MAKING SCHOOLS SAFE AGAINST WINDS 6

6.1 INTRODUCTION

A well-designed, constructed, and maintained school may be damaged by a wind event that is much stronger than what the building was designed for; however, except for tornado damage, this scenario is a very rare occurrence. Rather, most damage occurs because various building elements have limited wind resistance due to inadequate design, application, or material deterioration. Wind with sufficient speed to cause damage to weak schools can occur anywhere in the United States and its possessions.[1] Although the magnitude and frequency of strong windstorms varies by locale, all schools should and can be designed, constructed, and maintained to avoid wind damage (other than that associated with tornadoes). In tornado-prone regions, consideration should be given to designing and constructing portions of schools to provide occupant protection.[2]

This chapter discusses structural and nonstructural building components and illustrates a variety of wind-induced damages. Because of the frequency and significant consequences of nonstructural component failure, emphasis is given to these elements.

Numerous examples of best practices pertaining to new and existing schools are presented for consideration. Incorporation of those practices that are applicable to a specific project will result in greater wind-resistance reliability and will, therefore, provide enhanced protection for occupants and decreased expenditures for repair of wind-damaged facilities.

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[1] The U.S. possessions include American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands.

[2] Tornado-prone regions are defined in Section 6.7.1.

6.2 THE NATURE AND PROBABILITY OF HIGH WINDS

A variety of windstorm types occur in different areas of the U.S. The characteristics of the type of storms that can impact the site should be considered by the design team. The primary storm types are:

- **Straight-line wind.** This type of wind event is the most common. The wind is considered, in general, to blow in a straight line. Straight-line wind speeds range from very low to very high. High winds associated with intense low pressure can last for upward of a day at a given location. Straight-line winds occur throughout the U.S. and its possessions (see Figure 6-1).

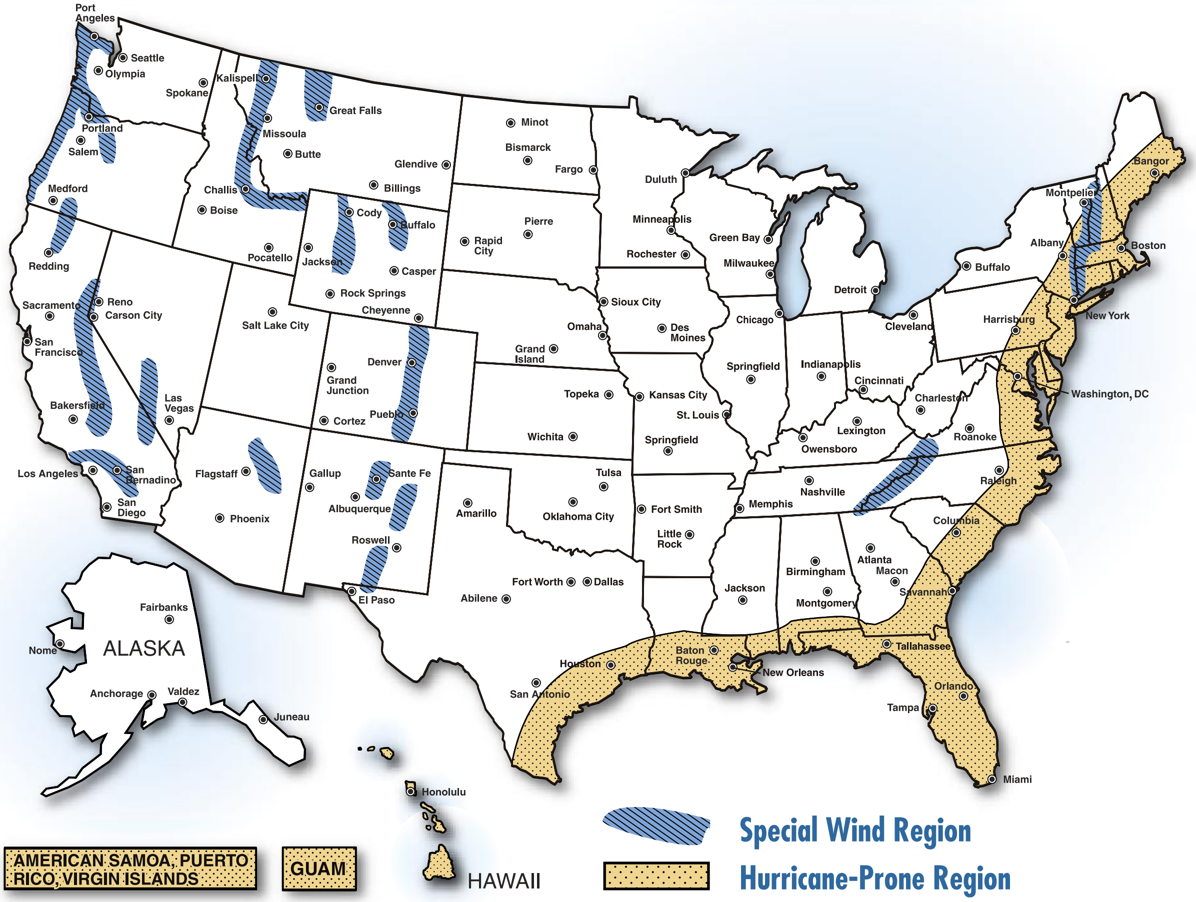


Figure 6-1 Hurricane-prone regions and special wind regions

Note: Hurricane/typhoon-prone regions also include American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands.

SOURCE: ADAPTED FROM ASCE 7-02

- **Down-slope wind.** Wind flowing down the slope of mountains is referred to as down-slope wind. Down-slope winds with very high wind speeds frequently occur in Alaska and Colorado. In the continental U.S., mountainous areas are referred to as "special wind regions" (see Figure 6-1). Neither ASCE 7 or model building codes provide guidance on wind speeds in special wind regions. If the local building department has not established the basic speed, use of regional climatic data and consultation with a wind engineer or meteorologist is advised.

- **Thunderstorm.** This type of storm can rapidly form and produce high wind speeds. Approximately 10,000 severe thunderstorms occur in the U.S. each year, typically in the spring and summer. They are most common in the Southeast and Midwest. Besides producing high winds, they often create heavy rain. Hail and tornadoes are also sometimes produced. Thunderstorms commonly move through an area quite rapidly, often causing high winds for only a few minutes at a given location. However, thunderstorms can also stall and become virtually stationary.

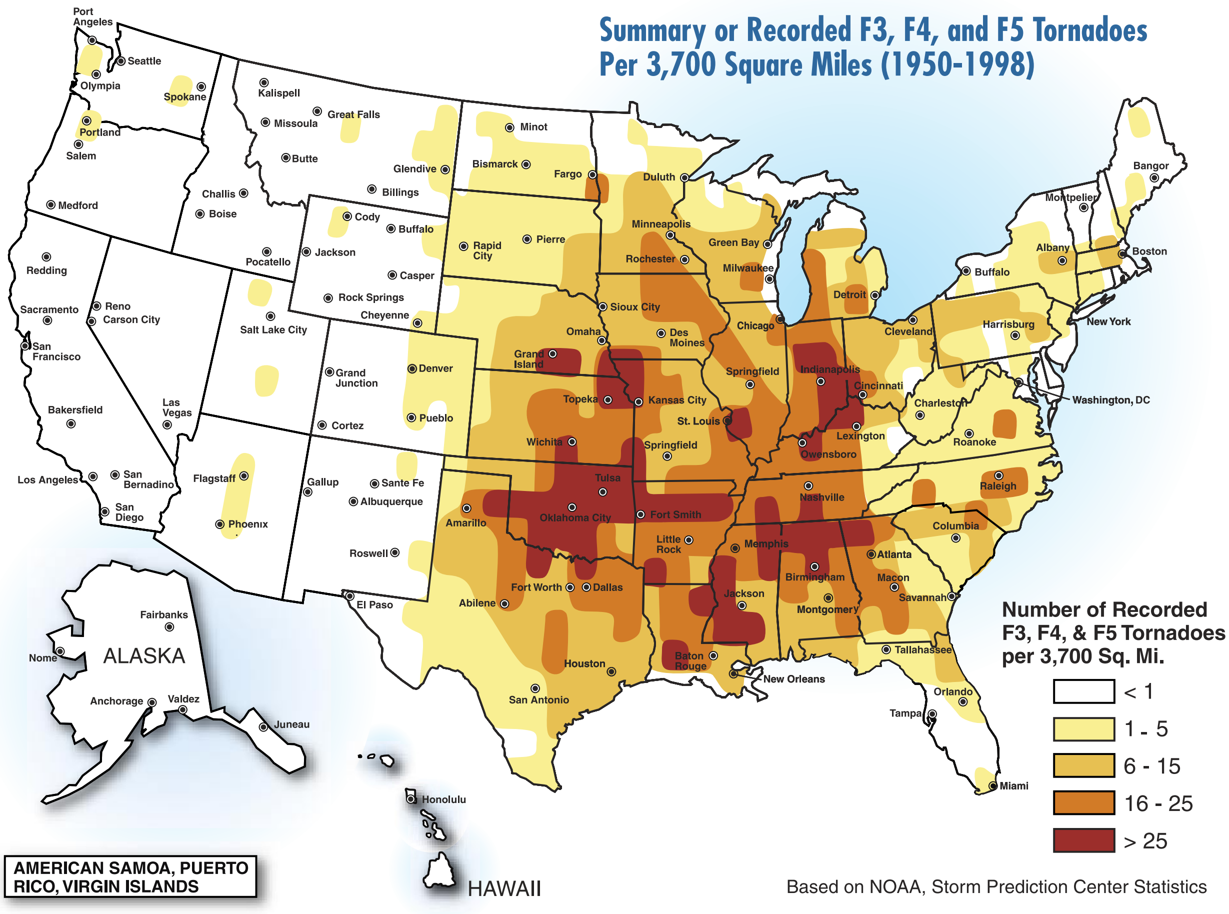
- **Downburst.** Also known as microburst, it is a powerful downdraft associated with a thunderstorm. When the downdraft reaches the ground, it spreads out horizontally and may form one or more horizontal vortex rings around the downdraft. The outflow is typically 6,000 to 12,000 feet across and the vortex ring may rise 2,000 feet above the ground. The life-cycle of a downburst is usually between 15 to 20 minutes. Observations suggest that approximately 5 percent of all thunderstorms produce a downburst, which can result in significant damage in a localized area.

