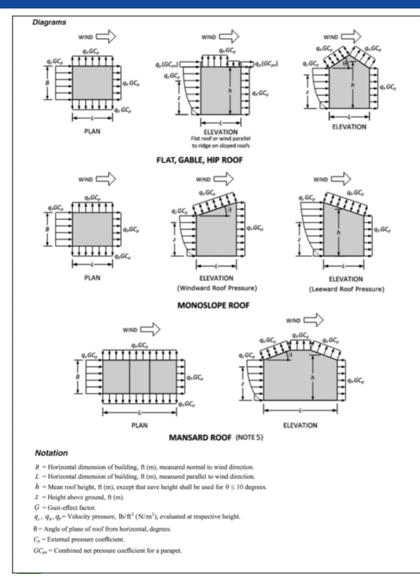
Unit 3

Tornado Load Coefficients and Equations

Unit 3 Outline

Tornado Load Coefficients and Equations

- Exposure, Topographic and Ground Elevation Effects
- Tornado Velocity Pressure
- Tornado Directionality and Gust Effect Factors
- Tornado Enclosure Classification, Internal Pressure Coefficients, and Protection of Glazed Openings
- Tornado External Pressure Coefficients
- Main Wind Force Resisting System Loads
- Components and Cladding Loads
- Wind Tunnel Method
- Summary



Unit 3: Learning Outcomes

- Upon completion of this unit, you will be able to :
  - **Explain** the differences between wind load and tornado load coefficients and equations
  - **Choose** appropriate values for the different tornado load coefficients
  - **Calculate** tornado velocity pressures and design pressures for various elements of a building or other structure
- This is important on the job because …
  - Establishes the foundation for calculation of tornado loads

Wadena Deer Creek High School
Wadena, Minnesota
June 17, 2010

Credit: FEMA

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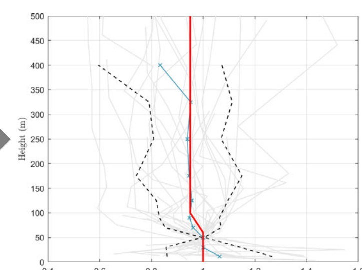
Tornadic Wind Characteristics

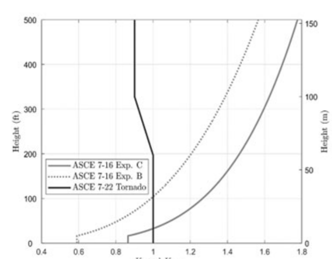
Very different from straight-line winds

- Short duration
- Rapidly changing speeds and directions
- Strong updrafts
- Decreasing speed with height above ground
- Atmospheric Pressure Change
- More intense windborne debris

Source: NSF



Normalized Tornado Velocity Profiles



ASCE 7-22 Velocity Pressure Profiles
for Tornadic and Straight-Line Winds

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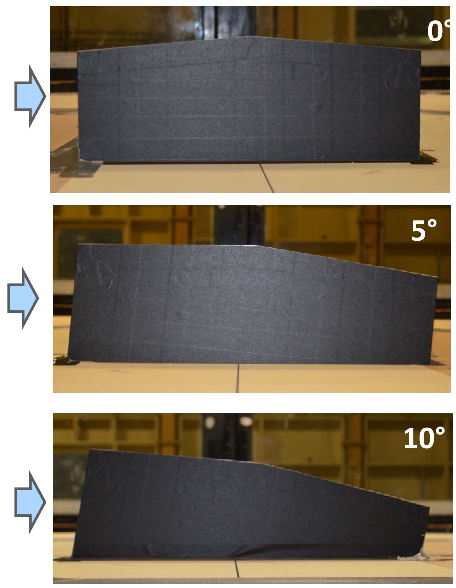
Tornadic Wind-Structure Interaction

Very different from straight-line winds

- Short duration
  - Changes to gust effect factor
- Rapidly changing speeds and directions
  - Changes to directionality factor
- Strong updrafts
  - New factor accounting for increase in roof uplift pressures
- 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
- More intense windborne debris
  - Requirements for protection of glazed openings

Wind Direction



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Tornado Load Procedures

- Based on wind load procedures framework
- Most wind load parameters and equations have been modified to reflect differences between tornadic and non-tornadic wind and wind-structure interaction characteristics
- A few wind parameters have been dropped and new tornado parameters added
- Tornado chapter heavily references wind chapters 26-31, except 28
- Chapter 28 (Envelope Procedure for MWFRS Loads) not applicable to tornadoes
- Explicit provisions permitting the use performance-based tornado design

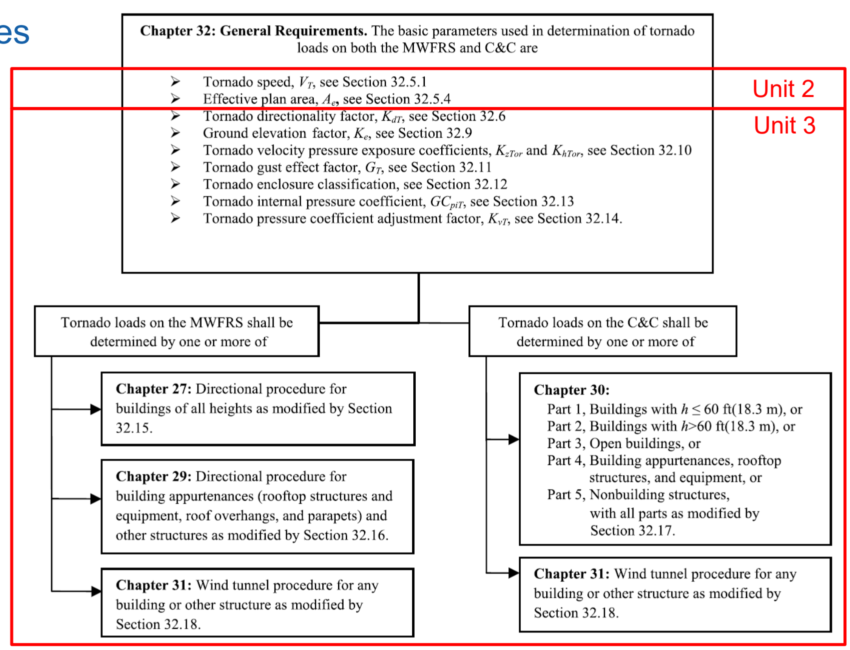

Figure 32.1-3. Outline of process for determining tornado loads.

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Unit 3 Introduction

Questions / Discussion

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Exposure, Topographic and Ground Elevation Effects

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Exposure, Topographic and Ground Elevation Effects

- Surface Roughness and Exposure
- Topographic Effects
- Ground Elevation Factor

- Review ASCE 7-16 Wind Provisions
- Changes for ASCE 7-22 Wind
- Changes for ASCE 7-22 Tornado

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Surface Roughness: Part 1

- Surface roughness effects the vertical velocity profile
- z_0 = roughness length, which is a length-scale representation of the roughness of the surface

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Table C26.7-2. Davenport Classification of Effective Terrain Roughness.

Class	z_0, ft (m)[a]	α[b]	z'_g, ft (m)[b]	z_d (ft or m)[c]	Wind Flow and Landscape Description[d]
1	0.0007 (0.0002)	12.9	509 (155)	$z_d = 0$	*Sea:* Open sea or lake (irrespective of wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac, and concrete, with a free fetch of several kilometers.
2	0.016 (0.005)	11.4	760 (232)	$z_d = 0$	*Smooth:* Featureless land surface without any noticeable obstacles and with negligible vegetation (e.g., beaches, pack ice without large ridges, marsh, and snow-covered or fallow open country).
3	0.1 (0.03)	9.0	952 (290)	$z_d = 0$	*Open:* Level countryside with low vegetation (e.g., grass) and isolated obstacles with separations of at least 50 obstacle heights (e.g., grazing land without windbreaks, heather, moor, and tundra, runway area of airports). Ice with ridges across-wind.
4	0.33 (0.10)	7.7	1,107 (337)	$z_d = 0$	*Roughly open:* Cultivated or natural area with low crops or plant covers, or moderately open country with occasional obstacles (e.g., low hedges, isolated low buildings, or trees) at relative horizontal distances of at least 20 obstacle heights.
5	0.82 (0.25)	6.8	1,241 (378)	$z_d = 0.2z_H$	*Rough:* Cultivated or natural area with high crops or crops of varying height and scattered obstacles at relative distances of 12 to 15 obstacle heights for porous objects (e.g., shelterbelts) or 8 to 12 obstacle heights for low solid objects (e.g., buildings).
6	1.64 (0.5)	6.2	1,354 (413)	$z_d = 0.5z_H$	*Very rough:* Intensely cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 8 obstacle heights. Low, densely planted major vegetation like bushland, orchards, young forest. Also, area moderately covered by low buildings with interspaces of 3 to 7 building heights and no high trees.
7	3.3 (1.0)	5.7	1,476 (450)	$z_d = 0.7z_H$	*Skimming:* Landscape regularly covered with similar-size large obstacles, with open spaces of the same order of magnitude as obstacle heights (e.g., mature regular forests, densely built-up area without much building height variation).
8	≥*matu* (≥*mat*)	5.2	1,610 (490)	Analysis by wind tunnel advised	*Chaotic:* City centers with mixture of low-rise and high-rise buildings or large forests of irregular height with many clearings. (Analysis by wind tunnel advised.)

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Surface Roughness: Part 2

- Surface roughness is handled in ASCE 7 wind provisions using 3 roughness categories
- For each upwind direction considered in the design of the building, surface roughness(es) are characterized for the for the purpose of assigning an exposure category
- The commentary of ASCE 7-22 (Section C26.7) describes modest changes in the assumed z_0 values used to derive the actual velocity profiles, but no changes were made to the general surface roughness category descriptions shown at right

26.7.2 Surface Roughness Categories.

Surface Roughness B. Urban and suburban areas, wooded areas, or other terrain with numerous, closely spaced obstructions that have the size of single-family dwellings or larger.

Surface Roughness C. Open terrain with scattered obstructions that have heights generally less than 30 ft (9.1 m). This category includes flat, open country and grasslands.

Surface Roughness D. Flat, unobstructed areas and water surfaces. This category includes smooth mud flats, salt flats, and unbroken ice.

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Exposure: Part 1

26.7 EXPOSURE

For each wind direction considered, the upwind exposure shall be based on ground surface roughness that is determined from natural topography, vegetation, and constructed facilities.

26.7.1 Wind Directions and Sectors.

For each selected wind direction at which the wind loads are to be determined, the exposure of the building or structure shall be determined for the two upwind sectors extending 45° on either side of the selected wind direction. The exposure in these two sectors shall be determined in accordance with Sections 26.7.2 and 26.7.3, and the exposure the use of which would result in the highest wind loads shall be used to represent the winds from that direction.

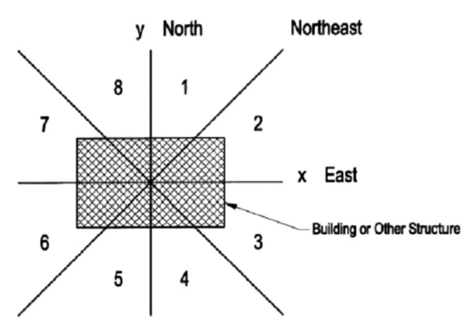

Figure C26.7-8. Determination of wind loads from different directions.

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Exposure: Part 2

26.7.3 Exposure Categories.

Exposure B:

Exposure C: Exposure C shall apply for all cases where Exposure B or D does not apply.

Exposure D:

For a site located in the transition zone between exposure categories, the category resulting in the largest wind forces shall be used.

EXCEPTION: An intermediate exposure between the preceding categories is permitted in a transition zone, provided that it is determined by a rational analysis method defined in the recognized literature.

Figure C26.7-1. Upwind surface roughness conditions required for Exposure B

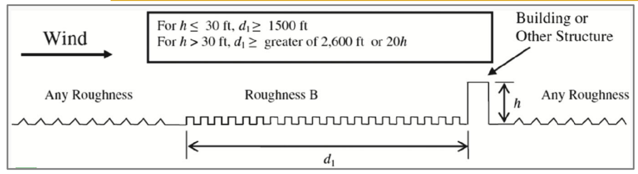
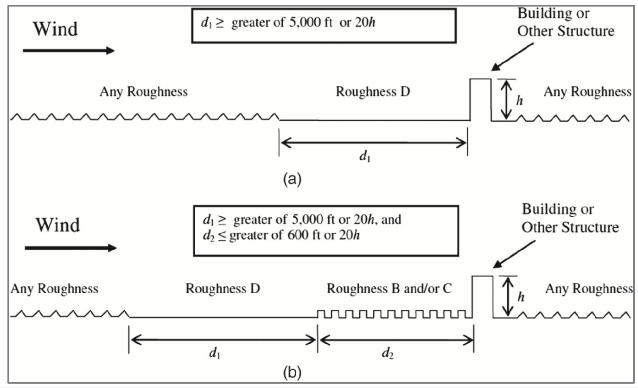


Figure C26.7-2. Upwind surface roughness conditions required for Exposure D, for the cases with (a) Surface Roughness D immediately upwind of the building, and (b) Surface Roughness B and/or C immediately upwind of the building.



