  - 1,000,000 years
  - 10,000,000 years
Tornadic Wind Characteristics

Very different from straight-line winds
- Short duration
- Rapidly changing speeds and directions
- Strong updrafts
- Decreasing speed with height above ground
- Atmospheric Pressure Change

Worked closely with mobile radar community
- Analyzed radar-measured tornado wind speeds
- Developed tornado velocity pressure profiles

Normalized Tornado Velocity Profiles

Source: NSF
Tornadic Wind-Structure Interaction

**Very different from straight-line winds**

- Short duration
  - Changes to gust effect factor
- Rapidly changing speeds and directions
  - Changes to directionality factor
- Strong updrafts
  - Addition of new factor to account for increase in uplift pressures on roofs

Conducted wind tunnel tests to simulate the effective change in wind angle at the leading edge of the roof

- Decreasing speed with height above ground
  - Changes to velocity pressure exposure coefficient
- Atmospheric Pressure Change
  - Changes to internal pressure coefficient to account for contributions of APC
ASCE/SEI 7-22
Tornado Provision Highlights

Marc Levitan
Chair
ASCE 7-22 Tornado Task Committee
Tornado Loads - New in ASCE 7-22

NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory (NSSL).
Tornado Loads: Placement in 7-22

- **Chapter 1: General**
  - Add Tornadoes to Risk Categorization Table 1.5-1

- **Chapter 2: Load Combinations**
  - Add Tornado Loads to load combinations

- **Chapter 26: Wind Loads**
  - Add requirement to check Tornado Loads per Ch. 32

- **New Chapter 32: Tornado Loads**
  - Complete provisions to determine Tornado Loads

- **New Appendix G: Tornado Hazard Maps for Long Return Periods**
  - Tornado speed maps for longer return periods, in support of tornado PBD and other applications

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**Table 1.5-1 Risk Category of Buildings and Other Structures for Flood, Wind, Tornado, Snow, Earthquake, and Ice Loads**

<table>
<thead>
<tr>
<th>Use or Occupancy of Buildings and Structures</th>
<th>Risk Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings and other structures that represent low risk to human life in the event of failure</td>
<td>I</td>
</tr>
<tr>
<td>All buildings and other structures except those listed in Risk Categories I, III, and IV</td>
<td>II</td>
</tr>
<tr>
<td>Buildings and other structures, the failure of which could pose a substantial risk to human life</td>
<td>III</td>
</tr>
<tr>
<td>Buildings and other structures designated as essential facilities</td>
<td>IV</td>
</tr>
<tr>
<td>Buildings and other structures, the failure of which could pose a substantial hazard to the community</td>
<td></td>
</tr>
<tr>
<td>Buildings and other structures required to maintain the functionality of other Risk Category IV structures</td>
<td></td>
</tr>
</tbody>
</table>
Ch. 32: Tornado Loads

- Built on ASCE 7 wind load procedures framework
  - Designed to provide similar look and feel with the wind provisions for improved ease of use
- Most wind load coefficients and equations are modified to account for differences in tornadic wind and wind-structure interaction
- Despite similarities in procedures, tornado loads are treated separately from wind loads

32.1 PROCEDURES

32.1.1 Scope Building and other structures classified as Risk Category III or IV and located in the tornado prone region as shown in Figure 32.1.1, including the main wind force resisting system (MWFRS) and all components and cladding (C&C) thereof, shall be designed and constructed to resist the greater of the tornado loads determined in accordance with the provisions of this chapter or the wind loads determined in accordance with Chapters 26 through 31, using the load combinations provided in Chapter 2.

User Note: The tornado loads specified in this chapter provide reasonable consistency with the reliability delivered by the existing criteria in Chapters 26 and 27 for MWFRS and, therefore are only required for Risk Category III and IV buildings and other structures (see Return Period discussion in Section C32.5.1 for more information). The tornado loads are based on tornado speeds using 1,700- and 3,000-year return periods for Risk Category III and IV, respectively (which are the same return periods used for basic wind speeds in Chapter 26). The tornado speed at a given geographic location will range from approximately Enhanced Fujita Scale EF0 – EF2 intensity, depending on the risk category and effective plan area of the building or other structure (see Section C32.5.1).