- **Northeaster (nor'easter).** This type of storm is cold and violent and occurs along the northeastern coast of the U.S. These storms blow in from the Northeast and may last for several days.

- **Hurricane.** This is a system of spiraling winds converging with increasing speed toward the storm's center (the eye of the hurricane). Hurricanes form over warm oceans. The diameter of the storm varies between 50 and 600 miles. A hurricane's forward movement (translational speed) can vary between approximately 10 to 25 miles per hour (mph). Besides being capable of delivering extremely strong winds for several hours, many hurricanes also bring very heavy rainfall. Hurricanes also occasionally spawn tornadoes. The Saffir-Simpson Hurricane Scale rates the intensity of hurricanes. The five-step scale ranges from Category I (the weakest) to Category V (the strongest). Hurricane-prone regions are defined in Section 6.2.1.

Of all the storm types, hurricanes have the greatest potential for devastating a very large geographical area and, hence, affect great numbers of people. The terms "hurricanes, tropical cyclones, and typhoons" are synonymous for the same type of storm. See Figure 6-1 for hurricane-prone regions.

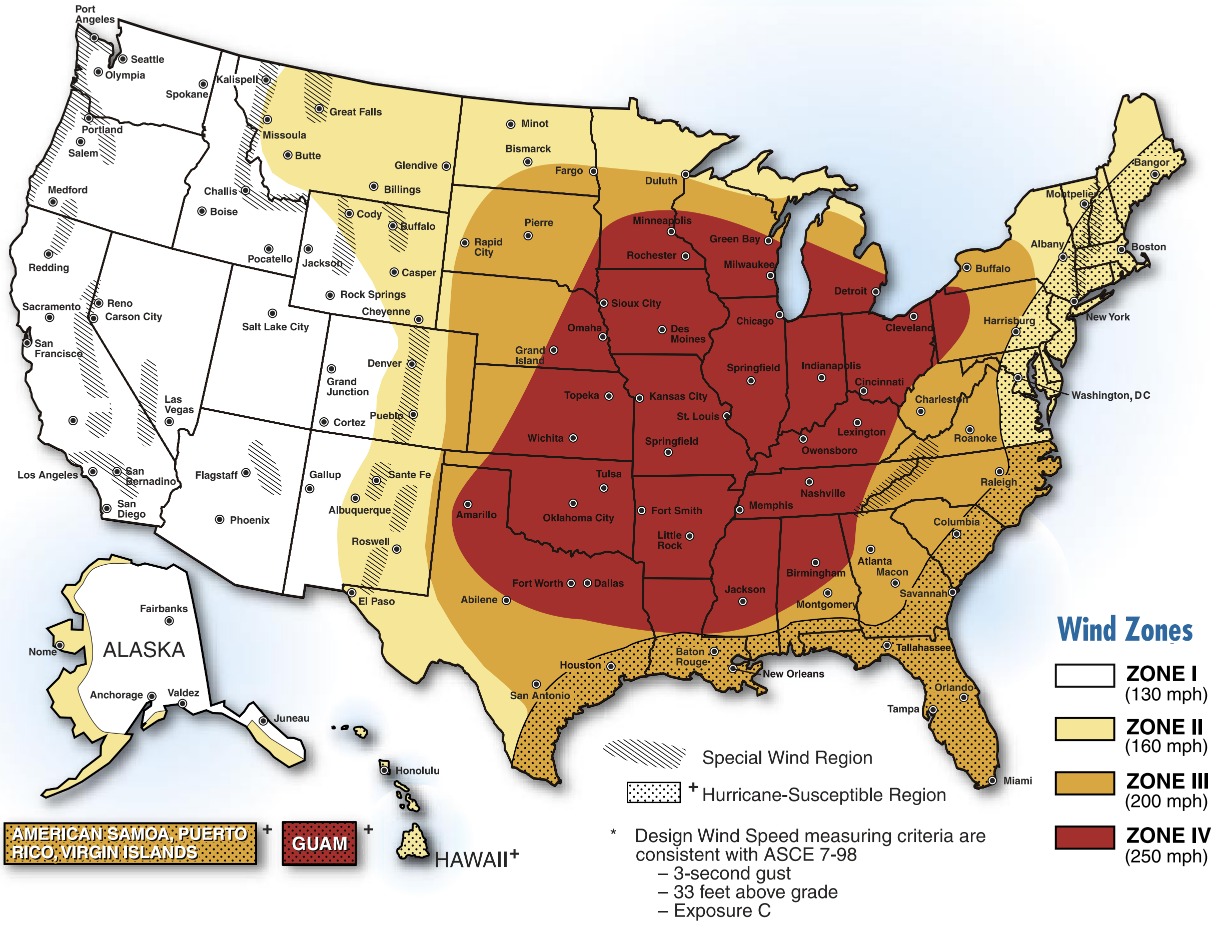
- **Tornado.** This is a violently rotating column of air extending from the base of a thunderstorm to the ground. The Fujita scale categorizes tornado severity based on observed damage. The six-step scale ranges from F0 (light damage) to F5 (incredible damage). Weak tornadoes (F0 and F1) are most common, but strong tornadoes (F2 and F3) frequently occur. Violent tornadoes (F4 and F5) are rare. Tornado path widths are typically less than 1,000 feet; however, widths of approximately 1 mile have been reported. Wind speed rapidly decreases with increased distance from the center of a tornado. A school on the periphery of a strong or violent tornado could be subjected to moderate to high wind speeds, depending upon the distance from the core of the tornado. However, even though the wind speed might not be great, a school on the periphery could still be impacted by many large pieces of wind-borne debris. Tornadoes are responsible for the greatest number of wind-related deaths each year in the U.S. Figure 6-2 shows frequency of occurrence for 1950 to 1998 and Figure 6-3 shows the design wind speeds used for the design of community tornado shelters.


Summary or Recorded F3, F4, and F5 Tornadoes Per 3,700 Square Miles (1950-1998)

Based on NOAA, Storm Prediction Center Statistics

Figure 6-2 Tornado occurrence in the United States based on historical data

SOURCE: FEMA 361, *DESIGN AND CONSTRUCTION GUIDANCE FOR COMMUNITY SHELTERS*, 2000



* Design Wind Speed measuring criteria are consistent with ASCE 7-98
- 3-second gust
- 33 feet above grade
- Exposure C

Figure 6-3 Design wind speeds for community tornado shelters

SOURCE: FEMA 361, *DESIGN AND CONSTRUCTION GUIDANCE FOR COMMUNITY SHELTERS*, 2000

6.2.1 Wind/Building Interactions

When wind interacts with a building, both positive and negative (i.e., suction) pressures occur simultaneously (see Figure 6-4). (Note: negative pressures are less than ambient pressure, and positive pressures are greater than ambient pressure.) The school must have sufficient strength to resist the applied loads in order to prevent wind-induced building failure. The magnitude of the pressures is a function of the following primary factors:

- **Exposure.** The characteristics of the ground roughness and surface irregularities in the vicinity of a building influence the wind loading. ASCE 7 defines three exposure categories, Exposures B, C, and D.[3] Exposure B is the roughest terrain and Exposure D is the smoothest. Exposure B includes urban, suburban, and wooded areas. Exposure C includes flat open terrain with scattered obstructions and areas adjacent to water surfaces in hurricane-prone regions (which are defined below under “basic wind speed”). Exposure D includes areas adjacent to water surfaces outside hurricane-prone regions, mud flats, salt flats, and unbroken ice. Because of the wave conditions generated by hurricanes, areas adjacent to water surfaces in hurricane-prone regions are considered to be Exposure C rather than the smoother Exposure D.

The smoother the terrain, the greater the wind load; therefore, schools (with the same basic wind speed) located in Exposure D would receive higher wind loads than those located in Exposure C.

For additional information, see the *Commentary* of ASCE 7, which includes several aerial photographs that illustrate the different terrain conditions associated with Exposures B, C, and D.

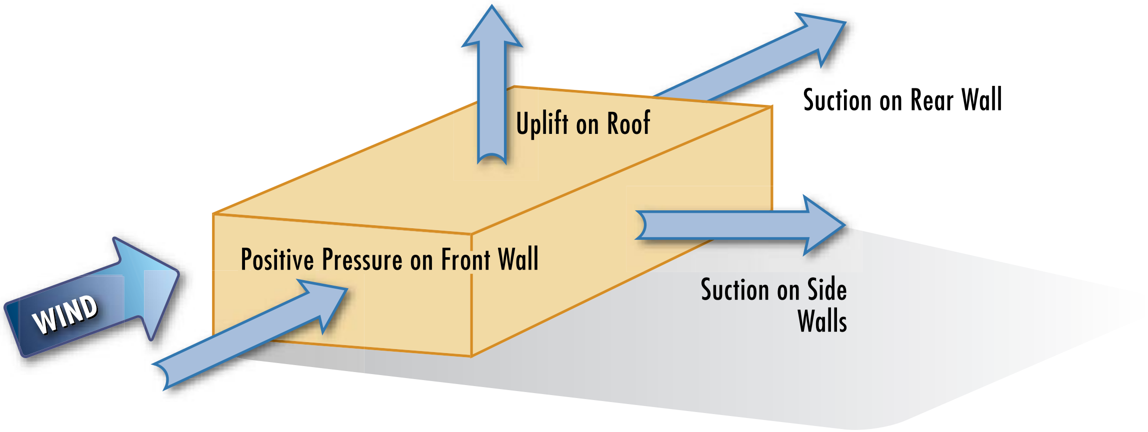


Figure 6-4
Schematic of wind-induced pressures on a building

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[3] Chapter 6 of ASCE 7 provides guidance for determining wind loads on buildings. The IBC and NFPA 5000 refer to ASCE 7 for wind load determination.

- **Basic wind speed.** ASCE 7 defines the basic wind speed as the wind speed with a 50-year mean recurrence interval (2 percent annual probability), measured at 33 feet above grade in Exposure C (flat open terrain). If the building is located in Exposure B or D, rather than C, an adjustment for the actual exposure is made in the ASCE 7 calculation procedure.