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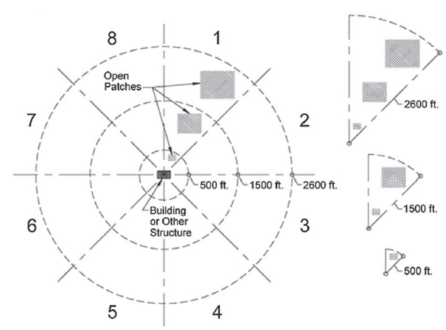
Exposure: Part 3

- Commentary provides much more guidance on exposure considerations
  - Guidance on to handle “open patches” in Exposure B (Section C26.7)
    - how big can these patches be an still be considered B
  - Method for determining velocity pressure profile for “intermediate” exposure between B and C, or between C and D (Section C26.10.1)
- Selection of correct exposure has significant impact on wind loads, and on determination of when tornado loads are required
  - For a building with mean roof height of 15 ft –
    - Exposure C results in 49% greater wind loads than Exposure B
    - Exposure D results in 81% greater wind loads than Exposure B



Notes:
1. For each selected wind direction at which the wind loads are to be determined, the exposure of the building or structure shall be determined for the two upwind sectors extending 45 degrees to either side of the selected wind direction.
2. Consider open patches of sizes equal to or greater than the areas given in Figure C26.7-4 per Commentary Section C26.7.

Figure C26.7-3. Sector analysis for Exposure B with upwind open patches.

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Exposure: Part 4

26.7.4 Exposure Requirements.

26.7.4.1 Directional Procedure (Chapter 27).
For each wind direction considered, wind loads for the design of the MWFRS of enclosed and partially enclosed buildings using the Directional Procedure of Chapter 27 shall be based on the exposures as defined in Section 26.7.3. Wind loads for the design of open buildings with monoslope, pitched, or troughed free roofs shall be based on the exposures, as defined in Section 26.7.3, resulting in the highest wind loads for any wind direction at the site.

26.7.4.3 Directional Procedure for Building Appurtenances and Other Structures (Chapter 29).
Wind loads for the design of building appurtenances (such as rooftop structures and equipment) and other structures (such as solid freestanding walls and freestanding signs, chimneys, tanks, open signs, single-plane open frames, and trussed towers) as specified in Chapter 29 shall be based on the appropriate exposure for each wind direction considered.

26.7.4.4 Components and Cladding (Chapter 30).
Design wind pressures for C&C shall be based on the exposure category resulting in the highest wind loads for any wind direction at the site.

Exposure Examples

- Several examples of Exposures B, C, and D provided in ASCE 7 Commentary Section C26.7

Figure C26.7-5(b). Exposure B: Urban area with numerous closely spaced obstructions having the size of single family dwellings or larger. For all structures shown, terrain representative of Surface Roughness Category B extends more than 20 times the height of the structure or 2,600 ft (792 m), whichever is greater, in the upwind direction.

Tornado Exposure

- Effects of terrain exposure on tornado velocity profiles are not well understood at this time
- Commentary section C32.7 provides a brief description of the state of knowledge and references
- Exposure can also change during the tornado due to damage

32.7 TORNADO EXPOSURE

Tornado velocity pressure exposure coefficients K_{zTor} and K_{hTor} are determined in Section 32.10.1.

Exposure requirements in Section 26.7 shall not apply to the determination of K_{zTor} and K_{hTor}.

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Surface Roughness and Exposure can Change During the Tornado

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Topographic Factor: Part 1

- K_{zt}, accounts for speed-up effects of wind flowing over hills and escarpments

ASCE 7-16 Wind Provisions

26.8 TOPOGRAPHIC EFFECTS

26.8.1 Wind Speed-Up over Hills, Ridges, and Escarpments.

Wind speed-up effects at isolated hills, ridges, and escarpments constituting abrupt changes in the general topography, located in any exposure category, shall be included in the determination of the wind loads when site conditions and locations of buildings and other structures meet all of the following conditions:

1. The hill, ridge, or escarpment is isolated and unobstructed upwind by other similar topographic features of comparable height for 100 times the height of the topographic feature (100*H*) or 2 mi (3.22 km), whichever is less. This distance shall be measured horizontally from the point at which the height *H* of the hill, ridge, or escarpment is determined.
2. The hill, ridge, or escarpment protrudes above the height of upwind terrain features within a 2-mi (3.22-km) radius in any quadrant by a factor of 2 or more.
3. The building or other structure is located as shown in Fig. 26.8-1 in the upper one-half of a hill or ridge or near the crest of an escarpment.
4. $H/L_H \geq 0.2$
5. is greater than or equal to 15 ft (4.5 m) for Exposure C and D and 60 ft (18 m) for Exposure B.

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Topographic Factor: Part 2

Equations

$$K_{zt} = (1 + K_1 K_2 K_3)^2$$

K_1 = determined from table

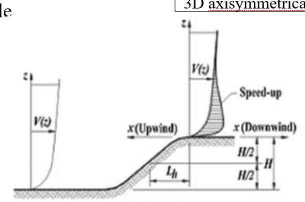
$$K_2 = (1 - |x| / \mu L_h)$$

$$K_3 = e^{-\gamma z / L_h}$$

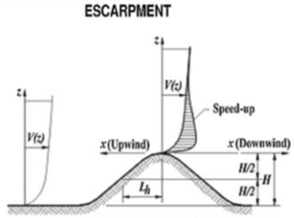
FIGURE 26.8-1 Topographic Factor, K_{zt}

Parameters for Speed-Up over Hills and Escarpments

Hill Shape	$K_1 / (H / L_h)$ Exposure B	C	D	γ	μ Upwind of Crest	Downwind of Crest
2D ridges (or valleys with negative H in $K_1 / (H / L_h)$	1.30	1.45	1.55	3	1.5	1.5
2D escarpments	0.75	0.85	0.95	2.5	1.5	4
3D axisymmetrical hill	0.95	1.05	1.15	4	1.5	1.5



ESCARPMENT



2-D RIDGE OR 3-D AXISYMMETRICAL HILL

Topographic Multipliers for Exposure C[a,b,c]

	K_1 Multiplier				K_2 Multiplier			K_2 Multiplier		
H / L_h	2D Ridge	2D Escarpment	3D Axisym-metrical Hill	x / L_h	2D Escarpment	All Other Cases	z / L_h	2D Ridge	2D Escarpment	3D Axisym-metrical Hill
0.20	0.29	0.17	0.21	0.00	1.00	1.00	0.00	1.00	1.00	1.00
0.25	0.36	0.21	0.26	0.50	0.88	0.67	0.10	0.74	0.78	0.67
0.30	0.43	0.26	0.32	1.00	0.75	0.33	0.20	0.55	0.61	0.45
0.35	0.51	0.30	0.37	1.50	0.63	0.00	0.30	0.41	0.47	0.30
0.40	0.58	0.34	0.42	2.00	0.50	0.00	0.40	0.30	0.37	0.20
0.45	0.65	0.38	0.47	2.50	0.38	0.00	0.50	0.22	0.29	0.14
0.50	0.72	0.43	0.53	3.00	0.25	0.00	0.60	0.17	0.22	0.09
				3.50	0.13	0.00	0.70	0.12	0.17	0.06
				4.00	0.00	0.00	0.80	0.09	0.14	0.04
							0.90	0.07	0.11	0.03
							1.00	0.05	0.08	0.02
							0.50	0.01	0.02	0.00
							2.00	0.00	0.00	0.00

ASCE 7-16 Wind Provisions

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Topographic Factor: Part 3

- Limitations 1 and 2 were removed
- Scope of Topographic Multiplier Tabular solution (bottom right on previous slide) was expanded to cover all Exposures, not just Exposure C
  - Reduced accuracy

ASCE 7-22 Wind Provisions

26.8 TOPOGRAPHIC EFFECTS

26.8.1 Wind Speed-Up over Hills, Ridges, and Escarpments. Wind speed-up effects at isolated hills, ridges, and escarpments constituting abrupt changes in the general topography, located in any exposure category, shall be included in the determination of the wind loads when site conditions and locations of buildings and other structures meet all of the following conditions:

1. ~~The hill, ridge, or escarpment is isolated and unobstructed upwind by other similar topographic features of comparable height for 100 times the height of the topographic feature (100*H*) or 2 mi (3.22 km), whichever is less. This distance shall be measured horizontally from the point at which the height *H* of the hill, ridge, or escarpment is determined.~~
2. ~~The hill, ridge, or escarpment protrudes above the height of upwind terrain features within a 2-mi (3.22-km) radius in any quadrant by a factor of 2 or more.~~
3. The building or other structure is located as shown in Fig. 26.8-1 in the upper one-half of a hill or ridge or near the crest of an escarpment.
4. $H/L_H \geq 0.2$
5. is greater than or equal to 15 ft (4.5 m) for Exposure C and D and 60 ft (18 m) for Exposure B.

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Tornado Topographic Factor

- Effects of topography on tornado velocity profiles are not well understood at this time
- Commentary section C32.8 provides a brief description of the state of knowledge and references

32.8 TOPOGRAPHIC FACTOR

Tornado velocity pressures q_{zT} and q_{hT} are determined in Section 32.10.2.

Topographic speedup effects in Section 26.8 shall not apply to the determination of q_{zT} and q_{hT}.

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Ground Elevation Factor

- K_e, accounts for reduced air density at locations with higher ground elevation
  - Lower density means lower design pressures
- No difference in ground elevation effects for wind or tornado

ASCE 7-16 and 7-22 Wind Provisions, and Tornado

Table 26.9-1. Ground Elevation Factor, K_e.

Ground Elevation above Sea Level		Ground Elevation
ft	m	Factor, K_e
<0	<0	See note 2
0	0	1.00
1,000	305	0.96
2,000	610	0.93
3,000	914	0.90
4,000	1,219	0.86
5,000	1,524	0.83
6,000	1,829	0.80
>6,000	>1,829	See note 2

Notes:

1. Conservative approximation $K_e = 1.00$ is permitted in all cases.
2. Factor K_e shall be determined from Table 26.9-1 using interpolation or from the following formula for all elevations: $K_e = e^{-0.0000362 z_e}$ (z_e= ground elevation above sea level, ft); or $K_e = e^{-0.000119 z_e}$ (z_e= ground elevation above sea level, m).
3. K_e is permitted to be taken as 1.00 in all cases.

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Exposure, Topographic and Ground Elevation Effects

Questions / Discussion

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Tornado Velocity Pressure

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Velocity Pressure

- Velocity Pressure Exposure Coefficient
- Wind Speed
- Velocity Pressure Equation

- Review ASCE 7-16 Wind equation and parameters
- Changes for ASCE 7-22 Wind
- Changes for ASCE 7-22 Tornado

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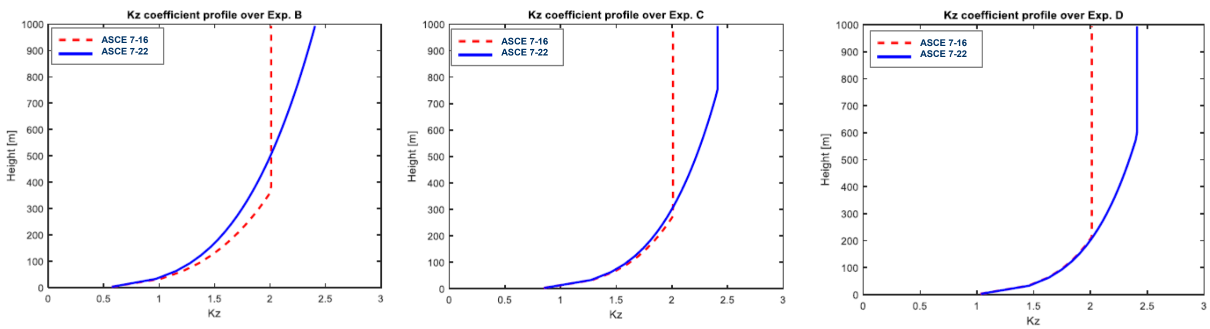
Velocity Pressure - Vertical Profiles

- New research indicates that the effects of surface roughness extend higher above the earth's surface than previously understood
- Gradient heights (z_g) have increased in ASCE 7-22, power law coefficients (α) also slightly modified (see Table 26.11-1)



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Velocity Pressure Exposure Coefficient

Table 26.10-1

Velocity Pressure Exposure Coefficients, Kh and Kz

Height above Ground Level, z		Exposure		
ft	m	B	C	D
0–15	0–4.6	0.57 (0.70)[a]	0.85	1.03
20	6.1	0.62 (0.70)[a]	0.90	1.08
25	7.6	0.66 (0.70)[a]	0.94	1.12
30	9.1	0.70	0.98	1.16
40	12.2	0.76	1.04	1.22
50	15.2	0.81	1.09	1.27
60	18.0	0.85	1.13	1.31
70	21.3	0.89	1.17	1.34
80	24.4	0.93	1.21	1.38
90	27.4	0.96	1.24	1.40
100	30.5	0.99	1.26	1.43
120	36.6	1.04	1.31	1.48
140	42.7	1.09	1.36	1.52
160	48.8	1.13	1.39	1.55
180	54.9	1.17	1.43	1.58
200	61.0	1.20	1.46	1.61
250	76.2	1.28	1.53	1.68
300	91.4	1.35	1.59	1.73
350	106.7	1.41	1.64	1.78
400	121.9	1.47	1.69	1.82
450	137.2	1.52	1.73	1.86
500	152.4	1.56	1.77	1.89

a Use 0.70 in Chapter 28, Exposure B, when $z < 30$ ft (9.1 m).