Options for protection of life and property from more intense tornadoes include construction of a storm shelter and/or design for longer return-period tornado speeds as provided in Appendix G, including performance-based design. A building or other structure designed for tornado loads determined exclusively in accordance with Chapter 32 cannot be designated as a storm shelter without meeting additional critical requirements provided in the applicable building code and ICC 500, the ICC/NSSA Standard for the Design and Construction of Storm Shelters. See Commentary Section C32.1.1 for an in-depth discussion on storm shelters.

32.1.2 Permitted Procedures The design tornado loads for buildings and other structures, including the MWFRS and C&C elements thereof, shall be determined using one of the procedures as specified in this section and subject to the applicable limitations of Chapters 26 through 32, excluding Chapter 28.

An outline of the overall process for the determination of the tornado loads, including section references, is provided in Figure 32.1.3.

32.1.2.1 Tornado Loads on the Main Wind Force Resisting System Tornado loads for the MWFRS shall be determined using one or more of the following procedures, as modified by Chapter 32:

1. Directional Procedure for buildings of all heights as specified in Chapter 27 for buildings meeting the requirements specified therein;
2. Directional Procedure for Building Appurtenances (such as rooftop structures and rooftop equipment) and Other Structures (such as solid freestanding walls and solid freestanding signs, chimneys, tanks, open signs, single-plane open frames, and raised towers as specified in Chapter 29) for buildings meeting the requirements specified therein; or
3. Wind Tunnel Procedure for all buildings and all other structures as specified in Chapter 31 for buildings meeting the requirements specified therein.

32.1.2.2 Tornado Loads on Components and Cladding Tornado loads on the C&C of all buildings and other structures shall be determined using one or more of the following procedures, as modified by Chapter 32:

1. Analytical Procedures as specified in Parts 1 through 5, as appropriate, of Chapter 30, for buildings meeting the requirements specified therein; or
2. Wind Tunnel Procedure for all buildings and all other structures as specified in Chapter 31, for buildings meeting the requirements specified therein.

32.1.3 Performance-Based Procedures Tornado design of buildings and other structures using performance-based procedures shall be permitted subject to the approval of the Authority Having Jurisdiction. The performance-based tornado design procedures used shall, at a minimum, conform to Section 1.3.1.3 and be documented and submitted to the Authority Having Jurisdiction in accordance with Section 1.3.1.3.

3.2 DEFINITIONS
The following definitions apply to the provisions of Chapter 32. Terms not defined in this chapter shall be defined in accordance with Chapters 26 through 31, as appropriate, excluding Chapter 28.

ASCE TORNADO DESIGN GEODATABASE: The ASCE database version 2020-1.0 of geocoded tornado speed design data.

OTHER STRUCTURES, SEALED: A structure that is completely sealed or has controlled ventilation such that tornado-induced atmospheric pressure changes will not be transmitted to the inside of the structure, including but not limited to certain tanks and vessels.

TORNADO-PRONE REGION: The area of the contiguous United States most vulnerable to tornadoes, as shown in Figure 32.1.1.
Scope

- Risk Category III and IV buildings and other structures
- Located in the tornado-prone region
- Design of MWFRS and C&C
- Must resist the greater of tornado loads or wind loads, using load combinations in Chapter 2
User Note

- Highlights key features/ explanations of tornado load provisions
- Design tornado speeds range from 60-138 mph, approximately EF0-EF2 intensity,
  - Dependent on Risk Category, geographic location, and effective plan area (target size)
- Return periods for Risk Category III and IV are 1,700 and 3,000 years, respectively (the same as used for wind loads)
- Options for protection from more intense tornadoes include storm shelters and PBD
- Tornado shelters cannot be designed solely using Chapter 32 – pointers to commentary

User Note: The tornado loads specified in this chapter provide reasonable consistency with the reliability delivered by the existing criteria in Chapters 26 and 27 for MWFRS, and therefore are only required for Risk Category III and IV buildings and other structures (see Return Period discussion in Section C32.5.1 for more information). The tornado loads are based on tornado speeds using 1,700- and 3,000-year return periods for Risk Category III and IV, respectively (which are the same return periods used for basic wind speeds in Chapter 26). The tornado speed at any given geographic location will range from approximately Enhanced Fujita Scale EF0 – EF2 intensity, depending on the risk category and effective plan area of the building or other structure (see Section C32.5.1). Options for protection of life and property from more intense tornadoes include construction of a storm shelter and/or design for longer-return-period tornado speeds as provided in Appendix G, including performance-based design. A building or other structure designed for tornado loads determined exclusively in accordance with Chapter 32 cannot be designated as a storm shelter without meeting additional critical requirements provided in the applicable building code and ICC 500, the ICC/NSSA Standard for the Design and Construction of Storm Shelters. See Commentary Section C32.1.1 for an in-depth discussion on storm shelters.
Conducted a series of risk informed analyses to compare the proposed tornadic wind load criteria with the reliability delivered by the existing (ASCE 7-16) wind load provisions