  Since the 1995 edition of ASCE 7, the basic wind speed has been a peak gust speed. Prior to that time, the basic wind speed was a fastest-mile speed (i.e., the speed averaged over the time required for a mile-long column of air to pass a fixed point). Because the measuring time for peak gust versus fastest-mile is different, peak gust speeds are typically about 20 miles per hour (mph) faster than fastest-mile speeds (e.g., a 90-mph peak basic wind speed is equivalent to a 70-mph fastest-mile wind speed). Most of the U.S. has a basic wind speed (peak gust) of 90 mph, but much higher speeds occur in Alaska and in hurricane-prone regions. The highest speed, 170 mph, occurs in Guam.

  Hurricane-prone regions are along the Atlantic and Gulf of Mexico coasts (where the basic wind speed is greater than 90 mph), Hawaii, and the U.S. possessions in the Caribbean and South Pacific (see Figure 6-1).

  In determining wind pressures, the basic wind speed is squared; therefore, as the velocity is increased, the pressures are exponentially increased. For example, the uplift load on a 30-foot high roof covering at a corner area of a school in Exposure B is 37.72 pounds per square foot (psf) with a basic wind speed of 85 mph (per ASCE 7-02). If the speed is doubled to 170 mph, the roof corner load increases by a factor of four to 151 psf.

- **Topography.** Abrupt changes in topography, such as isolated hills, ridges, and escarpments, cause wind speed-up; therefore, a school located near a ridge would receive higher wind loads than a school located on relatively flat land. ASCE 7 provides a procedure to account for topographic influences.

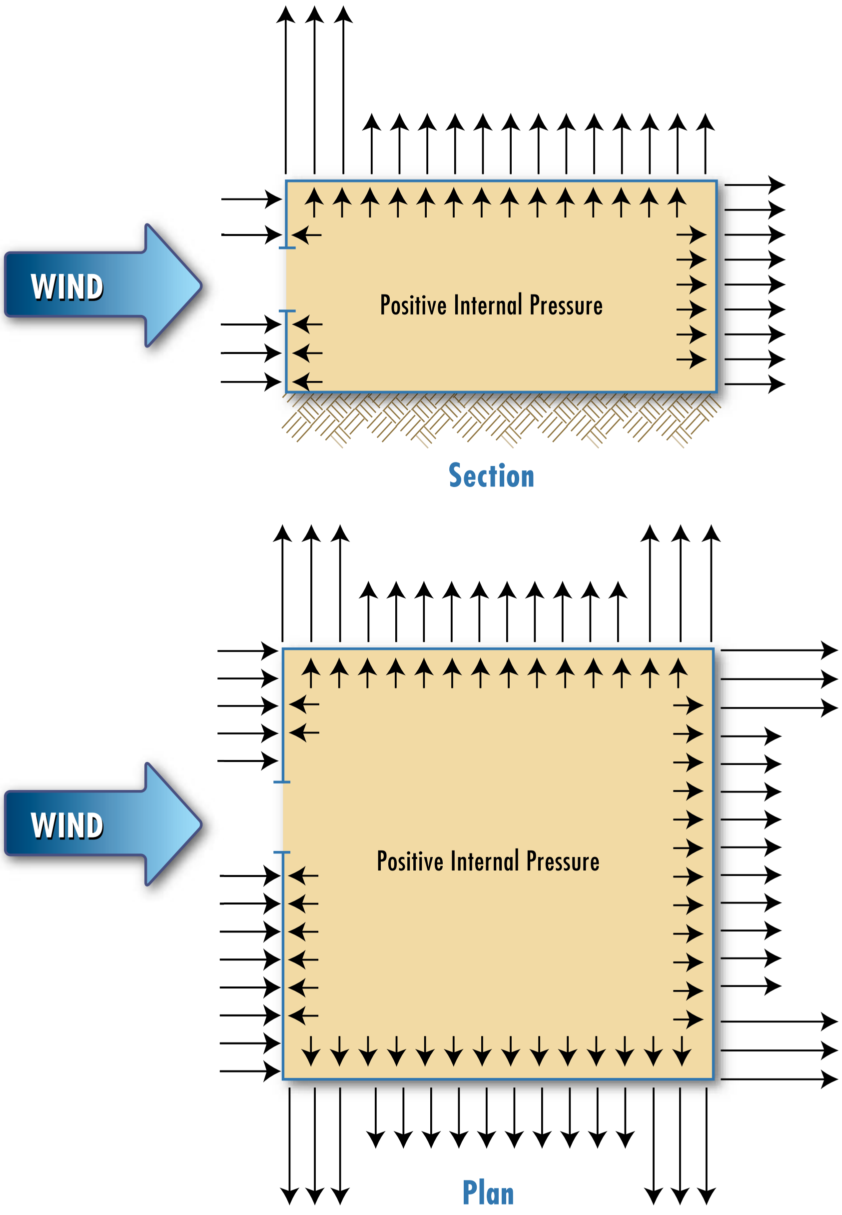
- **Building height.** Wind speed increases with height above the ground. Therefore, the taller the school, the greater the speed and, hence, the greater the wind loads. ASCE 7 provides a procedure to account for building height.

- **Internal pressure (i.e., building pressurization/ depressurization)**. Wind striking a building can cause either an increase in the pressure within the building (i.e., positive pressure), or it can cause a decrease in the pressure (i.e., negative pressure). Internal pressure changes occur because of the porosity of the building envelope. Porosity is caused by openings around doors and window frames, and by air infiltration through walls that are not absolutely airtight. A door or window left in the open position also contributes to porosity.

  Wind striking an exterior wall exerts a positive pressure on the wall, which forces air through openings and into the interior of the building (this is analogous to blowing up a balloon). At the same time the windward wall is receiving positive pressure, the side and rear walls are receiving negative (suction) pressure; therefore, air within the building is being pulled out at openings in these other walls. As a result, if the porosity of the windward wall is greater than the combined porosity of the side and rear walls, the interior of the building is pressurized. But if the porosity of the windward wall is less than the combined porosity of the side and rear walls, the interior of the building is depressurized (this is analogous to letting air out of a balloon).

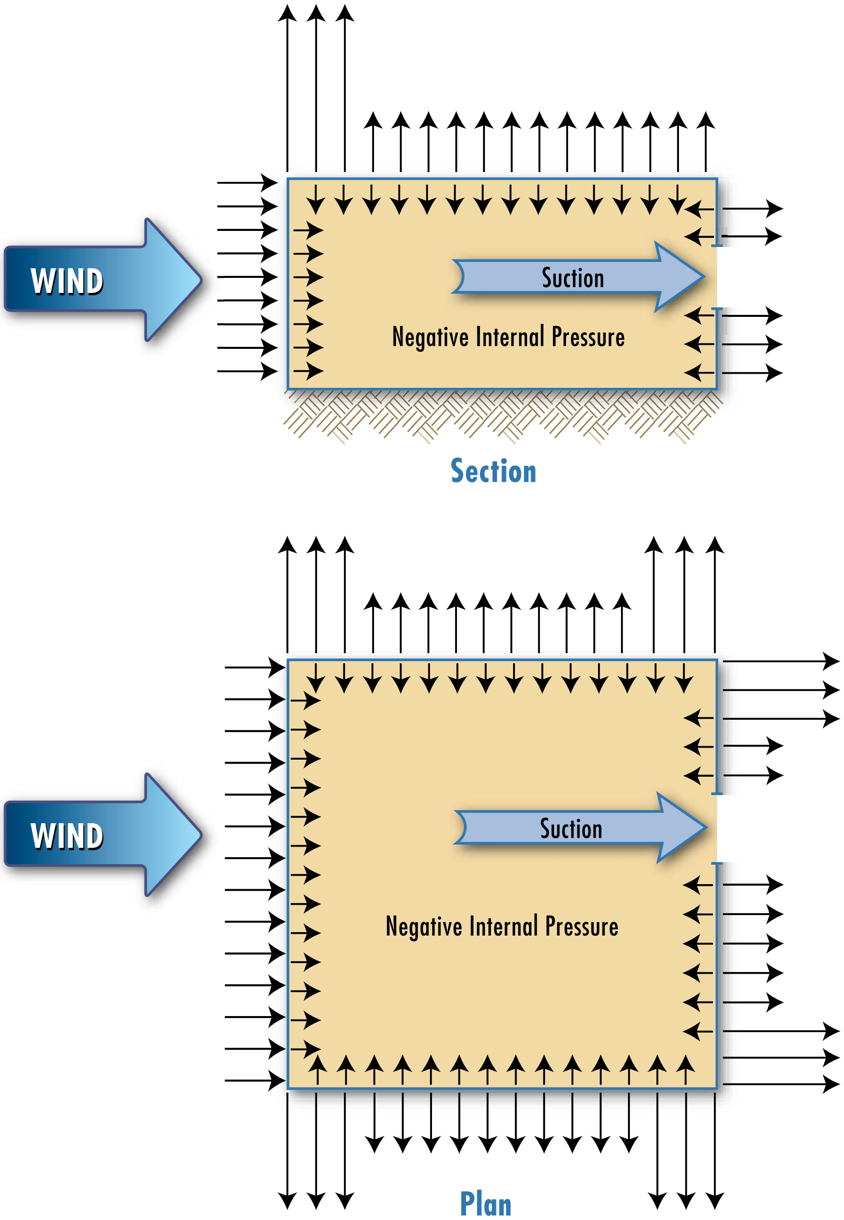
  When a building is pressurized, the internal pressure pushes up on the roof. This push from below the roof is combined with the suction above the roof, resulting in an increased wind load on the roof. The internal pressure also pushes on the side and rear walls. This outward push is combined with the suction on the exterior side of these walls. Therefore, a pressurized building increases the wind load on the side and rear walls (see Figure 6-5) as well as on the roof.

Figure 6-5
Schematic of internal pressure condition when the dominant opening is in the windward wall



NOTE: Arrows indicate direction and magnitude of applied force.

When a building is depressurized, the internal pressure pulls the roof down, which reduces the amount of uplift exerted on the roof. The decreased internal pressure also pulls inward on the windward wall, which increases the wind load on that wall (see Figure 6-6).



NOTE: Arrows indicate direction and magnitude of applied force.