- K_z accounts for boundary layer effect, where wind speed increases with increasing height above ground
- Rate of increase is a function of upwind terrain exposure, which depends on surface roughness

ASCE 7-16

Notes

1. The velocity pressure exposure coefficient K_z may be determined from the following formula:

   For 15 ft (4.6 m) $\leq z \leq z_g$ $K_z = 2.01(z/z_g)^{2/\alpha}$

   For $z <$ 15 ft (4.6 m) $K_z = 2.01(15/z_g)^{2/\alpha}$
2. α and z_g are tabulated in Table 26.11-1.
3. Linear interpolation for intermediate values of height z is acceptable.
4. Exposure categories are defined in Section 26.7.

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Table 26.10-1 Velocity Pressure Exposure Coefficients, K_h and K_z

K_z Changes for 7-22

Height above Ground Level, z		Exposure		
Ft	m	B	C	D
0–15	0–4.6	0.57 (0.70)[a]	0.85	1.03
20	6.1	0.62 (0.70)[a]	0.90	1.08
25	7.6	0.66 (0.70)[a]	0.94	1.12
30	9.1	0.70	0.98	1.16
40	12.2	~~0.76~~ 0.74	1.04	1.22
50	15.2	~~0.81~~ 0.79	1.09	1.27
60	~~18.0~~ 18.3	~~0.85~~ 0.83	1.13	1.31
70	21.3	~~0.89~~ 0.86	1.17	1.34
80	24.4	~~0.93~~ 0.90	1.21	1.38
90	27.4	~~0.96~~ 0.92	1.24	1.40
100	30.5	~~0.99~~ 0.95	1.26	1.43
120	36.6	~~1.04~~ 1.00	1.31	1.48
140	42.7	~~1.09~~ 1.04	~~1.36~~ 1.34	1.52
160	48.8	~~1.13~~ 1.08	1.39	1.55
180	54.9	~~1.17~~ 1.11	~~1.43~~ 1.41	1.58
200	61.0	~~1.20~~ 1.14	~~1.46~~ 1.44	1.61
250	76.2	~~1.28~~ 1.21	~~1.53~~ 1.51	1.68
300	91.4	~~1.35~~ 1.27	~~1.59~~ 1.57	1.73
350	106.7	~~1.41~~ 1.33	~~1.64~~ 1.62	1.78
400	121.9	~~1.47~~ 1.38	~~1.69~~ 1.66	1.82
450	137.2	~~1.52~~ 1.42	~~1.73~~ 1.70	1.86
500	152.4	~~1.56~~ 1.46	~~1.77~~ 1.74	1.89

a Use 0.70 in Chapter 28, Exposure B, when $z < 30$ ft (9.1 m).

ASCE 7-22 Wind Provisions

- Increased gradient heights z_g and revised power law coefficient α
- Resulting slight revisions to K_z in lowest few hundred feet
- Greater impacts for tall buildings

Final ASCE 7-22 K_z Table

Table 26.10-1.

Velocity Pressure Exposure Coefficients, Kh and Kz.

Height above Ground Level, z or h		Exposure		
ft	m	B	C	D
0–15	0–4.6	0.57 (0.70)*	0.85	1.03
20	6.1	0.62 (0.70)*	0.90	1.08
25	7.6	0.66 (0.70)*	0.94	1.12
30	9.1	0.70	0.98	1.16
40	12.2	0.74	1.04	1.22
50	15.2	0.79	1.09	1.27
60	18.3	0.83	1.13	1.31
70	21.3	0.86	1.17	1.34
80	24.4	0.90	1.21	1.38
90	27.4	0.92	1.24	1.40
100	30.5	0.95	1.26	1.43
120	36.6	1.00	1.31	1.48
140	42.7	1.04	1.34	1.52
160	48.8	1.08	1.39	1.55
180	54.9	1.11	1.41	1.58
200	61.0	1.14	1.44	1.61
250	76.2	1.21	1.51	1.68
300	91.4	1.27	1.57	1.73
350	106.7	1.33	1.62	1.78
400	121.9	1.38	1.66	1.82
450	137.2	1.42	1.70	1.86
500	152.4	1.46	1.74	1.89

* Use 0.70 in Chapter 28, Exposure B, when $z < 30$ ft (9.1 m).

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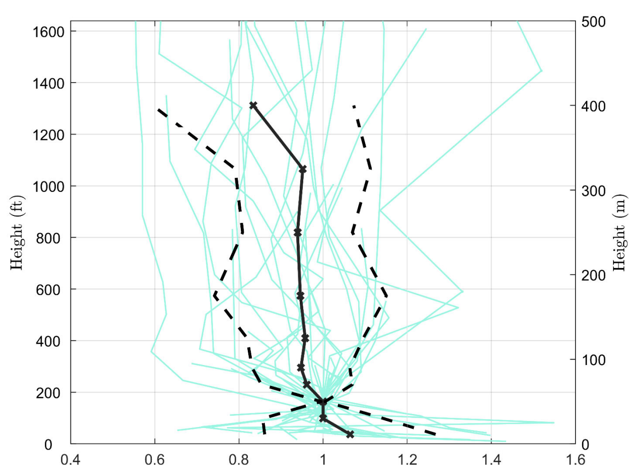
Tornado Speed – Vertical Profiles: Part 1



Horizonal Speed, Normalized at Height = 164 ft (50 m)

- Worked closely with mobile radar community to obtain records and analyze radar-measured tornadic wind speeds to develop tornado velocity profile of horizontal winds
  - Blue lines are profiles from 36 individual tornadoes
  - Black line is the median profile
  - Dashed lines are median +/- one standard deviation

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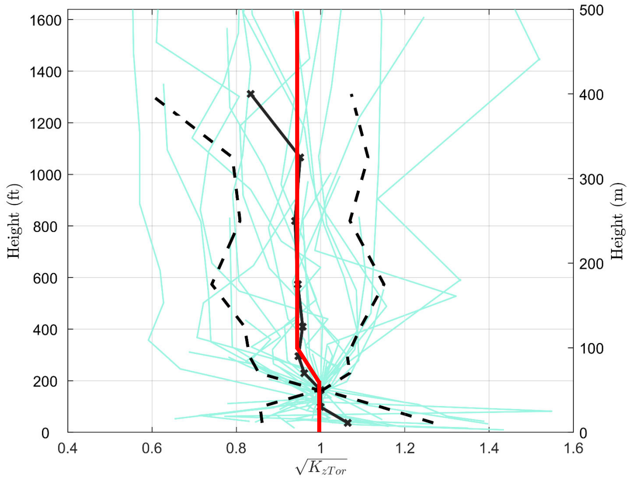
Tornado Speed – Vertical Profiles: Part 2



Horizonal Speed, Normalized
at Height = 164 ft (50 m)

- Tornado profile used in the standard (red) closely follows the median profile
  - Normalized speed = $\sqrt{K_{zTor}}$

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Tornado Velocity Pressure Exposure Coefficient

- Tornado velocity pressure variation with exposure is not yet understood
- Therefore, K_{zTor} as currently defined is independent of exposure

Table 32.10-1 Tornado Velocity Pressure Exposure Coefficients, K_{zTor} and K_{hTor}

Height above Ground Level, z		K_{zTor} and K_{hTor}
ft	m	
0-200	0-61.0	1.0
250	76.2	0.96
300	91.4	0.92
>328	>100	0.90

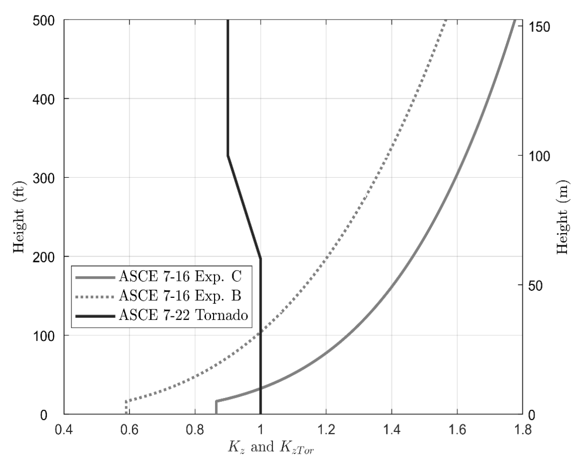

Figure C32.10-2 Vertical profiles of tornado velocity pressure (K_{zTor}) versus that of Exposure B and Exposure C for non-tornado winds (K_z) in Chapter 26 for the lowest 500 ft (152.4 m)

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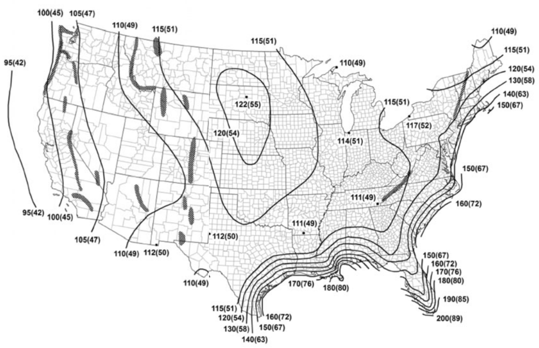
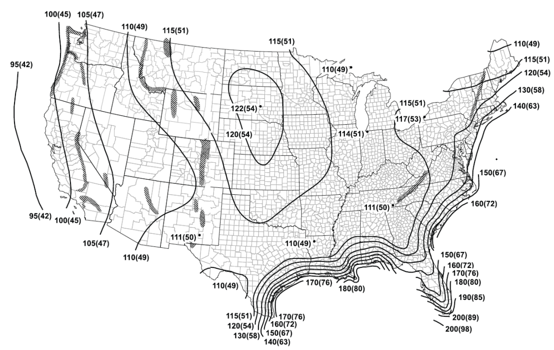
Basic Wind Speed: Part 1

- *V*, in mph (m/s)
- RC III maps shown (1,700 year MRI)

- ASCE 7-22 maps have updated hurricane wind speeds
  - Modest increases along Gulf Coast
  - Slight decreases in New England



ASCE 7-16 Wind Speed Map



ASCE 7-22 Wind Speed Map

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Basic Wind Speed: Part 2

- Other changes in ASCE 7-22
  - Modifications to special wind regions
  - PR and USVI maps in hazard tool include topographic effects
  - HI maps include topographic and directionality effects
  - Some special wind regions have wind speeds available in the Hazards Tool – Colorado and So. Cal.
  - Maps notes reordered – 5 and 8 are new

Location	V (mi/h)	V (m/s)
American Samoa	170	(76)
Guam & Northern Mariana Islands	210	(94)
Hawaii	ASCE Wind Design Geodatabase	
Puerto Rico	ASCE Wind Design Geodatabase	
U.S. Virgin Islands	ASCE Wind Design Geodatabase	

ASCE 7-22 Wind Speed Map

Notes:
1. Values are 3 s gust wind speeds in mi/h (m/s) at 33 ft (10 m) above ground for Exposure Category C.
2. Linear interpolation is permitted between contours. Point values are provided to aid with interpolation.
3. Islands, coastal areas, and land boundaries outside the last contour shall use the last wind speed contour.
4. Location-specific basic wind speeds shall be permitted to be determined using the ASCE Wind Design Geodatabase.
5. Wind speeds for Hawaii, US Virgin Islands, and Puerto Rico shall be determined from the ASCE Wind Design Geodatabase.
6. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions. Site-specific values for selected special wind regions shall be permitted to be determined using the ASCE Wind Design Geodatabase.
7. Wind speeds correspond to approximately a 15% probability of exceedance in 50 years (Annual Exceedance Probability = 0.000588, MRI = 1,700 years).
8. The ASCE Wind Design Geodatabase can be accessed at the ASCE 7 Hazard Tool (https://asce7hazardtool.online) or approved equivalent.

Figure 26.5-1C. Basic wind speeds for Risk Category III buildings and other structures.