- Collaboration between ASCE 7 Load Combinations Subcommittee and Wind Load Subcommittee
- Adaptation of the reliability analysis used for ASCE 7-16 wind maps

### Key Finding
Using 1,700- and 3,000-year maps for Risk Category III and IV, respectively, the tornadic wind load criteria provide reasonable consistency with the reliability delivered by the existing criteria in Chapters 26 and 27 for main wind force-resisting systems.

### ASCE 7-22 Wind and Tornado Map Return Periods

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Ch. 26 Wind Return Period (years)</th>
<th>Ch. 32 Tornado Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>300</td>
<td>n/a</td>
</tr>
<tr>
<td>II</td>
<td>700</td>
<td>n/a</td>
</tr>
<tr>
<td>III</td>
<td>1,700</td>
<td>1,700</td>
</tr>
<tr>
<td>IV</td>
<td>3,000</td>
<td>3,000</td>
</tr>
</tbody>
</table>

No significant tornado risk at 300 and 700 year return periods
A flowchart is provided at the beginning of Chapter 32 identifying the process to determine where design for tornado loads are not required

- **Steps 1 and 2** – per Section 32.1.1
- **Steps 3 and 4** – per Section 32.5.2
  - The tests on $V_T$ represent approximate threshold tornado speeds at which tornado loads might begin to control some aspect of the wind load design
  - For step 4, the Basic Wind Speed $V$ and the exposure category are determined accordance with Ch. 26, based on the exposure resulting in the greatest wind loads for any wind direction at the site
Tornado loads are more likely to control at least some element(s) of the wind load design for structures that

- are located in the central and southeast US (except near the coast where dominated by hurricanes)
- are Risk Category IV
- are designated as Essential Facilities
- have large effective plan areas
- are located in Exposure B
- have low mean roof heights
- are classified as enclosed buildings for wind loads

Tornado loads can control over wind loads when tornado speeds are as little as half of the basic wind speeds

Where tornado loads control, design uplift pressures on roofs will typically increase. This will help reduce the most common tornado and other windstorm failures.
Example: 2-Story Elementary School
MWFRS Mid-Roof Uplift Pressure Ratios
Risk Category III
Effective Plan Area = 100,000 ft²
Exposure B

Uplift pressures in the field of the roof are almost double the straight-line wind pressures, across much of the central and southeast US

Legend
- Outside Tornado-Prone Region
  - \( V_t < 60 \text{ (mph)} \) OR
  - \( V_t < 0.5V \) (for Exposure B)
- Ratio of Tornado design pressure to Wind design pressure, \( \left( \frac{p_t}{p} \right) \)
  - < 1.0
  - 1.0
  - Max \( \left( \frac{p_t}{p} \right) = 2.02 \) for Exp B
  - ≤ 1.46 for Exp C (not shown)

Where Will Tornado Loads Control?
It depends on a number of variables.

1 mph = 0.447 m/s
Tornados will control uplift in the field of the roof over most of the eastern 2/3 of the US for this specific example building.
ASCE/SEI 7-22
Emerging Trends in Wind Design Safety for the Architectural and Engineering Community

Donald R. Scott, P.E., S.E., F.SEI, F.ASCE
Chair ASCE 7 Wind Load Subcommittee
February 15, 2022
Case Study of New Tornado Load Provisions

Objectives

- Compare MWFRS and C&C pressures between ASCE 7-16 (non-tornado) and tornado provisions in the DFW Area
- Consider cost impact

Facilities

- Risk Category III
  - New Elementary School, $V_T = 90\text{ mph}$
  - New High School, $V_T = 102\text{ mph}$
- Risk Category IV
  - New Fire Station, $V_T = 97\text{ mph}$
  - New Hospital Campus, $V_T = 123\text{ mph}$