Figure 6-6
Schematic of internal pressure condition when the dominant opening is in the leeward wall

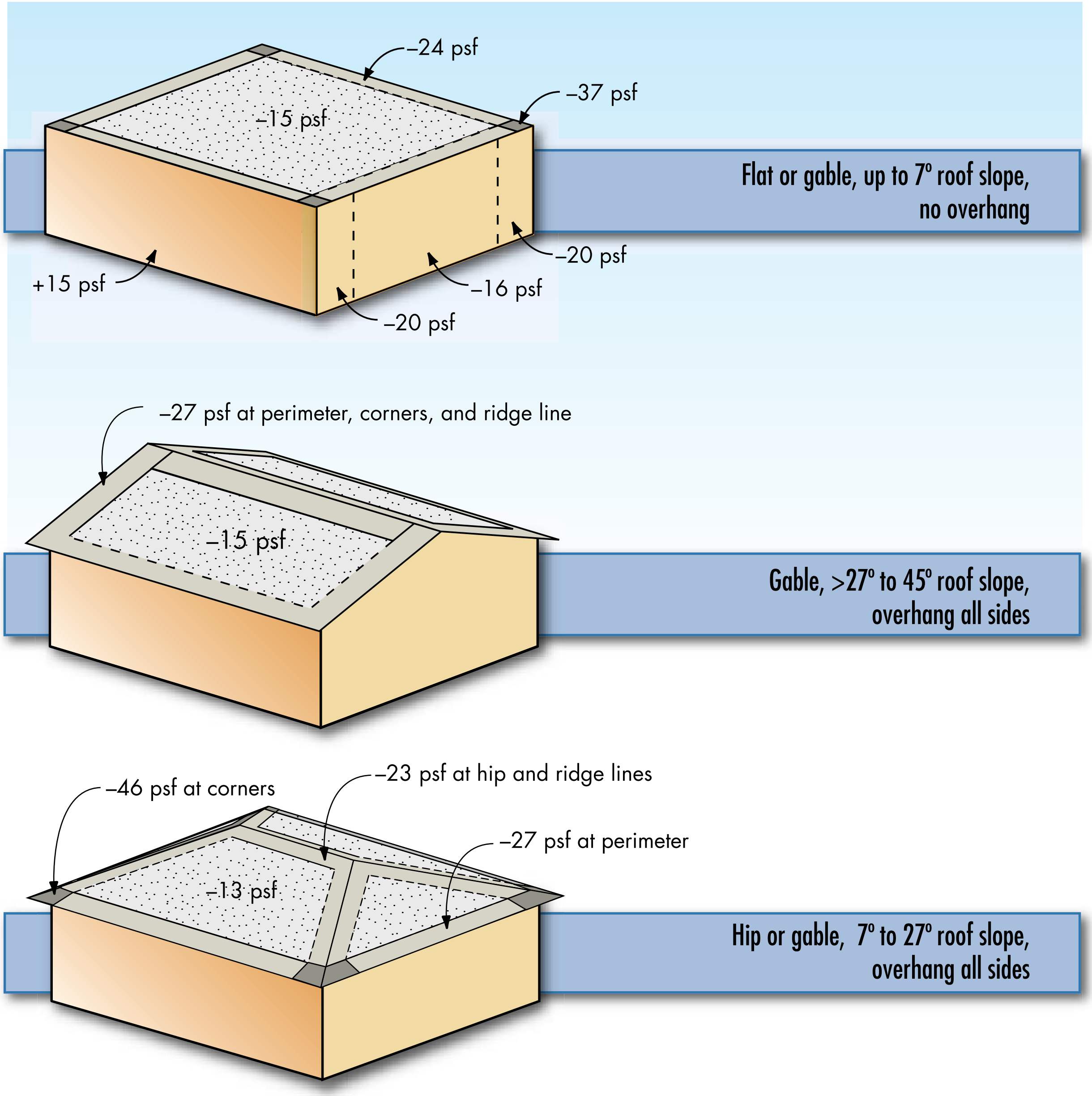
When a school becomes fully pressurized (e.g., due to window breakage), the loads applied to the exterior walls and roof are significantly increased. The build-up of high internal pressure can also blow down interior partitions and blow ceiling boards out of their support grid. The breaching of a small window is typically sufficient to cause full pressurization of the school's interior.

ASCE 7 provides a design procedure to assess the influence of internal pressure on the wall and roof loads, and it provides positive and negative internal pressure coefficients for use in load calculations. Buildings that can be fully pressurized are referred to as partially enclosed buildings. Buildings that have limited internal pressurization capability are referred to as enclosed buildings.

- **Aerodynamic pressure.** Because of building aerodynamics (i.e., the interaction between the wind and the building), the highest uplift loads occur at roof corners. The roof perimeter has a somewhat lower load, followed by the field of the roof. Exterior walls typically have lower loads than the field of the roof. The ends of walls have higher suction loads than the portion of wall between the ends. However, when the wall is loaded with positive pressure, the entire wall is uniformly loaded. Figure 6-7 illustrates these aerodynamic influences. The negative values shown in Figure 6-7 indicate suction pressure acting upward from the roof surface and outward from the wall surface. Positive values indicate positive pressure acting inward on the wall surface.

  Aerodynamic influences are accounted for by use of external pressure coefficients, which are used in load calculations. The magnitude of the coefficient is a function of the location on the building (e.g., roof corner or field of roof) and building shape as discussed below. Positive coefficients represent a positive pressure, and negative coefficients represent negative (suction) pressure. External pressure coefficients are found in ASCE 7.

  Building shape affects the magnitude of pressure coefficients and, therefore, the loads applied to the various building surfaces. For example, the uplift loads on a low-slope roof are larger than the loads on a gable or hip roof. The steeper the slope, the lower the uplift load. Pressure coefficients for monoslope (shed) roofs, sawtooth roofs, and domes are all different from those for low-slope and gable/hip roofs.



NOTE: Design pressures all assume an enclosed building with the same basic wind speed of 90 mph, exposure B, and 30' roof height.

Figure 6-7

Relative roof uplift pressures as a function of roof geometry, roof slope, and location on roof, and relative positive and negative wall pressures as a function of location along the wall.

Building irregularities such as bay window projections, a stair tower projecting out from the main wall, dormers, chimneys, etc., can cause localized turbulence. Turbulence causes wind speed-up, which increases the wind loads in the vicinity of the building irregularity as shown in Figures 6-8 and 6-9.

Figure 6-8
The aggregate ballast on this single-ply membrane roof was blown away in the vicinity of the corners of the wall projections at the window bays. The irregular wall surface created turbulence, which led to wind speed-up and loss of aggregate in the turbulent flow areas.

Figure 6-9
The metal roof is over a stair tower. The irregularity created by the stair tower caused turbulence that resulted in wind speed-up.

As shown in Figure 6-9, the built-up roof's base flashing was pulled out from underneath the coping and caused a large area of the membrane to lift and peel. Some of the wall covering on the stair tower was also blown away. Had the stair tower not existed, the built-up roof would not have been damaged.

Loads exerted on the building envelope are transferred to the structural system, where they are transferred through the foundation and into the ground.

Information pertaining to load calculations is presented in Section 6.8.2.

For further general information on the nature of wind and wind-building interactions, see *Buildings at Risk: Wind Design Basics for Practicing Architects,* American Institute of Architects, 1997.

To avoid damage in the vicinity of building irregularities, attention needs to be given to attachment of building elements located in turbulent flow areas.

6.2.2 Probability of Occurrence

Most buildings are designed for a 50-year mean recurrence interval wind event (2 percent annual probability). A 50-year storm would be expected to happen about once every 50 years; however, a 50-year storm can occur more or less frequently. A 50-year storm may not occur within any 50-year interval, but two 50-year storms could occur within 1 year.

ASCE 7 requires schools with a capacity greater than 250 occupants and schools used for hurricane or other emergency shelters to be designed for a 100-year mean recurrence interval wind event (1 percent annual probability); therefore, these schools are designed to resist stronger, rarer storms than most buildings. The importance factor is used to adjust the mean recurrence interval. For a 50-year interval, the importance factor is 1.00. For a 100-year interval, the importance factor is 1.15.

When designing a school, architects and engineers should consider the following:

- **Routine winds.** In many locations, winds with low to moderate speeds occur daily. Damage is not expected to occur during these events.

- **Stronger winds.** At a given site, stronger winds (e.g., winds with a basic wind speed in the range of 70 to 80 mph peak gust) may occur from several times a year to only once a year or less frequently. 70 to 80 mph is the threshold at which damage normally begins to occur to building elements that have limited wind resistance due to problems associated with inadequate design, strength, application, or material deterioration.

- **Design level winds.** Schools that experience design level events and events that are somewhat in excess of design level should experience little, if any damage; however, design level storms frequently cause extensive building envelope damage. Structural damage also occurs, but less often. Damage experienced with design level events is typically associated with inadequate design, application, or material deterioration. The exceptions are wind-driven water infiltration and wind-borne debris (missiles) damage. Water infiltration is discussed in Sections 6.10.4, 6.11.3, and 6.13.3.

Missile damage is very common during hurricanes and tornadoes. Missiles can puncture roof coverings, many types of exterior walls, and glazing. The IBC does not address missile-induced damage, except for glazing in wind-borne debris regions. (Wind-borne debris regions are limited to portions of hurricane-prone regions.) In hurricane-prone regions, significant school damage should be expected even during design level hurricane events, unless special enhancements are incorporated into the school's design (see Section 6.15).

- **Tornadoes.** Although more than 1,200 tornadoes typically occur each year in the U.S., the probability of a tornado occurring at any given location is quite small. The probability of occurrence is a function of location. As shown in Figure 6-2, only a few areas of the U.S. frequently experience tornadoes, and tornadoes are very rare in the west. The Oklahoma

City area is the most active location in the U.S., with 106 recorded tornadoes between the years 1890 and 2000.

Except for window breakage, well designed, constructed, and maintained schools should experience little if any damage from weak tornadoes. However, because many schools have wind-resistance deficiencies, weak tornadoes often cause building envelope damage. Most schools experience significant damage if they are in the path of a strong or violent tornado (see Figure 6-10). In the classroom wing, shown in Figure 6-10, all of the exterior windows were broken, and virtually all of the cementitious wood-fiber deck panels were blown away. Much of the metal decking over the band and chorus area also blew off. The gymnasium collapsed, as did a portion of the multi-purpose room. The school was not in session at the time the tornado struck.