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Design for Tornado Loads Not Required

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

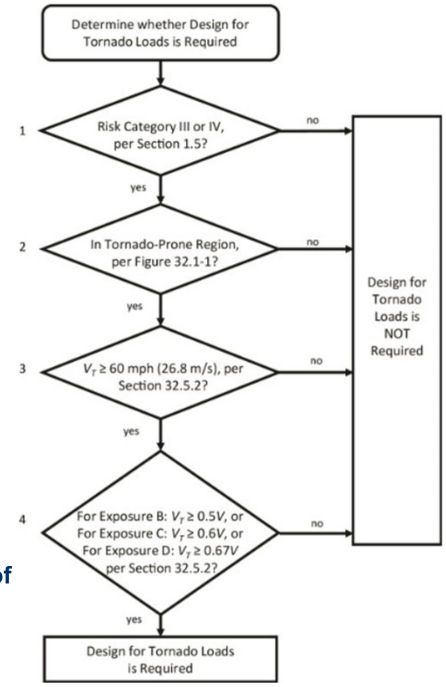

FIGURE 32.1-2 Flowchart of Process for Determining when Design for Tornado Loads is Required

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Wind Velocity Pressure: Part I

- $q = ½ \rho V^2$ (section C26.10.2)
- $q = 0.00256 * K_z K_{zt} K_d K_e V^2$ (equation 26.10-1)

q Velocity pressure (psf)

ρ Air density

- 0.00256 = ½ ρ (incl. unit conversions)

K_z Velocity pressure exposure coefficient

K_{zt} Topographic factor

K_d Directionality factor

K_e Ground elevation factor

V Basic wind speed (mph)

ASCE 7-16 Equation

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Wind Velocity Pressure: Part 2

- $q = ½\,\rho\,V^2$ (section C26.10.2)
- $q = 0.00256{*}K_zK_{zt}K_dK_eV^2$ (equation 26.10-1)

q Velocity pressure (psf)
ρ Air density
- 0.00256 = ½ ρ (incl. unit conversions)

K_z Velocity pressure exposure coefficient
K_{zt} Topographic factor
~~K_d Directionality factor~~
K_e Ground elevation factor
V Basic wind speed (mph)

Notes:
- ASCE 7-22 equations
- K_z slightly revised
- K_{zt} slightly revised
- K_d has been removed from this equation and placed into the pressure and force equations, since it is not *purely* a function of the extreme wind climatology (it also depends on the geometry of the building)
- V slightly revised basic wind speed maps

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Tornado Velocity Pressure

Red indicates differences from ASCE 7-16 wind load parameters

- $q = ½\,\rho\,V^2$ (section C26.10.2)
- $q_T = 0.00256{*}K_{zTor}K_eV_T^2$ (equation 32.10-1)

q_T Tornado velocity pressure (psf)
ρ Air density
- 0.00256 = ½ ρ (incl. unit conversions)

K_{zTor} Tornado velocity pressure exposure coeff
~~K_{zt} Topographic factor~~
K_e Ground elevation factor
V_T Tornado speed (mph)

Notes:
- Different exposure coefficients
- No topographic factor for tornadoes
- Tornado directionality factor moved to pressure and force equations
- Tornado speed uses different maps than wind speed

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Tornado Velocity Pressure

Questions / Discussion

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Tornado Directionality and Gust Effect Factors

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Tornado Directionality and Gust Effect Factors

- Directionality Factor
- Gust Effect Factor

- Review ASCE 7-16 Wind parameters
- Changes for ASCE 7-22 Wind
- Changes for ASCE 7-22 Tornado

Directionality Factor

K_d accounts for

1. The reduced probability of maximum winds coming from any given direction, and
2. the reduced probability of the maximum pressure coefficient occurring for any given wind direction

- K_d is a function of both
  1. The extreme wind climate
  2. Type and shape of building or structure

ASCE 7-16 and ASCE 7-22* Wind Provisions

* No direct changes to K_d in ASCE 7-22, but the factor is now used in a different equation.

Table 26.6-1. Wind Directionality Factor, K_d.

Structure Type	Directionality Factor K_d
Buildings	
Main wind force resisting system	0.85
Components and cladding	0.85
Arched roofs	0.85
Circular domes	1.0*
Chimneys, tanks, and similar structures	
Square	0.90
Hexagonal	0.95
Octagonal	1.0*
Round	1.0*
Solid freestanding walls, roof top equipment, and solid freestanding and attached signs	0.85
Open signs and single-plane open frames	0.85
Trussed towers	
Triangular, square, or rectangular	0.85
All other cross sections	0.95

*Directionality factor $K_d = 0.95$ shall be permitted for round or octagonal structures with nonaxisymmetric structural systems.

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Tornado Directionality Factor

- Methodology to determine K_{dT} adapted from K_d analysis for Chapter 26, incorporating the tornado model used to develop the hazard maps
- Unlike straight-line winds, the wind speeds acting on a building during a tornado can vary significantly over the building at any given instant in time, particularly for large buildings.
  - These variations in tornado speed as a function of building size are captured in the modeling process to determine K_{dT}

Table 32.6-1 Tornado Directionality Factor, K_{dT}

Structure Type	Tornado Directionality Factor K_{dT}	Wind Directionality Factor (Ch. 26) K_d
Buildings		
Main Wind Force Resisting System	0.80	0.85
Components and Cladding		0.85
For Essential Facilities and for buildings and other structures required to maintain the functionality of Essential Facilities	1.0	
Roof Zone 1′ as shown on Figure 30.3-2A	0.90	
All other cases	0.75	
Arched Roofs, Circular Domes, and All Other Structures	Use value from Table 26.6-1	Table 26.6-1

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Tornado Directionality Factor - Essential Facilities

For Essential Facilities, it is critical to avoid breaches in the building envelope

- Loss of any wall cladding can permit intrusion of wind, wind-borne debris, wind-driven rain, and/or falling rain into the building
- Even minor damage to these elements, such as roof coverings, can allow significant amounts of rainwater to enter the building
- This often results in serious damage to building interiors, contents, and mechanical and electrical systems, rendering the facility or parts of it nonoperational

- It is likely that for a design tornado event that one or more portions of the building envelope are loaded with the maximum pressure, so there would be no reduction in probability
- a K_{dT} value of 1.0 is therefore appropriate, as some portion of the envelope is nearly certain to have its maximum pressure coefficient at the direction of the maximum winds

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Gust Effect Factor for Rigid Buildings/Structures

G accounts for the decorrelation of wind gusts over the size of the structure, and the background response of the structure to the wind loads

- G = 0.85, or
- Value from full rigid structure analysis using Section 26.11.4
- Depends on wind gust size and building size characteristics

BUILDING OR OTHER STRUCTURE, RIGID:

A building or other structure whose fundamental frequency is ≥ 1 Hz.

ASCE 7-16 and ASCE 7-22* Wind Provisions

* No direct changes to *G* in ASCE 7-22, but Table 26.11-1 Terrain Exposure Constants has been updated as mentioned in the previous video

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Gust Effect Factor for Flexible Buildings/Structures

G_f additionally accounts for the load magnification effect caused by gusts, in resonance with along-wind vibrations of flexible buildings

- dependent on dynamic characteristics of the structure, including
  - fundamental natural frequency
  - damping
- Procedure to determine G_f in Section 26.11.5
- *G_f does not account for across-wind loading, vortex shedding, or instability caused by galloping or flutter*

BUILDING OR OTHER STRUCTURE, FLEXIBLE:

Slender buildings and other structures that have a fundamental natural frequency < 1 Hz

ASCE 7-16 and ASCE 7-22* Wind Provisions

* No changes G_f 'values' in ASCE 7-22, but the provisions and equations have been revised]make them easier to follow

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Tornado Gust Effect Factor

- G_T Uses the rigid structure gust effects provisions from Chapter 26
  - 0.85, or
  - Full rigid structure analysis
    - with exposure C terrain constants
- The duration of a tornado is sufficiently short such that the gust factor provisions for flexible or dynamically sensitive buildings and other structures (G_f) do not apply.

Tornadic winds may vary in both direction and speed over the building or structure, resulting in lower peak load effects compared to atmospheric boundary layer winds, whose mean wind speed and direction are comparatively more constant over the building or structure

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Tornado Directionality and Gust Effect Factors

Questions / Discussion

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End of Day 1

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Tornado Load Design per ASCE 7-22 and the 2024 International Building Code
Seminar Day 2

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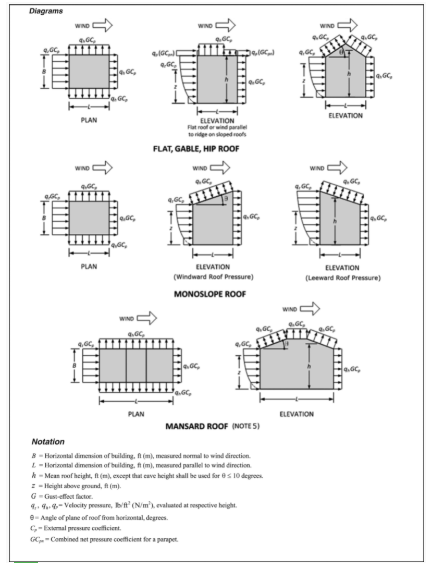
Unit 3 Outline

Tornado Load Coefficients and Equations

- Exposure, Topographic and Ground Elevation Effects
- Tornado Velocity Pressure
- Tornado Directionality and Gust Effect Factors
- Tornado Enclosure Classification, Internal Pressure Coefficients, and Protection of Glazed Openings
- Tornado External Pressure Coefficients
- Main Wind Force Resisting System Loads
- Components and Cladding Loads
- Wind Tunnel Method



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Tornado Enclosure Classification, Internal Pressure Coefficients, and Protection of Glazed Openings

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Enclosure Classification and Internal Pressure

- Enclosure Classification
- Protection Requirements for Glazed Openings
- Internal Pressure Coefficient and Atmospheric Pressure Change

- Review ASCE 7-16 Wind parameters
- Changes for ASCE 7-22 Wind
- Changes for ASCE 7-22 Tornado

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Enclosure Classification: Part 1

- Enclosure *'Definitions'* in Section 26.2
- 4 Classifications
  - Enclosed
  - Partially Enclosed (Dominant Opening)
  - Partially Open
  - Open
- Application requirements in Section 26.12

OPENINGS: Apertures or holes in the building envelope that allow air to flow through the building envelope and that are designed as "open" during design winds as defined by these provisions.

ASCE 7-16 Wind Provisions

BUILDING, ENCLOSED: A building that has the total area of openings in each wall, that receives positive external pressure, less than or equal to 4 sq ft (0.37 m²) or 1% of the area of that wall, whichever is smaller. This condition is expressed for each wall by the following equation:

$$A_o < 0.01A_g \text{, or } 4 \text{ sq ft } (0.37 \text{ m}^2)\text{, whichever is smaller,}$$

where A_o and A_g are as defined for Open Buildings.

BUILDING, PARTIALLY ENCLOSED: A building that complies with both of the following conditions:

1. The total area of openings in a wall that receives positive external pressure exceeds the sum of the areas of openings in the balance of the building envelope (walls and roof) by more than 10%.
2. The total area of openings in a wall that receives positive external pressure exceeds 4 ft^2 (0.37 m^2) or 1% of the area of that wall, whichever is smaller, and the percentage of openings in the balance of the building envelope does not exceed 20%.

These conditions are expressed by the following equations:

$$A_o > 1.10A_{oi}$$

$$A_o > 4 \text{ ft}^2 (0.37 \text{ m}^2) \text{ or } > 0.01A_g\text{, whichever is smaller, and } A_{oi}/A_{gi} \le 0.20$$

where A_o and A_g are as defined for Open Building;

A_{oi} = sum of the areas of openings in the building envelope (walls and roof) not including A_o, in ft^2 (m^2); and

A_{gi} = sum of the gross surface areas of the building envelope (walls and roof) not including A_g, in ft^2 (m^2).

BUILDING, PARTIALLY OPEN: A building that does not comply with the requirements for open, partially enclosed, or enclosed buildings.

BUILDING, OPEN: A building that has each wall at least 80% open. This condition is expressed for each wall by the equation $A_o \ge 0.8A_g$, where

A_o = total area of openings in a wall that receives positive external pressure, in ft^2 (m^2); and

A_g = the gross area of that wall in which A_o is identified, in ft^2 (m^2).

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Enclosure Classification: Part 2

- "Openings' redefined
- Clarifications to application requirements in Section 26.12
- Extensive and much needed additions and revisions to commentary

OPENINGS: Holes that allow air to flow through the building envelope during a design wind event.

Holes in the building envelope, including air intake and exhaust vents for ventilation systems, should always be considered as openings. Whether doors, operable windows and skylights, and flexible and operable louvers are considered as openings depends on their intended use during a storm event. For example, a door of a fire station or hospital ambulance bay should be considered an opening if the intended function for such essential facilities requires the door to remain in an open position during a design wind event. However, if doors, windows, and skylights are likely be in a closed position during a design wind event, they do not need to be considered as openings.