Key Variables

- Assumed Effective Plan Areas (ft²):
  - Elementary school: 100K
  - High schools: 500K
  - Fire stations: 15K
  - Hospital campuses: 1M
- Assumed mean roof heights:
  - Elementary & high schools (two-story): 33 ft
  - Fire stations: 20 ft
  - Hospital campuses (mostly five-story buildings): 80 ft
- Exposure B & C considered
- Enclosure for tornado loads
  - Elementary & high schools: no impact-resistant glazing = partially enclosed
  - Fire stations & hospitals: require impact-resistant glazing = enclosed
  - For basic ASCE 7-16 wind loads, all buildings in this study are enclosed

Case study by Benchmark Harris and Blake Haney, with Huckabee, Inc. Information and graphics used with permission.
#### Key Takeaways

- Overall/net lateral force **higher** than basic ASCE 7-16 wind forces for high schools or essential facilities, but likely negligible impact on structure cost.

- Mainly see increases in MWFRS uplift (greater foundation anchorage demands).

<table>
<thead>
<tr>
<th>Case</th>
<th>(C_p)</th>
<th>(K_{eq})</th>
<th>(K_{st})</th>
<th>(G_{m4}/G_{m3})</th>
</tr>
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<tbody>
<tr>
<td>Windward</td>
<td>0.8</td>
<td>0.8</td>
<td>1</td>
<td>neg</td>
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<tr>
<td>Leeward</td>
<td>-0.2</td>
<td>0.8</td>
<td>1</td>
<td>pos</td>
</tr>
<tr>
<td>Uplift Edge</td>
<td>-0.9</td>
<td>0.8</td>
<td>1.1</td>
<td>pos</td>
</tr>
<tr>
<td>Uplift Field</td>
<td>-0.3</td>
<td>0.8</td>
<td>1.1</td>
<td>pos</td>
</tr>
</tbody>
</table>
Case Study of New Tornado Load Provisions
C&C – Effective Wind Area = 200 sf

**KEY TAKEAWAYS**

- **Highest RELATIVE** (percentage) impact is on Zones 1 and 1’ (higher net uplift for roof framing)
- Uplift in Zone 2 and 3 of Essential Facilities may increase cost of non-structural roof items (roofing assemblies, RTUs, etc)

<table>
<thead>
<tr>
<th>Zone 1</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.1 (+25%)</td>
<td>42.1 (+25%)</td>
<td>42.1 (+25%)</td>
<td>42.1 (+25%)</td>
</tr>
<tr>
<td>33.1 (+15%)</td>
<td>33.1 (+15%)</td>
<td>33.1 (+15%)</td>
<td>33.1 (+15%)</td>
</tr>
</tbody>
</table>

EWA @ < 10 sf

Case Study by Benchmark Harris and Blake Haney, with Huckabee, Inc. Information and graphics used with permission.
Case Study of New Tornado Load Provisions

This cost study only considered primary structural steel, foundation concrete and reinforcing, and exterior wall stud costs.

It did not include other costs, including but not limited to:

- roofing assemblies
- rooftop equipment (including anchorages)
- miscellaneous steel
- glazing

### ADDITIONAL COSTS DUE TO TORNADO PROVISIONS:

#### EXPOSURE B

<table>
<thead>
<tr>
<th>School Type</th>
<th>Steel</th>
<th>Diaph. Connection</th>
<th>Foundation Anchorage</th>
<th>Wall Studs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES</td>
<td>$24,240.30</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$24,120.00</td>
</tr>
<tr>
<td>HS</td>
<td>$139,777.61</td>
<td>$7,500.50</td>
<td>$20,000.00</td>
<td>$</td>
<td>$257,278.11</td>
</tr>
</tbody>
</table>

#### EXPOSURE C

<table>
<thead>
<tr>
<th>School Type</th>
<th>Steel</th>
<th>Diaph. Connection</th>
<th>Foundation Anchorage</th>
<th>Wall Studs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES</td>
<td>$24,240.30</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$24,240.30</td>
</tr>
<tr>
<td>HS</td>
<td>$139,777.61</td>
<td>$</td>
<td>$20,000.00</td>
<td>$</td>
<td>$159,777.61</td>
</tr>
</tbody>
</table>

Consider this in the context of the overall building cost:

<table>
<thead>
<tr>
<th>School Type</th>
<th>Budget</th>
<th>Cost Increase EXPOSURE B</th>
<th>Cost Increase EXPOSURE C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES</td>
<td>$20M</td>
<td>$48,360.30 +0.24%</td>
<td>$24,240.30 +0.12%</td>
</tr>
<tr>
<td>HS</td>
<td>$200M</td>
<td>$257,278.11 +0.13%</td>
<td>$159,777.61 +0.08%</td>
</tr>
</tbody>
</table>
ICC Tornado Awareness and Risk Mitigation

- Wind Speed Maps / ASCE Hazard Tool
- Velocity Pressure / Directionality Factor
- Elevated Buildings
- Roof Pressures for Load Cases
- Simplified Sloped Roof Pressure Coefficients
- Loads on Building Canopies
- Tornado Loads for Risk Category III & IV Structures
ICC Tornado Awareness and Risk Mitigation

Wind Speed Maps / ASCE Hazard Tool – https://asce7hazardtool.online – FREE!
Elevated Buildings

Figure C27.3-1. High-rise and low-rise examples of dimensions and heights used in Section 27.3.1.1.
Simplified Sloped Roof Pressure Coefficients

External Pressure Coefficients

Notation

\(a\) = 75% of the roof horizontal dimension on 0.45, whichever is smaller, but not less than either 4% of the roof horizontal dimension or 0.015 m (0.5 in). If an overhanging edge, the overhang distance shall be measured from the outside edge of the overhang. The horizontal dimension used to compute the edge distance shall not include any overhang dimensions.

\(a\) = horizontal dimension of building measured normal to sloping surface, except as indicated.

\(a\) = angle of roof from horizontal, degrees.

External Pressure Coefficients (QC)

Notes:

1. Vertical scale equals \(QC\) to be read with \(a\).
2. Partially overhanging roofs used to call out \(QC\) or \(Qp\).
3. Plan view of building, if pressure is applied to the area and away from the walls, respectively.
4. Each roof shown type of pressure used in design and irregular pressure.
5. Values of \(QC\) for not overhanging to be determined in accordance with Section 30.7 Roof Overhangs.

Figure 36.3-02: Components and labeling (\(a\) = 40 ft (12.2 m): external pressure coefficients, (QC), for enclosed, partially enclosed, and partially open buildings—gable roofs; 30° > \(a\) > 15°).
1.3.1.3 Performance-Based Procedures Structural and nonstructural components and their connections designed with performance-based procedures shall be demonstrated by analysis in accordance with Section 2.3.5 or by analysis procedures supplemented by testing to provide a reliability that is generally consistent with the target reliabilities stipulated in this section. Structural and nonstructural components subjected to dead, live, environmental, and other loads except earthquake, tsunami, flood, and loads from extraordinary events shall be based on the target reliabilities in Table 1.3-1. Structural systems subjected to earthquake shall be based on the target reliabilities in Tables 1.3-2 and 1.3-3. The design of structures subjected to tsunami loads shall be based on the target reliabilities in Table 1.3-4. Structures, components, and systems that are designed for extraordinary events using the requirements of Section 2.5 for scenarios approved by the Authority Having Jurisdiction shall be based on the target reliabilities in Table 1.3-5. The analysis procedures used shall account for uncertainties in loading and resistance.

32.1.3 Performance-Based Procedures Tornado design of buildings and other structures using performance-based procedures shall be permitted subject to the approval of the Authority Having Jurisdiction. The performance-based tornado design procedures used shall, at a minimum, conform to Section 1.3.1.3 and be documented and submitted to the Authority Having Jurisdiction in accordance with Section 1.3.1.3.
QUESTIONS?

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dscott@pcs-structural.com
FEMA P-320 - Taking Shelter from the Storm: Building or Installing a Safe Room for Your Home

FEMA P-361 - Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms

Community Tornado Safe Room Doors Installation and Maintenance Fact Sheet

Best Available Refuge Area Checklist

Residential Tornado Safe Room Doors Fact Sheet

Foundation and Anchoring Criteria for Safe Rooms Fact Sheet

Highlights of ICC 500-2020

Flood Hazard Elevation and Siting Criteria for Community Safe Rooms

Flood Hazard Elevation and Siting Criteria for Residential Safe Rooms

Additional One-Page Safe Room Resources