Figure 6-10
This high school in northern Illinois was heavily damaged by a strong tornado.

6.3 VULNERABILITY: WHAT WIND CAN DO TO SCHOOLS

When damaged by wind, schools typically experience the following types of building component damage in descending order of frequency of occurrence (see Figures 6-11 through 6-16):

Roof covering damage (including rooftop mechanical, electrical, and communications equipment).

Figure 6-11
A portion of the built-up membrane at this school lifted and peeled after the metal edge flashing lifted. The cast-in-place concrete deck kept a lot of water from entering the school. Virtually all of the loose aggregate blew off the roof and broke many windows in nearby houses. This school was being used as a hurricane shelter at the time of the blow-off.

Exterior glazing damage – very common during hurricanes and tornadoes, less common during other storms.

Figure 6-12
The outer panes of these windows were broken by aggregate from a built-up roof. The inner panes had several impact craters. In several of the adjacent windows, both the outer and inner panes were broken. The aggregate had a flight path in excess of 245 feet. The wind speed was less than the design wind speed.

Exterior wall coverings and soffit damage.

Figure 6-13
The metal wall covering on this school was applied to plywood over metal studs. The metal stud wall collapsed in this area, but, in other areas, it was blown completely away. The CMU wall behind the studs did not appear to be damaged. This school was on the periphery of a violent tornado.

SOURCE: *OKLAHOMA AND KANSAS MIDWEST TORNADOES OF MAY 3, 1999*, 1999

Collapse of non-load bearing exterior walls.

Figure 6-14
The unreinforced CMU wall at this school collapsed during a storm that had wind speeds that were less than the design wind speed.

Structural damage (e.g., roof deck blow-off, blow-off or collapse of the roof structure, collapse of exterior bearing walls, or collapse of the entire school or major portions thereof). Structural damage, along with damage to the building envelope, is the number one type of damage during strong and violent tornadoes.

Figure 6-15
The roof and all the walls of a wing of this elementary school were blown away by a violent tornado.

Figure 6-16
This portable classroom was blown up against the main school building during a storm that had wind speeds that were less than the design wind speed. Depending upon the type of exterior wall, an impacting portable classroom may or may not cause wall collapse.

Ramifications of the above types of damages include:

- **Property damage.** Including repair/replacement of the damaged components (or replacement of the entire facility), plus repair/replacement of interior building components, mold remediation, furniture, equipment, and books caused by water and/or wind entering the school. Even when damage to the building envelope is limited, such as blow-off of a portion of the roof covering or broken glazing, substantial water damage frequently occurs because heavy rains often accompany strong winds (particularly in the case of thunderstorms, hurricanes, and tornadoes; see Figure 6-17).

Figure 6-17
This newly-constructed gymnasium had a structural metal roof panel (3-inch trapezoidal ribs at 24 inches on center) applied over metal purlins. The panels detached from their concealed clips. A massive quantity of water entered the school and buckled the wood gym floor.

Debris such as roof aggregate, gutters, HVAC equipment, and siding blown from schools can damage automobiles, residences, and other buildings in the vicinity of the school.

Debris can travel well in excess of 300 feet in wind events. If non-school property is damaged by school building debris, the school district will likely be responsible for the damage.

Portable classrooms are often particularly vulnerable to significant damage because they are seldom designed to the same wind loads as permanent school buildings. Portable

Modest wind speeds can drive rain into the school's exterior walls. Unless adequate provisions are taken to account for water infiltration (see Sections 6.10.4, 6.11.3, and 6.13.3), damaging corrosion, dry rot, and mold can occur within the walls.

Although people are not usually outside a school during a high wind event, exceptions are schools used as hurricane shelters. In this case, it is common for people to arrive at a school during very high winds. Missiles such as roof aggregate shedding from the school could injure or kill late arrivers to the shelter. Another exception is the period of time when students are arriving at or departing from school. Thirteen students at the Belvidere High School in northern Illinois were killed and many others were seriously injured by a tornado in 1967. School had been dismissed shortly before the tornado struck and many students were in school buses as the tornado approached the school. An attempt was made to get the students back inside the school, but 12 of the buses were thrown about by the tornado before the students could seek shelter within the school. Aggregate from the school's built-up roof penetrated the flesh of several students.

classrooms are frequently blown over during high-wind events because the inexpensive techniques that are typically used are inadequate to anchor the units to the ground. Wind-borne debris from portables or an entire portable classroom may impact the permanent school building and cause serious damage.

- **Injury or death.** Although infrequent, school occupants or people outside schools have been injured and killed when struck by collapsed building components (such as exterior masonry walls or the roof structure) or wind-borne building debris. The greatest risk of injury or death is during strong hurricanes and strong/violent tornadoes.

- **Interrupted use.** Depending upon the magnitude of wind and water damage, it can take days, months, or more than a year to repair the damage or replace a facility (see Figure 6-18). In addition to the costs associated with repairing/replacing the damage, other financial ramifications related to interrupted use of the school can include the cost of bussing students to an alternative school and/or rental of temporary facilities. These additional costs can be quite substantial.

There are also social and psychological factors, such as difficulties imposed on students, parents, faculty and the administration during the time the school is not usable.

Figure 6-18
A portion of the roof structure blew off of this school, and a portion of it collapsed into classrooms. Because of extensive water damage, a school such as this can be out of operation for a considerable period of time.

6.4 SCOPE, EFFECTIVENESS, AND LIMITATIONS OF BUILDING CODES

In the following section, the IBC is discussed. In some jurisdictions, NFPA 5000 or one of the earlier model building codes or a specially written state or local building code may be used. The specific scope and/or effectiveness and limitations of these other building codes will be somewhat different than that of the IBC. It is incumbent upon the architect/engineer to be aware of the specific code (including the edition of the code and local amendments) that has been adopted by the authority having jurisdiction.

6.4.1 Scope

With respect to wind performance, the scopes of the model building codes have greatly expanded since the mid-1980s. Significant improvements include:

- **Recognition of increased uplift loads at the roof perimeter and corners.** Prior to the 1982 edition of the Standard Building Code and Uniform Building Code and the 1987 edition of the National Building Code, these model codes did not account for the increased uplift at the roof perimeter and corners. Therefore, schools designed in accordance with earlier editions of these codes are very susceptible to blow-off of the roof deck and/or roof covering.

- **Adoption of ASCE 7 for wind design loads.** Although the three model codes permitted use of ASCE 7, the 2000 edition of the IBC was the first model code to require ASCE 7 for determining wind design loads. ASCE 7 has been more reflective of the current state of the knowledge than the model codes, and use of this procedure has typically resulted in higher design loads.

- **Roof coverings.** Several performance and prescriptive requirements pertaining to wind resistance of roof coverings have been incorporated. The majority of these additional provisions were added after Hurricanes Hugo (1989) and Andrew (1992). Poor performance of roof coverings was widespread in both of those storms. Prior to the 1991 edition of the SBC and UBC and the 1990 edition of the NBC, these model codes were essentially silent on roof covering wind loads and test methods for determining uplift resistance. Code improvements continued to be made through the 2003 edition of the IBC.

- **Glazing protection.** The 2000 edition of the IBC was the first model code to address wind-borne debris requirements for buildings located in the wind-borne debris regions of hurricane-prone regions (via reference to the 1998 edition of

ASCE 7). (The 1995 edition of ASCE 7 was the first edition to address wind-borne debris requirements).

- **Parapets and rooftop equipment.** The 2003 edition of the IBC was the first model code to address wind loads on parapets and rooftop equipment (via reference to the 2002 edition of ASCE 7, which was the first edition of ASCE 7 to address these elements).

6.4.2 Effectiveness

Except for hurricanes and tornadoes, the 2003 edition of the IBC is believed to be a relatively effective code, provided that it is properly followed and enforced. This code is also believed to be an effective code for hurricanes, except that it does not account for water infiltration due to puncture of the roof membrane by missiles, nor does it adequately address the vulnerabilities of brittle roof coverings (such as tile) to missile-induced damage and subsequent progressive cascading failure.

The 2003 IBC relies on several referenced standards and test methods developed or updated in the 1990s. Most of these standards and test methods have not been validated by actual building performance during design level wind events. Therefore, the actual performance of buildings designed and constructed to the minimum provisions of the 2003 IBC remains to be determined. Future post-storm building performance evaluations may or may not show the need for further enhancements.

The 2003 IBC does not account for tornadoes; therefore, except for weak tornadoes, it is ineffective for this type of storm.

6.4.3 Limitations

Limitations to building codes include the following:

- Because codes are adopted on the local or state level, the adopting authority has the power to not adopt all wind-related provisions of a model code, or to write their own code rather than follow a model code. In either case, important provisions of the current model code may be stricken, thereby resulting in schools that are more susceptible to wind damage when they are designed and constructed in accordance with the minimum requirements of the locally adopted code. Also, often there is a significant time lag between the time a model code is updated and the time it is implemented by the adopting authority. When lag occurs, schools designed to the minimum requirements of the outdated code are not taking advantage of the current state of the knowledge. Therefore, these schools are prone to poorer wind performance compared to schools designed according to the current model code.

- Adoption of the current model code does not ensure good wind performance. Rather, the code is a minimum tool that should be used by knowledgeable design professionals in conjunction with their training, skills, and professional judgment. To achieve good wind performance, in addition to good design, the construction work must be effectively executed and the school must be adequately maintained and repaired.

- Specific limitations of the 2003 IBC include lack of provisions pertaining to blow-off of aggregate from built-up and sprayed polyurethane foam roofs, and limitations of some of the test methods used to assess wind and wind-driven rain resistance of building envelope components (improved test methods need to be developed before this code limitation can be overcome). In addition, the code does not address protection of occupants in schools (and other buildings) located in tornado-prone regions.

- The 2003 IBC does not address the need for continuity, redundancy, or energy-dissipating capability (ductility) to limit the effects of local collapse and to prevent or minimize progressive collapse in the event of the loss of one or two primary structural members such as a column. However, even though this issue is not addressed in the IBC, Chapter 1 of ASCE 7 does address general structural integrity, and the ASCE 7 Chapter 1 *Commentary* provides some guidance on this issue.

6.5 PRIORITIES, COSTS, AND BENEFITS: NEW SCHOOLS

Prior to evaluating schools for risk from high winds and beginning the risk reduction design process, it is first necessary to consider the priorities, costs, and benefits of potential risk reduction measures. These factors, as discussed below, should be considered within the context of performance-based wind design as discussed in Section 2.12.3.