ASCE 7-22 Wind Provisions

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Tornado Enclosure Classification: Part 1

32.12.2 Openings.

To assign the tornado enclosure classification, the amount of openings in the building envelope shall be determined by taking each wall of the building or other structure, assuming it functions as the windward wall, and summing the total area of openings present with respect to the area of the remaining building envelope.

Buildings shall be classified as enclosed, partially enclosed, partially open, or open as defined in Section 26.2.

Other structures shall be classified as sealed, defined in Section 32.2, or enclosed, partially enclosed, partially open, or open as defined in Section 26.2.

- Sealed structures are very susceptible to loads induced by atmospheric pressure change associated with a tornado
- New enclosure classification of "sealed" added

32.2 Definitions.

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.

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Tornado Enclosure Classification: Part 2

32.12.2 Openings. (Continued)

Where not required by Section 32.12.3 to protect glazed openings, enclosed buildings and other structures shall either:

(1) be reevaluated for classification as partially enclosed, with all unprotected glazed openings on each assumed windward wall considered as openings; or

(2) be protected in accordance with Section 32.12.3.1.

- Wind-borne debris hazards are greater for tornadoes than for hurricanes
- The updrafts in a tornado can loft debris higher in the air, creating the opportunity for more, larger, and faster traveling debris compared to hurricanes, where debris is mainly transported horizontally
- Unprotected glazing in any building is considered as an opening for determination of Enclosure Classification (one windward wall at a time)

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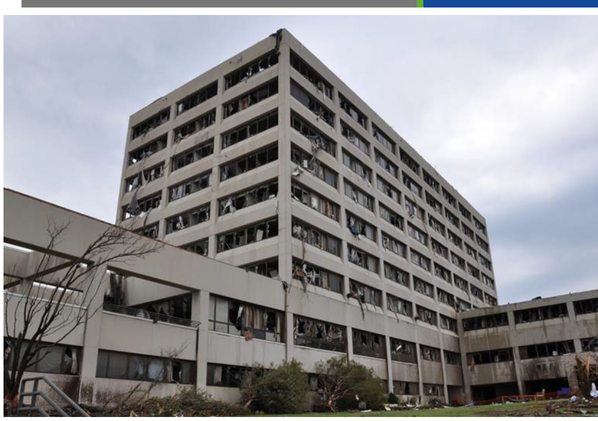
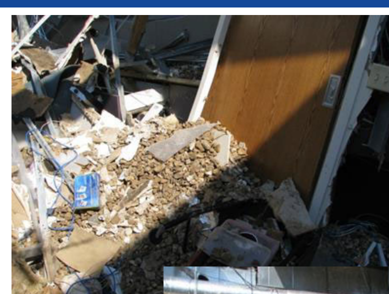
Debris Considerations: Part 1

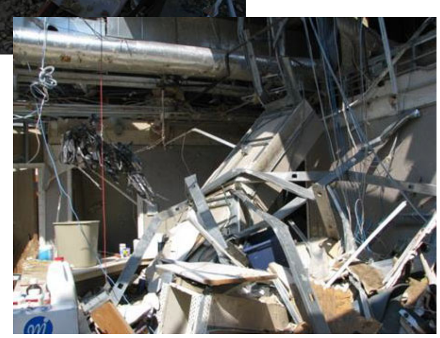


Credit: NIST

Most of the glazing destroyed



Roof aggregate inside building



Interior following breach of envelope

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Debris Considerations: Part 2

Credit: NIST

The Behavioral Health Unit had impact resistant glazing - for patient protection

Windows remained intact on fifth floor of West Tower

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Protection of Glazed Openings: Part 1

- Applicable to
  - Risk Category II, III and IV buildings, located in the
  - Wind-Borne Debris Region

ASCE 7-16 Wind Provisions

26.12.3 Protection of Glazed Openings.

Glazed openings in Risk Category II, III, or IV buildings located in hurricane-prone regions shall be protected as specified in this section.

26.12.3.1 Wind-Borne Debris Regions.

Glazed openings shall be protected in accordance with Section 26.12.3.2 in the following locations:

1. Within 1 mi (1.6 km) of the coastal mean high water line where the basic wind speed is equal to or greater than 130 mi / h (58 m / s), or
2. In areas where the basic wind speed is equal to or greater than 140 mi / h (63 m / s).

For Risk Category II buildings and other structures and Risk Category III buildings and other structures, except health-care facilities, the wind-borne debris region shall be based on Figs. 26.5-1B and 26.5-2B. For Risk Category III health-care facilities, the wind-borne debris region shall be based on Figs. 26.5-1C and 26.5-2C. For Risk Category IV buildings and structures, the wind-borne debris region shall be based on Figs. 26.5-1D and 26.5-2D. Risk Categories shall be determined in accordance with Section 1.5.

EXCEPTION: Glazing located more than 60 ft (18.3 m) above the ground and more than 30 ft (9.2 m) above aggregate-surfaced roofs, including roofs with gravel or stone ballast, located within 1,500 ft (458 m) of the building shall be permitted to be unprotected.

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Protection of Glazed Openings: Part 2

- Updated definition of Wind-Borne Debris Region
- Additional commentary,
  - including coverage of sectional, rolling, and flexible doors (i.e., garage doors)

26.12.3.1 Wind-Borne Debris Regions.

Glazed openings shall be protected in accordance with Section 26.12.3.2 in the following locations:

1. Within 1 mi (1.6 km) of the ~~coastal~~ mean high water line where an Exposure D condition exists upwind of the waterline and the basic wind speed is equal to or greater than 130 mi / h (58 m / s), or
2. In areas where the basic wind speed is equal to or greater than 140 mi / h (63 m / s).

ASCE 7-22 Wind Provisions

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Tornado Protection of Glazed Openings

- Only *required* for Essential Facilities and associated structures
- Commentary recommends for other buildings with functional performance objective

32.12.3 Protection of Glazed Openings. Glazed openings shall be protected for Essential Facilities and for buildings and other structures required to maintain the functionality of Essential Facilities.

Commentary: For buildings and other structures intended to remain operational in the event of a tornado (including Essential Facilities) and where a building owner's tornado performance objective is to reduce occupancy disruption and interior damage during a tornado, it is important to specify glazing assemblies that have been tested for wind-borne debris impact, in addition to meeting static pressure requirements.

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Protection Requirements for Glazed Openings

- Protection Requirements
  - Impact-resistant glazing, or
  - Impact-protective system
- Testing Requirements
  - Missile test and cyclic pressure differential tests
    - ASTM E1996 (Specification) and ASTM E1886 (Test Method)
    - ANSI/DASMA 115 for glazed openings in sectional garage doors, rolling doors, and flexible doors

26.12.3.2 Protection Requirements for Glazed Openings.

Glazing in buildings requiring protection shall be protected with an impact-protective system or shall be impact-resistant glazing.

Impact-protective systems and impact-resistant glazing shall be subjected to missile test and cyclic pressure differential tests in accordance with ASTM E1996 as applicable. Testing to demonstrate compliance with ASTM E1996 shall be in accordance with ASTM E1886. Impact-resistant glazing and impact-protective systems shall comply with the pass/fail criteria of Section 7 of ASTM E1996 based on the missile required by Table 3 or Table 4 of ASTM E1996. Glazing in sectional garage doors and rolling doors shall be subjected to missile tests and cyclic pressure differential tests in accordance with ANSI/DASMA 115 as applicable.

Glazing and impact-protective systems in buildings and other structures classified as Risk Category IV in accordance with Section 1.5 shall comply with the "enhanced protection" requirements of Table 3 of ASTM E1996. Glazing and impact-protective systems in all other structures shall comply with the "basic protection" requirements of Table 3 of ASTM E1996.

ASCE 7-16 and ASCE 7-22 Wind Provisions

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Tornado Protection Requirements for Glazed Openings

- Protection Requirements
  - Impact-resistant glazing, or
  - Impact-protective system
    - permanently affixed non-operable systems, or
    - permanently affixed operable systems capable of being fully deployed from inside the building within five minutes and used in buildings that are staffed 24 hours per day
- Testing Requirements
  - Missile test and ~~cyclic~~ static pressure differential tests
    - ASTM E1996 (Specification) and ASTM E1886 (Test Method)
    - ANSI/DASMA 115 for glazed openings in sectional garage doors, rolling doors, and flexible doors

Credit: FEMA

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Internal Pressure Coefficient

- GC_{pi}, internal pressure coefficient, accounts for internal pressures due to wind field surrounding the building

ASCE 7-16 and ASCE 7-22* Wind Provisions

* Much more commentary

Table 26.13-1 Internal Pressure Coefficient, (GCpi)

Enclosure Classification	Internal Pressure	Internal Pressure Coefficient, (GC_{pi})
Enclosed buildings	Moderate	+0.18
		- 0.18
Partially enclosed buildings	High	+0.55
		- 0.55
Partially open buildings	Moderate	+0.18
		- 0.18
Open buildings	Negligible	0.00

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Tornado Internal Pressure Coefficient

- GC_{piT}, Tornado internal pressure coefficient, accounts for combined effects of internal pressure and atmospheric pressure change (APC)
  - based on tornado load simulations

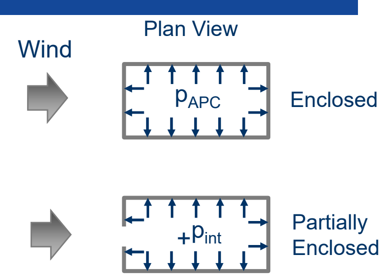

Table 32.13-1 MWFRS and C&C Tornado Internal Pressure Coefficient, (GC_{piT})

Enclosure Classification	Internal Pressure combined with APC	Tornado Internal Pressure Coefficient, (GC_{piT})
Sealed Other Structures	Extreme	+1.0
Enclosed buildings	High	+0.55
		- 0.18
Partially enclosed buildings	High	+0.55
		- 0.55
Partially open buildings	Moderate	+0.18
		- 0.18
Open buildings	Negligible	0.00

Note the high positive internal pressures for both enclosed and partially enclosed buildings

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Tornado Enclosure Classification, Internal Pressure Coefficients, and Protection of Glazed Openings

Questions / Discussion

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Tornado External Pressure Coefficients

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Tornado External Pressure Coefficients

- Building Aerodynamics
- MWFRS Pressure Coefficients
- C&C Pressure Coefficients
- Tornado Adjustment Factor for Vertical Winds

  - Review ASCE 7-16 Wind parameters
  - Changes for ASCE 7-22 Wind
  - Changes for ASCE 7-22 Tornado

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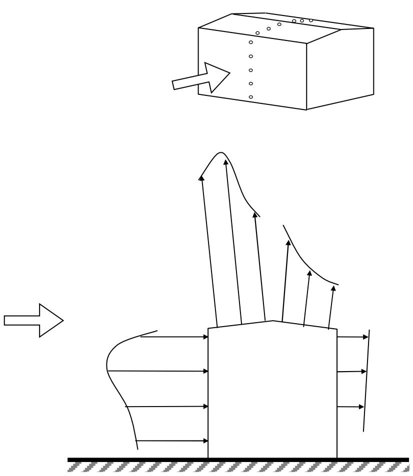
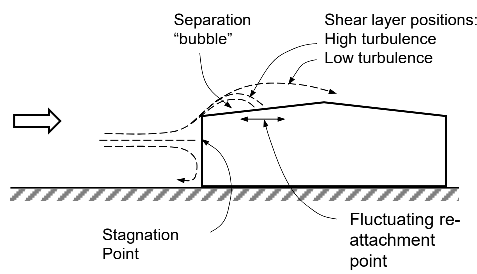
Aerodynamics of Low-Rise Buildings: Part 1



Credit: John Holmes



- General flow characteristics governed by roof height
- Flow characteristics over the roof
  - Flow separates at leading edge of roof
  - Flow separates at ridge for roof pitches > ≈ 10 degrees
  - Distance to reattachment depends on turbulence

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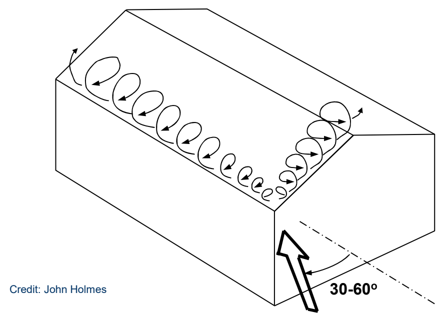
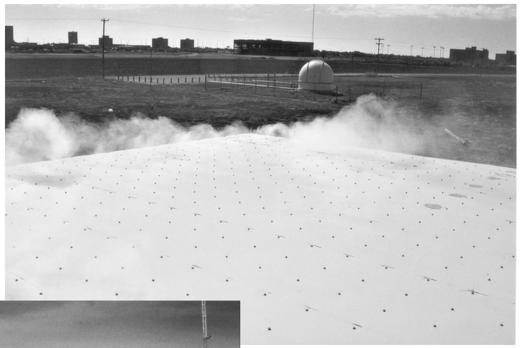
Aerodynamics of Low-Rise Buildings: Part 2

- Fluctuating and peak pressures at corners of roofs
- Formation of conical vortices





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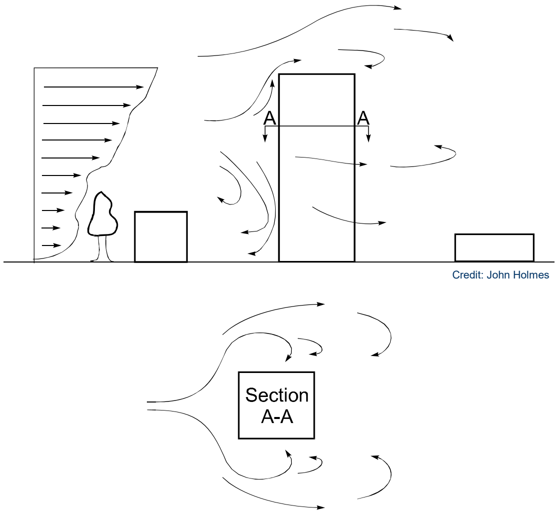
Aerodynamics of Tall Buildings

- General flow characteristics governed by the plan aspect ratio



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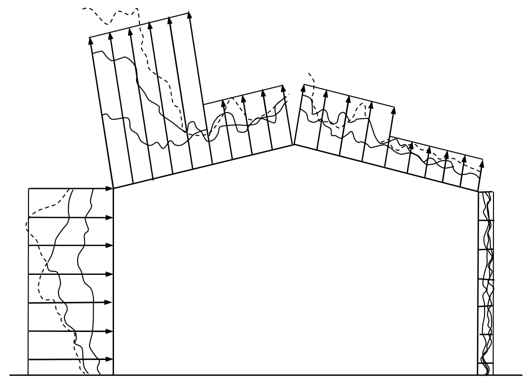
Codification of Pressures

- Structural loads (MWFRS)
  - Calculate peak structural loads and effective static load distributions
  - Instantaneous load around frame will vary in magnitude and distribution
  - Codes and standards give simplified uniform distributions on surfaces
- Components and Cladding
  - Area averaging of pressure from nearby taps for different size effective wind areas and locations



Credit: John Holmes

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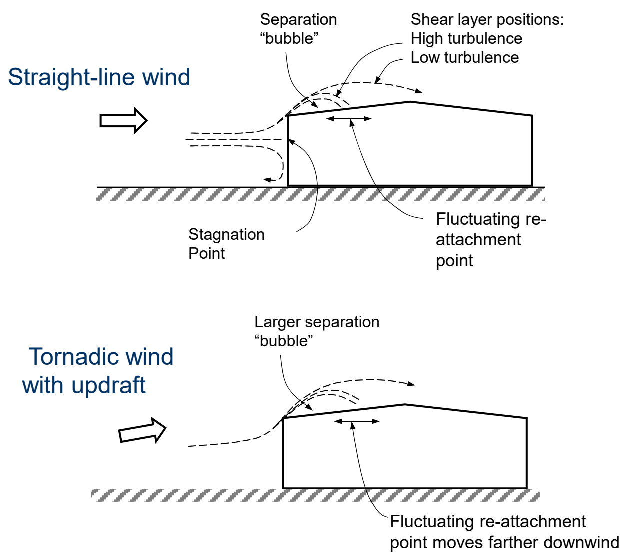
Tornado Aerodynamics of Low-Rise Buildings

- Not yet well understood
- Modest number of experiments conducted
  - Tornado-like vortex simulators
  - Boundary-layer wind tunnels (with models adapted to increase relative angle of attack)



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MWFRS Pressure Coefficients, C_p

- Chapter 27 – Directional Procedures for Buildings of All Heights
- Chapter 29 – Directional Procedure for Building Appurtenances and Other Structures

Major Changes in ASCE 7-22

- Chapter 27
  - Removed the simplified/tabular methods
  - Added Elevated Buildings
- Chapter 29
  - Added ground-mounted fixed-tilt solar panels

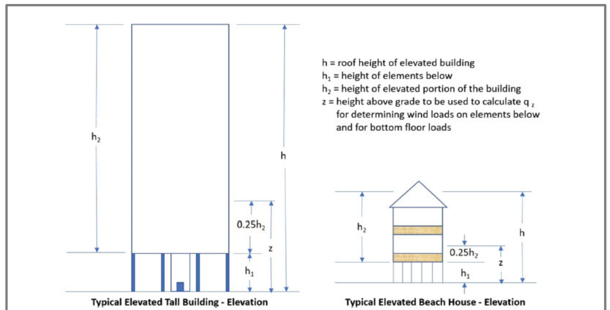

Figure C27.3-1. High-rise and low-rise examples of dimensions and heights used in Section 27.3.1.1.

ASCE 7-16 and ASCE 7-22 Wind Provisions

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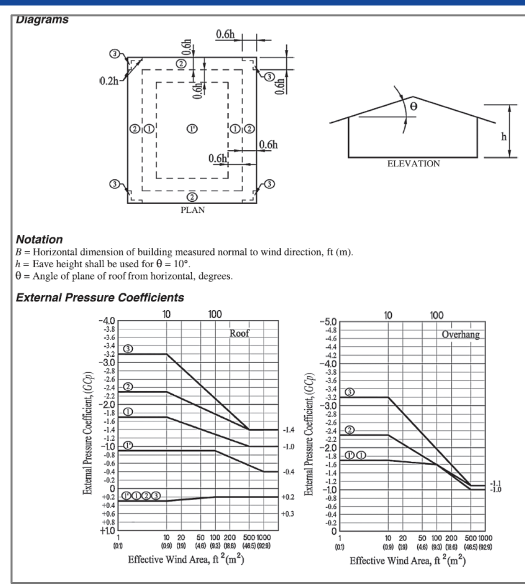
C&C Pressure Coefficients, (GC_p)

- Chapter 30 – Wind Loads: Components And Cladding
  - Applicable to buildings and non-building structures

Major Changes in ASCE 7-22

- Removed all simplified/tabular methods
- Added Elevated Buildings
- Added Roof Pavers
- Modest changes to many of the (GC_p) plots vs effective wind area for consistency

ASCE 7-16 and ASCE 7-22 Wind Provisions



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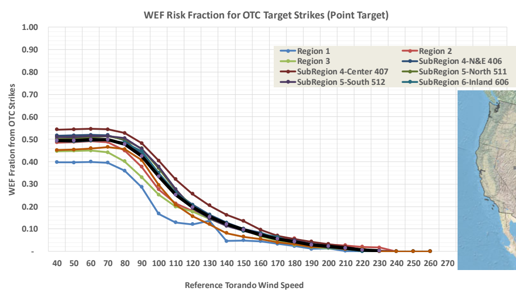
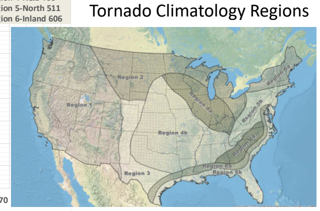
Modifications for Tornadic Updrafts

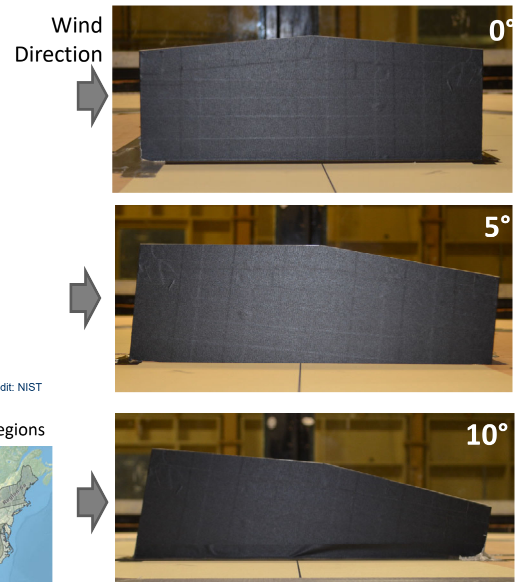
- Conducted tests in boundary layer wind tunnel where building model was 'tipped' into the floor, to simulate relative change in roof angle-of-attack due to vertical component of wind
- Developed a new coefficient that is applied to existing external pressure coefficients
- Coefficient includes a reduction factor accounting for average percentage of design tornado strikes where target building is outside the core (OTC)



Tornado Climatology Regions



Credit: NIST



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Tornado Pressure Coefficient Adjustment Factor for Vertical Winds

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- New modifier on external pressure coefficients to account for effects of updrafts in the core of the tornado (vertical component of tornadic wind)
- K_{vT} used to modify roof uplift pressure coefficients that were previously developed for boundary layer winds to account for these effects

$$C_p \text{ and } (GC_p) \rightarrow K_{vT}C_p \text{ and } K_{vT}(GC_p)$$

- $K_{vT} > 1.0$ for roof uplift coefficients (from 1.05 to 1.3)
- $K_{vT} = 1.0$ for downward acting roof pressure coefficients and wall coefficients

STRUCTURE TYPE	K_{vT}
Buildings	
Negative (Uplift) Pressures on Roofs	
Main Wind Force Resisting System	1.1
Components and Cladding	
Roof Slope <=7 degrees	
Zone 1	1.2
Zone 2	1.05
Zone 3	1.05
Roof Slope > 7 degrees	
Zone 1	1.2
Zone 2	1.2
Zone 3	1.3
Positive Pressures (Downward acting) on Roofs	1.0
Wall Pressures	1.0
All Other Cases	1.0

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Tornado External Pressure Coefficients

Questions / Discussion

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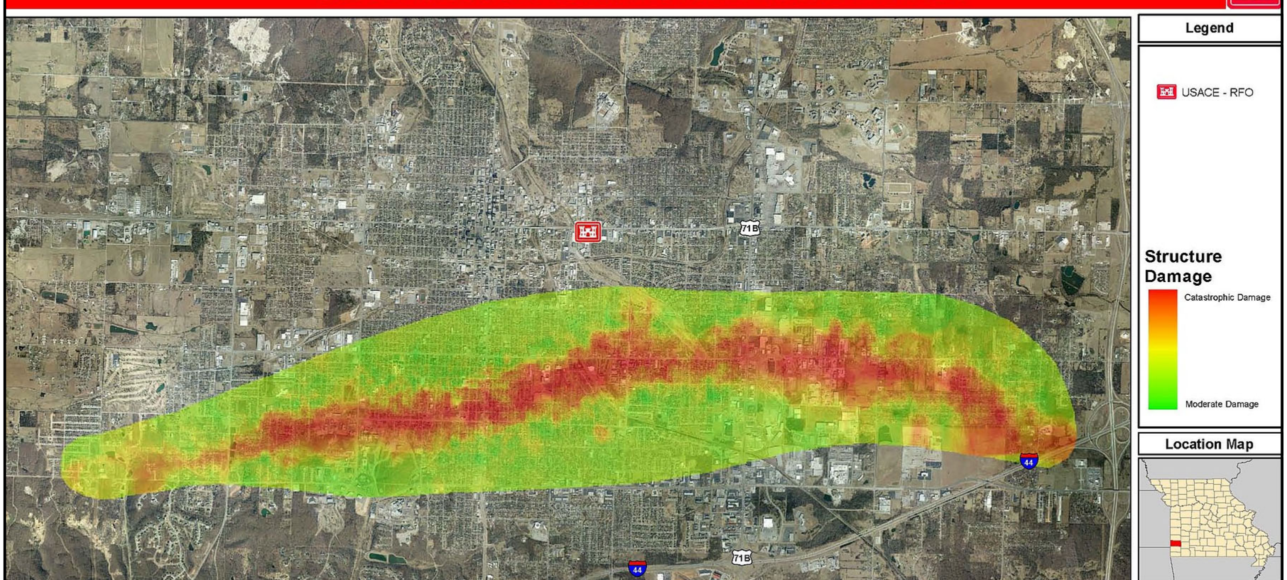
JOPLIN MISSOURI TORNADO PATH IMPACTED AREA



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Main Wind Force Resisting System Loads

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Main Wind Force Resisting System Loads

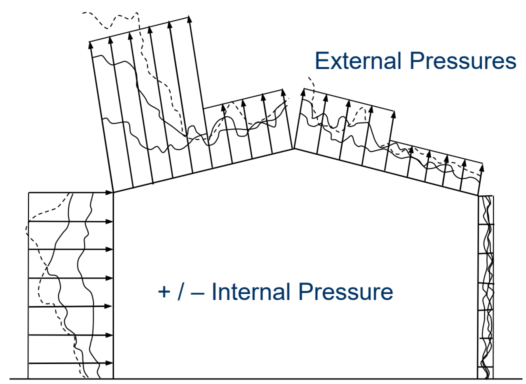
- MWFRS Pressure and Load Equations
  - Review ASCE 7-16 Wind load equations
  - Changes for ASCE 7-22 Wind
  - Changes for ASCE 7-22 Tornado