6.5.1 Priorities

As previously discussed in this manual, the first priority is the implementation of measures that will reduce risk of casualties to students, faculty, staff, and visitors. The second priority is the reduction of damage that leads to downtime and disruption. The third priority is the reduction of damage and repair costs. To realize these priorities, as a minimum the school should be designed and constructed in accordance with the latest edition of a current model building code such as the IBC (unless the local building code has more conservative wind-related provisions, in which case the local building code should be used as the basis for design). In addition, the school should be adequately maintained and repaired.

For schools that will be used for emergency response after a storm and/or those schools that will be used for hurricane shelters, measures beyond those required by the IBC should be given high priority (see Section 6.15).

For schools in coastal Alaska and other areas that experience frequent high-wind events (such as parts of Colorado), measures beyond those required by the IBC should be given high priority. Several of the recommendations for schools in hurricane-prone regions (Section 6.15) are also applicable to these schools, with the exception of the wind-borne debris recommendations. (Limited amounts of wind-borne debris are generated in storms other than hurricanes and tornadoes.)

For schools located in tornado-prone regions, priority should be given to the incorporation of specially designed occupant shelters within the school (see Section 6.16). The decision to incorporate occupant shelters should be based on the assessment of risk (see Section 6.7.1).

For schools located in areas where the basic wind speed is greater than 90 mph, priority should be given to incorporation of design, construction, and maintenance enhancements. The degree of priority given to these enhancements increases as the basic wind speed increases (see Sections 6.8.3 to 6.8.5 and 6.9 to 6.14 for enhancement examples).

The benefit/cost ratio of incorporating specially designed tornado shelters within schools can be assessed using software that accompanies FEMA 361.[4] Tornado shelters have been constructed in several schools in Kansas and Oklahoma. An architect involved with several of the Kansas schools reports that the additional cost to incorporate a shelter ranges from $30 to $38 per square foot of shelter space (year 2002 costs). FEMA 361 recommends using a minimum of 5 square feet per person for sheltering; therefore, the $30 to $38 psf equates to $150 to $190 per student and staff for "near absolute protection" (i.e., protection from injury or death) from a violent tornado. Tornado shelters are discussed in Section 6.16.

6.5.2 Cost, Budgeting, and Benefits

The cost for complying with the IBC should be considered as the minimum baseline cost.

For schools that will be used for emergency response after a storm and/or those schools that will be used for hurricane shelters, the additional cost for implementing measures beyond those required by the 2003 edition of the IBC will typically add only a small percentage to the total cost of construction. Sections 6.8 and 6.15 discuss additional measures that should be considered.

For all other schools other than those discussed above, the additional cost for implementing en-

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[4] FEMA 361, *Design and Construction Guidance for Community Shelters*, 2000, is a manual for architects and engineers. It presents detailed guidance concerning the design and construction of shelters that provide "near-absolute protection" from tornadoes. FEMA 361 discusses shelter location, design loads for wind pressure and wind-borne debris, performance criteria, and human factor criteria. It is accompanied by a benefit/cost analysis model.

hancements will typically add only a very small percentage to the total cost of construction. Sections 6.8 to 6.14 discuss additional measures that should be considered.

The yearly cost of periodic maintenance and repair will be greater than the alternative of not expending any funds for periodic maintenance (i.e., deferred maintenance and repair). If, however, the deferred maintenance option is selected, eventually maintenance and repairs will be required, and the extent and cost of the work will typically be much greater than the costs associated with the periodic option. Also, if a windstorm causes damage that would have otherwise been avoided had maintenance or repairs been performed, the resulting costs can be significantly higher. (Note: Maintenance and repair costs are reduced when more durable materials and systems are used; see Section 6.8.2, under "Step 4: Durability.")

Budgeting. It is important for the school district to give consideration to wind enhancement costs early in the development of a new school project. If enhancements, particularly those associated with schools used as hurricane shelters, emergency response after a storm, and tornado shelters, are not included in the initial project budget, often it is very difficult to find funds later during the design of the project. If the additional funds are not found, the enhancements may be eliminated because of lack of forethought and adequate budgeting.

Benefits. If strong storms do not occur during the life of a school, there is little benefit to spending the money and effort related to wind resistance. However, considering the long life of most schools (hence, the greater probability of them experiencing a design level event) and considering the importance placed on students and the value of the school to the community, clearly it is prudent to invest in adequate wind resistance. By doing so, the potential for loss of life and injuries can be significantly reduced or virtually eliminated. Investing in wind resistance also minimizes future expenditures for repair or replacement of wind-damaged schools and avoids costly interrupted building use.

Figure 6-19
The HVAC unit in the parking lot in the photo's lower right corner blew off the curb during a storm that had wind speeds that were less than the design wind speed. A substantial amount of water entered the building before a temporary covering could be placed over the opening. The blow-off was caused by a load path discontinuity; no provisions had been made to anchor the unit to the curb. The insignificant cost of a few fasteners would have prevented repairs costing several thousand dollars and also prevented interrupted use of a portion of the building.

Fortunately, most of the enhancements pertaining to increased wind resistance are relatively inexpensive compared to the benefit that they provide. In evaluating what enhancements are prudent for a specific school, an enhancement that provides greater performance reliability at little cost is an enhancement worthy of consideration (see Figure 6-19).

Wind resistance enhancements may also result in decreased insurance premiums. The school district's insurer should be consulted to see if premium reductions are available, and to see if special enhancements are required in order to avoid paying a premium for insurance. For those school districts that self-insure, enhanced wind resistance should result in a reduction of future payouts.

6.6 PRIORITIES, COSTS, AND BENEFITS: EXISTING SCHOOLS

Prior to evaluating existing schools for risk from high winds and beginning the risk reduction design process, it is first necessary to consider the priorities, costs, and benefits of potential risk reduction measures. These factors, as discussed below, should be considered within the context of performance-based wind design as discussed in Section 2.12.3.

6.6.1 Priorities

In prioritizing work at existing schools, an assessment should be made on all schools within the district to ascertain which schools are vulnerable to damage and therefore most in need of remedial work. As part of the assessment, the nature of the vulnerability and the needed remedial work should be identified at the various schools. In making the district-wide assessment, all applicable hazards should be assessed and the needs prioritized. For some districts or some schools within a given district, the high priority work may be related to wind, or it may be related to one of the other hazards. In some instances, the same remedial work item can mitigate wind and other hazards. For example, strengthening the roof deck attachment can improve both wind and seismic resistance.

School districts located in following areas are in greatest need of assessing their schools (listed in descending order of priority): hurricane-prone regions and school districts outside of hurricane-prone regions that have schools that will be used for emergency response after a storm; tornado-prone regions; areas where the basic wind speed is in excess of 90 mph (the priority increases as the basic wind speed increases); and areas where the basic wind speed is 90 mph or less.

For school districts in hurricane-prone regions, the first priority needs to be given to those schools that will be used as hurricane shelters. Other priorities are as discussed at the beginning of Section 6.5.1.

For school districts in tornado-prone regions, the first priority needs to be given to occupant protection (see Section 6.16). Other priorities are the same as discussed at the beginning of Section 6.5.1.

For all other school districts, the priorities are the same as discussed at the beginning of Section 6.5.1.

In some instances, perhaps all the funds available for the year for remedial work will be spent at one school. In other instances, perhaps the available funds will be used for remedial work at several different schools.

See Section 6.17 for specific remedial work guidance.

6.6.2 Cost, Budgeting, and Benefits

Wind-resistance improvements would ideally address all elements in the load path from the building envelope to the structural system and into the ground. (Load path is discussed in Section 6.8.2 under "Step 3: Detailed Design"); however, this approach can be very expensive if there are many inadequacies throughout the load path. The maximum return on dollars invested for wind-resistance improvements is typically achieved by performing work related to the building envelope. Obviously if there are serious structural deficiencies that could lead to collapse during strong storms, these types of deficiencies should receive top priority; however, this scenario is infrequent.

Because elements of the building envelope are the building components that are most likely to fail in the more commonly occurring moderate wind speed events, strengthening these elements will avoid damage during those storms. Of course, if a storm approaching a design level event occurs, in this scenario, the building envelope will remain attached to the structure, but a structural element may fail. For example, if the connections between the roof joists and bearing walls are the weak link, the roof covering will remain attached to the roof deck and the deck will remain attached to the joists, but the entire roof structure will blow off because the joists will detach from the wall. Although loss of the entire roof structure is more catastrophic than the loss of just the roof covering, much stronger events are typically required to cause structural damage. Hence, on a school district-wide level, strengthening building envelopes can result in maximum return on funds spent on wind-resistance improvements. Of course, for a specific school, the actual scope of wind-resistance work should be tailored for that school, commensurate with the findings from the evaluation (as discussed in Section 6.6.1) and the benefit/cost analysis (as discussed in below under "Benefits").

Costs can be minimized if wind-resistance improvements are executed as part of planned repairs or replacement. For example, if the roof deck is inadequately attached in the perimeter and corners, and the roof covering has another 10 years of remaining service life, it would typically be prudent to hold off performing deck attachment upgrade until it is necessary to replace the roof covering. Then, as part of the reroofing work, the existing roof system could be torn off, the deck reattached, and the new membrane installed.[5] With this approach, the full service life of the roof membrane (and, hence, its full economic value) is achieved.

Budgeting. As it is with new construction, it is important for the school district to give consideration to wind enhancement costs early in the development of a major repair/renovation project (see discussion in Section 6.5.2).

Benefits. The benefits for spending money and effort related to wind resistance of existing schools are the same as described for new schools in Section 6.5.2.

6.7 EVALUATING SCHOOLS FOR RISK FROM HIGH WINDS

To evaluate risk for wind storms other than tornadoes, the following steps are recommended:

❍ **Step 1:** Determine the basic wind speed from ASCE 7. As the basic wind speed increases beyond 90 mph, the risk of damage increases and it continues to increase as the speed increases. To compensate for the increased risk of damage, design, construction and maintenance enhancements are recommended (see Section 6.8).

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[5] In some cases, it is economical to reattach the decking from below the deck, but typically this approach is more costly.