General Form of Wind and Tornado Load Eqns

- Design pressure =

  External pressure – Internal pressure

- Sign Convention
  - Positive pressure act towards surface
  - negative pressures act away from surface



After: John Holmes

Wind Design Pressures (Ch 27): Part 1

Buildings

- MWFRS $p = qGC_p - q_i(GC_{pi})$ (eqn 27.3-1)

p	Design wind pressure (psf)
q	Velocity pressure (psf)
G	Gust effect factor
C_p	External pressure coefficient

ASCE 7-16 Equations

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Wind Design Pressures (Ch 27): Part 2

Buildings

- MWFRS $p = qK_dGC_p - q_iK_d(GC_{pi})$ (eqn 27.3-1)

p	Design wind pressure (psf)
q	Velocity pressure (psf)
K_d	Directionality factor
G	Gust effect factor
C_p	External pressure coefficient

Notes:

- ASCE 7-22 equations
- K_d has been removed from velocity pressure and placed into the pressure and force equations, since it is not *purely* a function of the extreme wind climatology (it also depends on the geometry of the building)

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Tornado MWFRS Design Pressures: Part 1

Buildings

- MWFRS $p_T = q_T G_T K_{dT} K_{vT} C_p - q_{iT}(GC_{piT})$ (eqn 32.15-1)

p_T	Tornado design pressure (psf)
q_T	Tornado velocity pressure (psf)
G_T	Tornado gust effect factor
K_{dT}	Tornado directionality factor
K_{vT}	Tornado pressure coefficient adjustment factor
C_p	External pressure coefficient
(GC_{piT})	Tornado internal pressure coefficient

Note – K_{dT} is not applied to tornado internal pressure coefficient (GC_{piT}), since atmospheric pressure change (APC) dominates internal pressures for enclosed buildings and APC is not dependent on direction.

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32.15 TORNADO LOADS ON BUILDINGS: MAIN WIND FORCE RESISTING SYSTEM

32.15.1 Enclosed, Partially Enclosed, and Partially Open Buildings Section 27.3.1 shall apply for determination of MWFRS loads for buildings of all heights, as modified in this section. Design tornado pressures, p_T, for the MWFRS of enclosed, partially enclosed, and partially open buildings of all heights shall be determined in accordance with the following equation, which replaces Equation (27.3-1):

$$p_T = qG_T K_{dT} K_{vT} C_p - q_i(GC_{piT})\ (\text{lb/ft}^2) \qquad (32.15\text{-}1)$$

$$p_T = qG_T K_{dT} K_{vT} C_p - q_i(GC_{piT})\ (\text{N/m}^2) \qquad (32.15\text{-}1.\text{SI})$$

where

$q = q_{zT}$ For external pressure on all walls evaluated at height z above the ground, lb/ft^2 (N/m^2),

$q = q_{hT}$ For external pressure on roofs evaluated at height h, lb/ft^2 (N/m^2),

$q_i = q_{hT}$ For internal pressure evaluation of roofs of enclosed and partially open buildings, lb/ft^2 (N/m^2),

$q_i = q_{zT}$ For internal pressure evaluation of walls of enclosed and partially open buildings, lb/ft^2 (N/m^2),

$q_i = q_{zop}$ For internal pressure evaluation of the roof and all walls in partially enclosed buildings, where height z_{op} is defined as the level of the lowest opening in the building that could affect the positive internal pressure, lb/ft^2 (N/m^2). Glazed openings not meeting the protection requirements of Section 32.12.3.1 shall be considered as openings,

G_T = Tornado gust-effect factor from Section 32.11,

K_{dT} = Tornado directionality factor from Section 32.6,

K_{vT} = Tornado pressure coefficient adjustment factor from Section 32.14,

C_p = External pressure coefficient from Section 27.3.1, and

GC_{piT} = Tornado internal pressure coefficient from Section 32.13.

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Tornado MWFRS Design Pressures: Part 2

Section 32.15 also includes MWFRS provisions for
- Elevated Buildings
- Open Buildings
- Roof Overhangs
- Parapets

- Based on Chapter 27 equations, with similar tornado modifications to associated design pressure and force equations

Section 32.16 has MWFRS provisions for
- Solid Freestanding Walls and Solid Signs
- Other Structures
  - chimneys, tanks, open signs, single-plane open frames, and trussed towers
- Trussed Towers
- Rooftop Structures and Equipment for Buildings
- Roofs of Isolated Circular Bins, Silos, and Tanks
- Rooftop Solar Panels

- Based on Chapter 29 equations

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Main Wind Force Resisting System Loads

Questions / Discussion

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Components and Cladding Loads

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Components and Cladding Loads

- C&C Pressure and Load Equations
  - Review ASCE 7-16 Wind load equations
  - Changes for ASCE 7-22 Wind
  - Changes for ASCE 7-22 Tornado

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C&C Wind Design Pressures (Ch 30)

- C&C (h<60') $p = q_h[(GC_p) - (GC_{pi})]$ (eqn 30.3-1)
- C&C (h>60') $p = q(GC_p) - q_i(GC_{pi})$ (eqn 30.5-1)

p Design wind pressure (psf)
q Velocity pressure (psf)
(GC_p) External C&C pressure coefficient
(GC_{pi}) Internal pressure coefficient

Notes:

- ASCE 7-16 equations shown
- h = mean roof height

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C&C Wind Design Pressures (Ch 30)

- C&C (h<60') $p = q_h K_d [(GC_p) - (GC_{pi})]$ (eqn 30.3-1)
- C&C (h>60') $p = qK_d (GC_p) - q_i K_d (GC_{pi})$ (eqn 30.4-1)

p Design wind pressure (psf)
q Velocity pressure (psf)
K_d Directionality factor
(GC_p) External C&C pressure coefficient
(GC_{pi}) Internal pressure coefficient

Notes:

- ASCE 7-22 equations shown
- In ASCE 7-22, K_d has been removed from velocity pressure and placed into the pressure and force equations, since it is not *purely* a function of the extreme wind climatology (it also depends on the geometry of the building)

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Tornado C&C Design Pressures: Part 1

- C&C (h<60') $p_T = q_{hT}[K_{dT}K_{vT}(GC_p) - (GC_{piT})]$ (eqn 32.17-1)
- C&C (h>60') $p_T = q_T K_{dT} K_{vT}(GC_p) - q_{iT}(GC_{piT})$ (eqn 32.17-2)

p_T	Tornado design pressure (psf)
q_T	Tornado velocity pressure (psf)
K_{dT}	Tornado directionality factor
K_{vT}	Tornado pressure coefficient adjustment factor
(GC_p)	External C&C pressure coefficient
(GC_{piT})	Tornado internal pressure coefficient

Note – K_{dT} is not applied to tornado internal pressure coefficient (GC_{piT}), since atmospheric pressure change (APC) dominates internal pressures for enclosed buildings and APC is not dependent on direction.

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32.17 TORNADO LOADS: COMPONENTS AND CLADDING

32.17.1 Low-Rise Buildings Section 30.3 shall apply for determination of component and cladding tornado loads on low-rise buildings, as modified in this section. The design tornado pressures, p_T, on C&C elements in low-rise buildings and buildings with $h \leq 60$ ft ($h \leq 18.3$ m) shall be determined in accordance with the following equation, which replaces Equation (30.3-1):

$$p_T = q_{hT}[K_{dT}K_{vT}(GC_p) - GC_{piT}] \ (\text{lb/ft}^2) \qquad (32.17\text{-}1)$$

$$p_T = q_{hT}[K_{dT}K_{vT}(GC_p) - GC_{piT}] \ (\text{N/m}^2) \qquad (32.17\text{-}1.\text{SI})$$

where

q_{hT} = Tornado velocity pressure from Section 32.10.2 evaluated at mean roof height h, lb/ft^2 (N/m^2);
K_{dT} = Tornado directionality factor from Section 32.6;
K_{vT} = Tornado pressure coefficient adjustment factor from Section 32.14;
GC_p = External pressure coefficient from Section 30.3; and
GC_{piT} = Tornado internal pressure coefficient from Section 32.13.

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32.17.2 Buildings with $h > 60$ ft ($h > 18.3$ m) Section 30.4 shall apply for the determination of component and cladding tornado loads on buildings with $h > 60$ ft ($h > 18.3$ m), as modified in this section. The design tornado pressures, p_T, on C&C elements for all buildings with $h > 60$ ft ($h > 18.3$ m) shall be determined in accordance with the following equation, which replaces Equation (30.4-1):

$$p_T = qK_{dT}K_{vT}(GC_p) - q_i(GC_{piT}) \text{ (lb/ft}^2\text{)} \quad (32.17\text{-}2)$$

$$p_T = qK_{dT}K_{vT}(GC_p) - q_i(GC_{piT}) \text{ (N/m}^2\text{)} \quad (32.17\text{-}2.SI)$$

where

$q = q_{zT}$ For external pressure on all walls evaluated at height z above the ground, lb/ft^2 (N/m^2);

$q =$ For external pressures on roofs evaluated at height h, lb/ft^2 (N/m^2);

$q_i = q_{hT}$ For internal pressure evaluation of roofs of enclosed and partially open buildings, lb/ft^2 (N/m^2);

$q_i = q_{zT}$ For internal pressure evaluation of walls of enclosed and partially open buildings, lb/ft^2 (N/m^2);

$q_i = q_{zop}$ For internal pressure evaluation of the roof and all walls in partially enclosed buildings, where height z_{op} is defined as the level of the lowest opening in the building that could affect the positive internal pressure, lb/ft^2 (N/m^2). Glazed openings not meeting the protection requirements of Section 32.12.3.1 shall be considered as openings;

K_{dT} = Tornado directionality factor from Section 32.6;

K_{vT} = Tornado pressure coefficient adjustment factor from Section 32.14;

GC_p = External pressure coefficient from Section 30.4; and

GC_{piT} = Tornado internal pressure coefficient from Section 32.13.

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Tornado C&C Design Pressures: Part 2

Section 32.17 includes C&C provisions for Buildings

- Low-rise Buildings
- Buildings with h>60 ft
- Bottom Horizontal Surfaces of Elevated Buildings (for low-rise and h>60 ft)

Building Appurtenances and Rooftop Structures and Equipment

- Parapets
- Roof Overhangs
- Attached Canopies

Nonbuilding Structures

- Isolated Circular Bins, Silos, and Tanks

- Based on Chapter 30 equations, with similar tornado modifications to associated design pressure and force equations

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Components and Cladding Loads

Questions / Discussion

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Wind Tunnel Method

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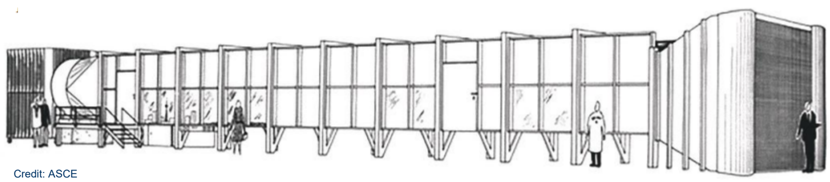
Wind Tunnel Method

- Wind Tunnel Testing Overview
- Wind Tunnel Method
- Referenced Wind Tunnel Test Standard

  - Review ASCE 7-16 Wind Tunnel Method
  - Changes for ASCE 7-22 Wind
  - Changes for ASCE 7-22 Tornado



Credit: ASCE

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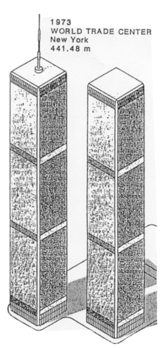
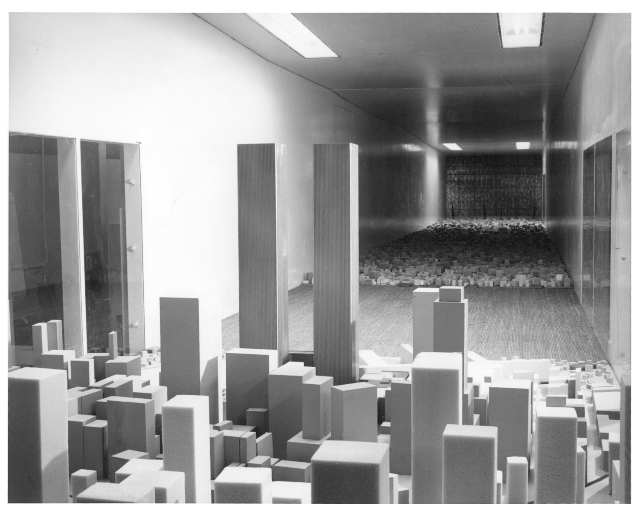
Boundary Layer Wind Tunnel Testing

- World Trade Center – New York 1973-2001
- First buildings to be tested in a turbulent boundary-layer flow wind tunnel (mid 1960's)





Credit: John Holmes

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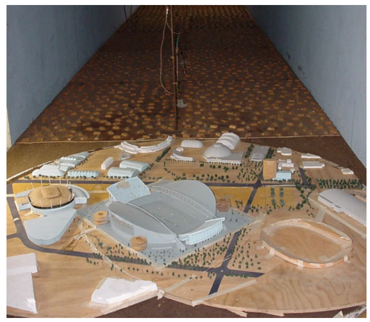
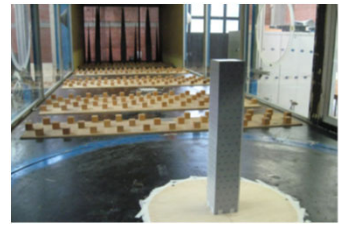
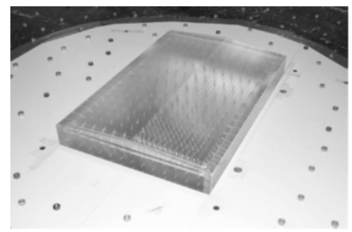
Wind Tunnel Testing Applications

- Tall buildings
  - Exploration of shapes
  - Design pressures
  - Dynamic and Crosswind loads
- Unusually shaped buildings
- Long span bridges
- Parametric studies for codification of wind loads
- Non-structural
  - Pedestrian-level winds
  - Dispersion studies



Credit: John Holmes





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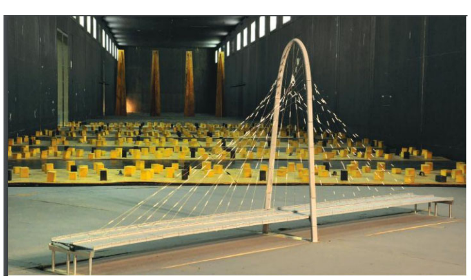
Wind Tunnel Testing Background

- First Boundary Layer Wind Tunnel Laboratory
- ASCE's Civil Engineering Magazine
  - Oct 2019
  - https://www.asce.org/-/media/asce-images-and-files/career-and-growth/pre-college-outreach/force-of-nature-ce-magazine-history-lesson-october-2019.pdf



· HISTORY LESSON ·

Force of Nature: The Boundary Layer Wind Tunnel Laboratory

WIND TUNNELS, which can generate wind at a reduced scale for research purposes, have been used by the aviation industry since the beginning of the 20th century. "However, the wind through which airplanes fly is markedly different from that near the earth's surface, where we construct our buildings and structures," says Nicholas Isyumov, Ph.D., P.Eng., a professor emeritus of civil and environmental engineering at Western University in London, Ontario, Canada, and a consulting director of the Boundary Layer Wind Tunnel Laboratory (BLWTL)—the first wind tunnel built explicitly to test the effects of wind on the built environment. The BLWTL, located at Western, was recognized in 2018 as a National Historic Site by the Canadian Society for Civil Engineering and as an international landmark in ASCE's Historic Civil Engineering Landmark program.

When engineers began to focus on the effects of turbulent wind on structures in the middle of the 20th century, they revolutionized a new civil engineering specialty, wind engineering, that has profoundly shaped high-rises, bridges, and ordinary buildings ever since.

The key figure in the development of this specialty was Canadian engineer Alan Davenport. Born in India and raised in South Africa, Davenport obtained bachelor's and master's degrees in mechanical sciences from Cambridge University, in the United Kingdom, earned a master's degree in civil engineering from the University of Toronto and a doctorate from the University of Bristol, in the United Kingdom. He began his academic career at Western.

Davenport's doctoral work centered on wind action on long-span bridges and guyed masts.

"He'd done some full-scale measurements on the Severn Bridge in England and realized that wind was highly turbulent and that the wind loads you really needed to be designing structures for must include that turbulence component," says J. Peter C. King, Ph.D., P.Eng., F.CSCE, currently a consulting director of the BLWTL. "At the time, there really were no codes that took that into account."

Davenport, King says, "wrote a number of seminal papers that described his theories on how you should be treating wind loads on structure." In 1963 he presented a paper at the first International Symposium on Wind Effects on Buildings and Structures in Teddington, England, United Kingdom, that drew the attention of Leslie E. Robertson, P.E., Dist.M.ASCE, the lead structural engineer of the twin towers at the World Trade Center. Robertson asked Davenport to join the design team as a wind expert. Davenport worked on the project for two years, shuttling between Ontario and New York City.

Wind tests on models of the twin towers were completed at two sites: the National Physical Laboratory (NPL) in the United Kingdom and Colorado State University, the latter of which had a wind tunnel that was used to study environmental issues for the U.S. military. Davenport, along with Jack E. Cermak, Ph.D., P.E., Hon.M.ASCE, who was then a professor of civil engineering at Colorado State, oversaw modifications on the tunnel.

King says Davenport "recognized there was a real niche

Testing at the Boundary Layer Wind Tunnel Laboratory helped shape a more elegant design for the CN Tower in Toronto.

COURTESY OF THE BOUNDARY LAYER WIND TUNNEL LABORATORY/UWO

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Wind Tunnel Method: Part 1

- Test Conditions – per ASCE 49
- Limitations on loads
  - C&C loads can't be less than 80% of wind loads from Ch. 30, with some exceptions
- Provisions for roof-mounted solar collectors
- Reference Standard
  - ASCE 49, Wind Tunnel Testing for Buildings and Other Structures, 2012

ASCE 7-16 Wind Provisions

CHAPTER 31
WIND TUNNEL PROCEDURE

31.1 SCOPE

The Wind Tunnel Procedure shall be used where required by Sections 27.1.3, 28.1.3, and 29.1.3. The Wind Tunnel Procedure shall be permitted for any building or other structure in lieu of the design procedures specified in Chapter 27 (main wind force resisting system [MWFRS] for buildings of all heights and simple diaphragm buildings with $h \leq 160$ ft (48.8 m)), Chapter 28 (MWFRS of low-rise buildings and simple diaphragm, low-rise buildings), Chapter 29 (MWFRS for all other structures), and Chapter 30 (components and cladding [C&C] for all building types and other structures).

User Note: Chapter 31 may always be used for determining wind pressures for the MWFRS and/or for C&C of any building or other structure. This method is considered to produce the most accurate wind pressures of any method specified in this standard.

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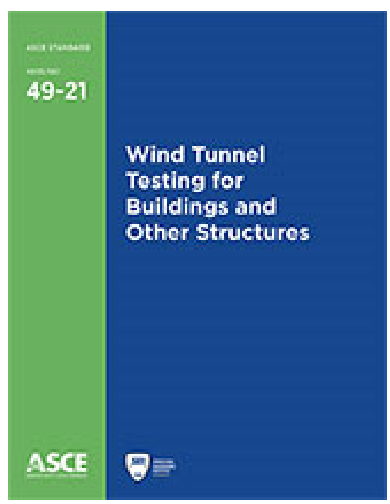
Wind Tunnel Method: Part 2

- Provisions added for Numerical Wind Tunnel (i.e., computational fluid dynamics)
- New Peer-review requirements
- Revisions to solar panel systems
- Updated Reference Standard
  - ASCE 49, Wind Tunnel Testing for Buildings and Other Structures, 2021

ASCE 7-22 Wind Provisions



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Tornado Loads - Wind Tunnel Procedure

32.18 TORNADO LOADS: WIND TUNNEL PROCEDURE
The wind tunnel procedure, as described in Chapter 31, is permitted for determination of external pressure coefficients and force coefficients for use with the tornado loading provisions of Sections 32.15 through 32.17.

The wind tunnel test shall be performed on an isolated building model (without a proximity model) in a boundary layer wind tunnel for open (Exposure C) terrain.

- Wind tunnel procedure is limited to determination of pressure and force coefficients for use with MWFRS and C&C
- Testing of isolated models in Exposure Category C is specified to be consistent with typical test conditions used for development of pressure and force coefficients in Chapters 27, 29, and 30

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Wind Tunnel Method Applicability

Practice Your Knowledge

Scenario –

A museum has contracted with the famous architect Frank Gehry to design a signature museum being planned for downtown St. Louis. The building has a very unusual shape. The design team contracts with a laboratory to conduct boundary layer wind tunnel tests on the model of the museum

a) as an isolated building in exposure C terrain, and

b) with an area model in place (containing all buildings for the surrounding few blocks in every direction) in exposure B terrain

Question –

For determination of tornado loads, will the engineering team be able to use all results from both test conditions a) and b), or only a subset of these results?

IAC Building in New York – one of many unusual designs by Gehry.

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Wind Tunnel Method

Questions / Discussion

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Summary

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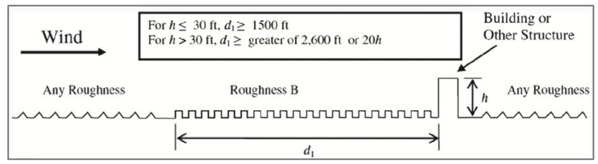
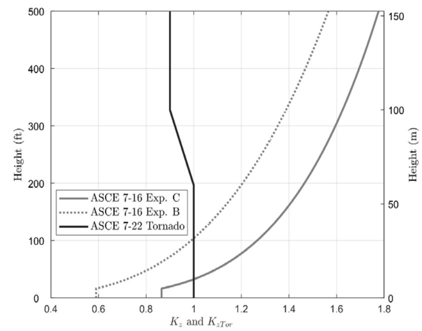
Unit 3: Summary Part 1

- Exposure, Topographic and Ground Elevation Effects
  - Importance of accurate determination of exposure for wind loads
  - Single, undefined exposure for tornadoes
- Topographic Effects
  - None for tornadoes at this time
- Velocity Pressure
  - Wind velocity pressure exposure coefficients modified in 7-22 – primarily impacts to tall buildings
  - Tornado - Uniform (K_{zTor} = 1.0) velocity pressure below 200 ft, decreases slightly above that

Upwind surface roughness conditions required for Exposure B





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Unit 3: Summary Part 2

- Tornado Directionality Factor
  - Generally less than for wind, except for roof zone 1'
  - K_{dT} = 1.0 for C&C on Essential Facilities
- Tornado Gust Effect Factor
  - Use 0.85 or Rigid Structure wind provisions
  - No flexible gust effect factor for tornadoes
- Tornado Enclosure Classification
  - Unprotected glazing must be assumed to have been broken by windborne debris
- Debris Considerations
  - Glazing protection required for Essential Facilities

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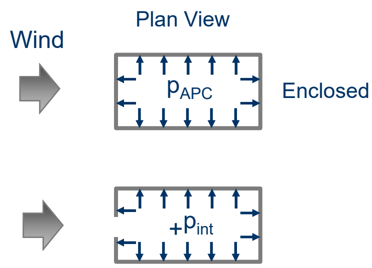
Unit 3: Summary Part 3

- Protection Requirements for Glazed Openings
  - Impact resistant glazing, or
  - impact-protective system
    - permanently affixed non-operable systems, or
    - permanently affixed operable systems capable of being fully deployed from inside the building within five minutes and used in buildings that are staffed 24 hours per day

- Tornado Internal Pressure Coefficients
  - Enclosed buildings have high internal pressure due to APC (GC_{piT} = +0.55)
- Tornado External Pressure Coefficients
  - New K_{vT} modification factor to account for increased uplift on roofs due to updrafts



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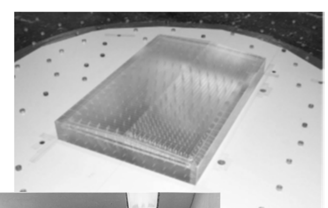
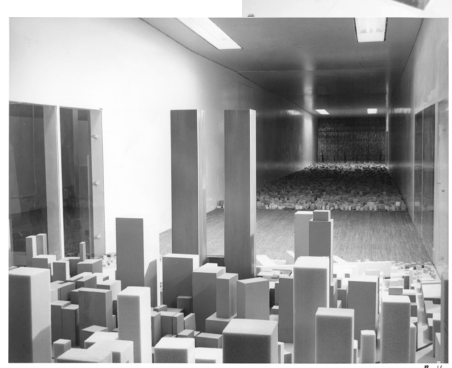
Unit 3: Summary Part 4

- Main Wind Force Resisting System Loads
  - Adaptation of Ch 27 and 29 methods
  - K_{dT} only applies to external pressures
  - Differences in treatment of velocity pressure q
- Components and Cladding Loads
  - Adaptation of Ch 30 methods
  - K_{dT} only applies to external pressures
  - Differences in treatment of velocity pressure q
- Wind Tunnel Method
  - Can only be used to determine pressure coefficients from isolated building model in Exposure C





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Break

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