As part of Steps 2 and 3, consider availability of other schools or other buildings in the community that could be used for educational purposes (and emergency response if the school is so designated) in the event that the school is damaged. For example, in an isolated community, the school may be the only facility available for education and/or emergency response, in which case loss of school use would be very serious. In this scenario, the enhancements given in Section 6.15 should be even more robust.

- **Step 2:** For schools not located in hurricane-prone regions, determine if the school will be used for emergency response after a storm (e.g., temporary housing, food or clothing distribution, or a place where people can fill out forms for assistance). If so, refer to the design, construction, and maintenance enhancements recommended for schools in hurricane-prone regions (see Section 6.15).

- **Step 3:** For schools in hurricane-prone regions, determine if the school will be used for a hurricane shelter and/or for emergency response after a storm. If so, refer to the design, construction, and maintenance enhancements recommended in Section 6.15.

- **Step 4:** For existing schools, evaluate the wind resistance of the building. The resistance will be a function of its original design and construction, various additions or modifications, and condition of building components (which may have weakened due to deterioration or fatigue).

  As a first step, calculate the wind loads on the school using ASCE 7 and compare these loads with the loads that the school was originally designed for. (The original design loads may be noted on the contract drawings. If not, determine what building code or standard was used to develop the original design loads and calculate the loads using that code or standard.) If the original design loads are significantly lower than current loads, upgrading the load resistance of the building envelope and/or structure should be considered (see Section 6.6.2). (Note: An alternative to comparing current loads with original design loads is to evaluate the resistance of the existing school as a function of the current loads to determine what elements are highly overstressed.)

As a second step, perform a field investigation to evaluate the primary building envelope elements and structural system elements to determine if the school was generally constructed as indicated on the original contract drawings. As part of the investigation, the primary elements should be checked for deterioration. Load path continuity should also be checked.

The above evaluations will allow development of a vulnerability assessment that can be used along with the site's wind regime to assess the risk. See Section 6.17 for remedial work recommendations.

6.7.1 Tornadoes

Neither the IBC or ASCE 7 require buildings (including schools) to be designed for tornadoes, nor are occupant shelters required in buildings (including schools) located in tornado-prone regions. Because of the extremely high pressures and missile loads that tornadoes can induce, constructing tornado-resistant schools is extremely expensive. Therefore, when consideration is voluntarily given to tornado design, the emphasis typically is on occupant protection, which is achieved by "hardening" portions of a school for use as safe havens.

In this manual, the term "tornado-prone regions" refers to those areas of the U.S. where the number of recorded F3, F4, and F5 tornadoes per 3,700 square miles is six or greater (see Figure 6-2). However, a school district may decide to use other frequency values (e.g., 1 or greater, 16 or greater, or greater than 25) in defining whether or not the district is in a tornado-prone area. In this manual, tornado shelters are recommended for schools in tornado-prone regions.

FEMA 361, *Design and Construction Guidance for Community Shelters*, includes a comprehensive risk assessment procedure that designers can use to assist school districts in determining whether a tornado shelter should be included as part of a new school. See Section 6.16 for design of tornado shelters.

Where the number of recorded F3, F4, and F5 tornadoes per 3,700 square miles is one or greater, if the school does not have a tornado shelter, the best available refuge areas should be identified as discussed in Section 6.16.

6.7.2 Portable Classrooms

Unless portables are designed and constructed (including anchorage to the ground) to meet the same wind loads as the main school building, students and faculty should be considered at risk during high winds. Therefore, portables should not be occupied when high winds are forecast (even though the forecast speeds are well below design wind conditions for the main building). Also, during winds that are well below design wind conditions, it should be recognized that wind-borne debris from disintegrating portables could impact and damage the main school building and/or nearby residences.

6.8 RISK REDUCTION DESIGN METHODS

The keys to enhanced wind performance are devoting sufficient attention to design, construction contract administration, construction, maintenance, and repair. Of course, it is first necessary for the school district to budget sufficient funds for this effort (see Sections 6.5.2 and 6.6.2). This section provides an overview of these elements:

6.8.1 Siting

Where possible, a school should not be located in Exposure D. Locating the facility on a site in Exposure C or preferably in Exposure B would decrease the wind loads. Also, where possible, avoid locating a school on an escarpment or upper half of a hill. Otherwise, if the school is located on an escarpment or upper half of a hill, the abrupt change in the topography would result in increased wind loads. When siting on an escarpment or upper half of a hill is necessary, the ASCE 7 design procedure accounts for wind speed-up associated with this abrupt change in topography.

Trees in excess of 6 inches in diameter, poles (e.g., light fixture poles, flag poles, power poles), or towers (e.g., electrical transmission and communication towers) should not be placed near the school. Blow-down of large trees, poles, and towers can severely damage a school and injure occupants.

Providing at least two means of site egress is prudent for all schools, but is particularly important for schools used for hurricane shelters and emergency response after a storm. Two means of egress facilitate emergency vehicles that need to reach or leave the site. With multiple site egress roads, if one route becomes blocked by trees or other debris or by floodwaters, another access route should be available.

To the extent possible, site portable classrooms so that, if they disintegrate during a storm that approaches from the prevailing wind direction, debris will avoid impacting the main school building and residences. Debris can travel in excess of 300 feet. Destructive winds from hurricanes and tornadoes can approach from any direction. These storms can also throw debris much farther.

6.8.2 School Design

Good wind performance depends on good design (including detailing and specifying), materials, application, maintenance, and repair. A significant shortcoming of any of these five elements could jeopardize the performance of a school against wind. Design, however, is the key element to achieving good performance of a school against wind. Design inadequacies frequently cannot be compensated for by the other four elements. Good design, however, can compensate for other inadequacies to some extent.

Step 1: *Calculate Loads*

Calculate loads on the main wind-force resisting system (MWFRS; i.e., the primary structural elements such as beams, columns, shear walls, and diaphragms that provide support and stability for the overall building), the building envelope, and

In the past, architects seldom performed load calculations on the building envelope (i.e., roof and wall coverings, doors, windows, and skylights) and rooftop equipment and neither did structural engineers. In large part, as a result of not determining loads on these elements and not designing them with adequate load resistance, building envelope and rooftop equipment failures have been the leading cause of failure during past wind events. Just as it is with the MWFRS, it is imperative that loads be determined by the architect or engineer for the building envelope and rooftop equipment, and the envelope and rooftop equipment designed to accommodate the design loads.

rooftop equipment in accordance with ASCE 7 or the local building code, whichever procedure results in the highest loads.[6] The importance factor for most schools will be required to be 1.15. For schools with an occupant load of 250 or less and not intended for use as shelters, a 1.00 importance factor is permitted; however, a value of 1.15 is recommended for all schools.

Uplift loads on roof assemblies can also be determined from Factory Mutual Global (FMG) Data Sheets. In some instances, the loads derived from ASCE 7 or the local code may exceed those derived from FMG, but, in other cases, the FMG loads may be higher. If the school is FMG-insured, and the FMG-derived loads are higher than those derived from ASCE 7 or the building code, the FMG loads should govern; however, if the ASCE 7 or code-derived loads are higher than those from FMG, the ASCE 7 or code-derived loads should govern (whichever procedure results in the highest loads).

Step 2: ***Determine Load Resistance***

After loads have been determined, it is necessary to determine a reasonable safety factor (when using allowable stress design) or reasonable load factor (when using strength design). For building envelope systems, a minimum safety factor of two is recommended; for anchorage of exterior-mounted mechanical, electrical and communications equipment (such as satellite dishes), a minimum safety factor of three is recommended.

For structural members and many cladding elements, load resistance can be determined by calculations, based on test data. For other elements (such as most types of roof coverings), load resistance is primarily obtained from system testing.

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[6] Criteria for determining loads on rooftop equipment were added to the 2002 edition of ASCE 7.

Load resistance criteria need to be given in contract documents. For structural elements, the designer of record typically accounts for load resistance by indicating the material, size, spacing, and connection of elements. For nonstructural elements, such as roof coverings or windows, the load and safety factor can be specified. In this case, the specifications should require the contractor's submittals to show that the system will meet the load resistance criteria. This performance specification approach is necessary if, at the time of design, it is unknown who will manufacture the system.

Regardless of which approach is used, it is important that the designer of record ensure that it can be demonstrated that the structure, nonstructural building envelope, and exterior-mounted mechanical, electrical, and communications equipment have sufficient strength to resist design wind loads.

Step 3: ***Detailed Design***

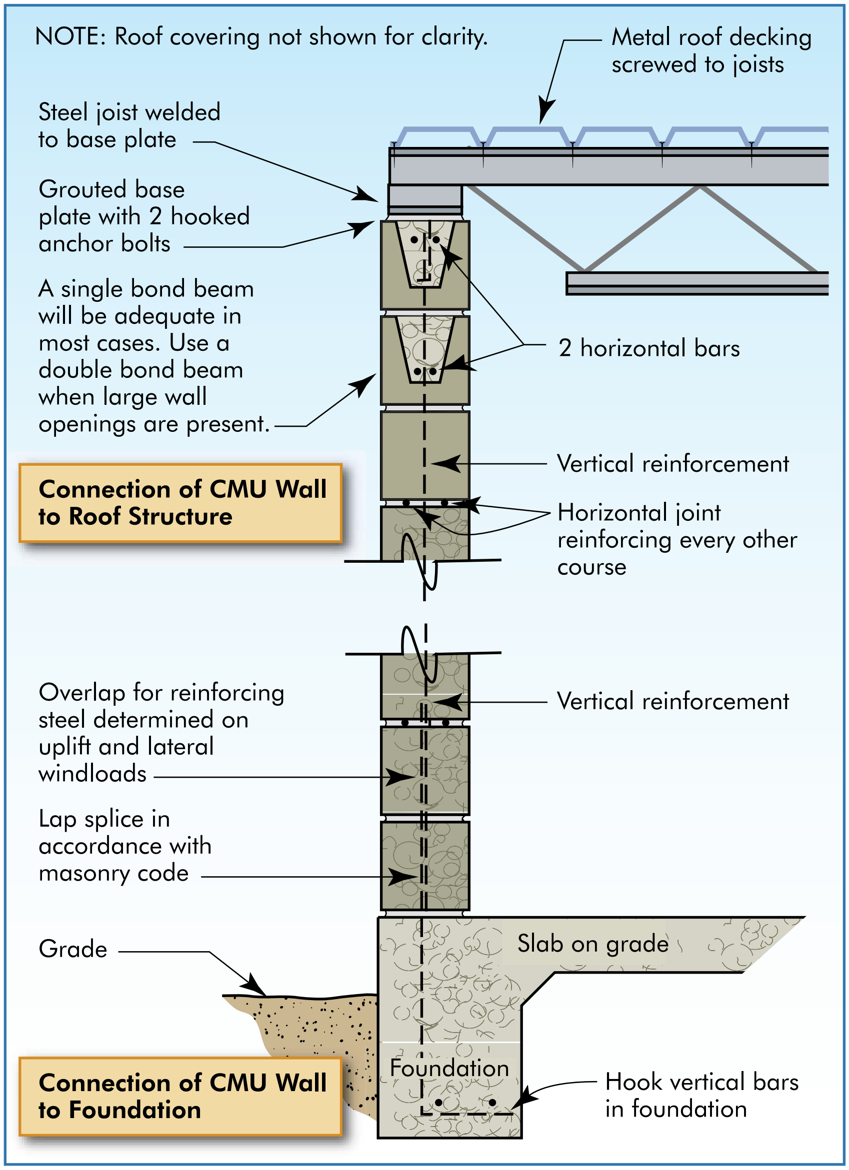
Design, detail, and specify the structural system, building envelope, and exterior-mounted mechanical, electrical, and communications equipment to meet the factored design loads (based on appropriate analytical or test methods) and as appropriate to respond to the risk assessment discussed in Section 6.7.

Connections: Connections are a key aspect of load path continuity between various structural and nonstructural building elements. For example, consider a window: the glass must be strong enough to resist the applied load and the glass must be adequately anchored to the window frame, the frame adequately anchored to the wall, the wall adequately anchored to the foundation, and the foundation adequately anchored to the ground. As loads increase, greater load capacity must be developed in the connections.

As part of the detailed design effort, load path continuity should be clearly indicated in the contract documents. Load paths need to accommodate design uplift, racking, and overturning loads. Load path continuity obviously applies to MWFRS elements, but it also applies to building envelope elements. Figure 6-19 shows a load path discontinuity between a piece of HVAC equipment and its equipment curb. Figure 6-20 illustrates the load path concept.

Figure 6-20
This figure illustrates load path continuity of the structural system. Members are sized to accommodate the design loads and connections are designed to transfer uplift loads applied to the roof, and the positive and negative loads applied to the exterior bearing walls down to the foundation and into the ground. The roof covering (and wall covering if there is one) is also part of the load path. To avoid blow-off, the nonstructural elements must also be adequately attached to the structure.

SOURCE: FEMA 342, *OKLAHOMA AND KANSAS MIDWEST TORNADOES OF MAY 3, 1999,* 1999



Step 4: *Durability*

Because some locales have very aggressive atmospheric corrosion (such as schools located near oceans), special attention needs to be given to specification of adequate protection for ferrous metals, or specify alternative metals such as stainless steel. *Corrosion Protection for Metal Connectors in Coastal Areas*, FEMA Technical Bulletin 8-96, August 1996, contains information on corrosion protection. Attention also needs to be given to dry rot avoidance, for example, by specifying preservative-treated wood. Appendix J of the *Coastal Construction Manual*, FEMA 55, Third Edition, 2000, presents information on wood durability.

Durable materials are particularly important for components that are concealed, which thereby prohibit knowing that the component is in imminent danger of failing.

Special attention also needs to be given to details. For example, details that do not allow water to stand at connections or sills are preferred. Without special attention to material selection and details, the demands on maintenance and repair will be increased, along with the likelihood of failure of components during high winds.

Step 5: *Rain Penetration*

Although prevention of building collapse and major building damage is the primary goal of wind-resistant design, consideration should also be given to minimizing water damage and subsequent development of mold from penetration of wind-driven rain. To the extent possible, non-load bearing walls and door and window frames should be designed in accordance with rain-screen principles. With this approach, it is assumed that some water infiltration will occur. The water is intercepted in an air-pressure equalized cavity that provides drainage from the cavity to the outer surface of the building. See Sections 6.11.3 and 6.13.3, and Figure 6-47 for further discussion and an example. Further information on the rain-screen principle can be found in *Facts and Fictions of Rain-Screen Walls*, M.Z. Rousseau, Construction Canada, 1990.

In conjunction with the rain-screen principle, it is desirable to avoid using sealant as the first line of defense against water infiltration. When joints are exposed, obtaining long-lasting watertight performance is difficult because of the complexities of sealant joint design and application.

6.8.3 Peer Review

If the design team's wind design expertise and experience is limited, wind design input and/or peer review should be sought from a qualified individual(s). The design input or peer review could be for the entire school or for specific components such as the roof or glazing systems that are critical and/or beyond the design team's expertise.

Regardless of the design team's expertise and experience, peer review should be considered when the school:

❍ is located in an area where the basic wind speed is greater than 90 mph (peak gust)

❍ will be used for emergency response after a storm

❍ will be used for a hurricane shelter

❍ will incorporate a tornado shelter

6.8.4 Construction Contract Administration

After a suitable design is complete, the design team should ensure the design intent is achieved during construction. The key elements of construction contract administration are submittal reviews and field observations, as discussed below.

Submittals. The specifications need to stipulate the submittal requirements. This includes specifying what systems require submittals (e.g., windows) and test data (where appropriate). Each submittal should demonstrate development of a load path through the system and into its supporting element. For example, a window submittal should show that the glazing has sufficient strength, its attachment to the frame is adequate, and the attachment of the frame to the wall is adequate.

During submittal review, it is important for the designer of record to be diligent in ensuring that all required submittals are submitted and that they include the necessary information. The submittal information needs to be thoroughly checked to ensure its validity. For example, if a test method used to demonstrate compliance with the design load appears erroneous, the test data should be rejected unless the contractor can demonstrate the test method was suitable.

Field Observations. It is recommended that the design team analyze the design to determine which elements are critical to ensuring high-wind performance. The analysis should include the structural system and exterior-mounted electrical equipment, but it should focus on the building envelope and exterior-mounted mechanical and communications equipment. After determining the list of critical elements to be observed, observation frequency needs to be determined. Observation frequency will depend on the magnitude of the results of the risk assessment described in Section 6.7, complexity of the facility, and the competency of the general contractor, subcontractors, and suppliers.

See Section 6.15.8 for schools located in hurricane-prone regions.

6.8.5 Post-occupancy Inspections, Periodic Maintenance, Repair, and Replacement

The design team should advise the school administration of the importance of periodic inspections, maintenance, and timely repair. It is important for the administration to understand that, over time, a facility's wind-resistance will degrade due to exposure to weather unless it is periodically maintained and repaired.

The building envelope and exterior-mounted equipment should be inspected once a year by persons knowledgeable of the systems/materials they are inspecting. Items that require maintenance, repair, or replacement should be documented and scheduled for work. [Note: The deterioration of glazing is often overlooked. After several years of exposure, scratches and chips can become extensive enough to weaken the glazing.]

The goal is to repair or replace items before they fail in a storm. This approach is less expensive than waiting for failure and then repairing the failed components and consequential damages.

If unusually high winds occur, a special inspection is recommended. The purpose of the inspection is to assess if the strong storm caused damage that needs to be repaired to maintain building strength and integrity. In addition to inspecting for obvious signs of damage, the inspector should determine if cracks or other openings have developed that allow water infiltration, which could lead to corrosion or dry rot of concealed components.

See Section 6.15.9 for schools located in hurricane-prone regions.

6.9 STRUCTURAL SYSTEMS

Based on post-storm damage evaluations, with the exception of tornado events, the structural systems (i.e., MWFRS and structural components such as roof decking) of school buildings have typically performed quite well during design wind events. There have, however, been notable exceptions; in these cases, the most common problem has been blow-off of the roof deck, but instances of collapse have also been documented (Figure 6-15). The structural problems have primarily been due to lack of an adequate load path, with connection failure being a common occurrence. Problems have also been caused by reduced structural capacity due to termites, workmanship errors (commonly associated with steel decks attached by puddle welds), and limited uplift resistance of deck connections in roof perimeters and corners (due to lack of code-required enhancement in older editions of the model codes).

With the exception of tornado events, structural systems designed and constructed in accordance with the IBC should typically offer adequate wind resistance, provided attention is given to load path continuity and to material durability (with respect to corrosion and termites). However, the greatest reliability is offered by cast-in-place concrete. There are no reports of any cast-in-place concrete buildings experiencing a significant structural problem during wind events, including the strongest hurricanes (Category V) and tornadoes (F5).

The following design parameters are recommended (see Section 6.15.2 for schools located in hurricane-prone regions):

- If a pre-engineered structure is being contemplated, special steps should be taken to ensure the structure has more redundancy than is typically the case with pre-engineered buildings.[7] Steps should be taken to ensure the structure is not vulnerable to progressive collapse in the event a primary bent is compromised or bracing components fail.

- Exterior load bearing walls of masonry or precast concrete should be designed to have sufficient strength to resist external and internal loading of components and cladding. CMU walls should have vertical and horizontal reinforcing and grout to resist wind loads. The connections of precast concrete wall panels should be designed to have sufficient strength to resist wind loads.

- For roof decks, specify concrete, steel, or wood sheathing (plywood or oriented strand board [OSB]). See Section 6.15.2 for schools located in hurricane-prone regions.

- For steel roof decks, specify screw attachment rather than puddle welds (screws are more reliable and much less susceptible to workmanship problems). See Figures 6-21 and 6-22. The decking shown in Figure 6-21 was attached with puddle welds. However, at most of the welds, there was only superficial bonding of the metal deck to the joist, as illustrated at this weld. Only a small portion of the deck near the center of the weld area (as delineated by the circle) was well fused to the joist. At the weld, shown in Figure 6-22, the deck was well bonded to the joist. When the decking blew off

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[7] Pre-engineered structures are composed of rigid steel frames, secondary members (including roof purlins and wall girts made of Z- or C-shaped members) and bracing.

due to failure of nearby weak welds, at this location the metal decking tore and a portion of it remained attached to the joist. Tearing of the decking, rather than debonding, is the desired failure mode, but deck tearing is rare due to welding reliability problems. Screw attachment is a more reliable attachment method.

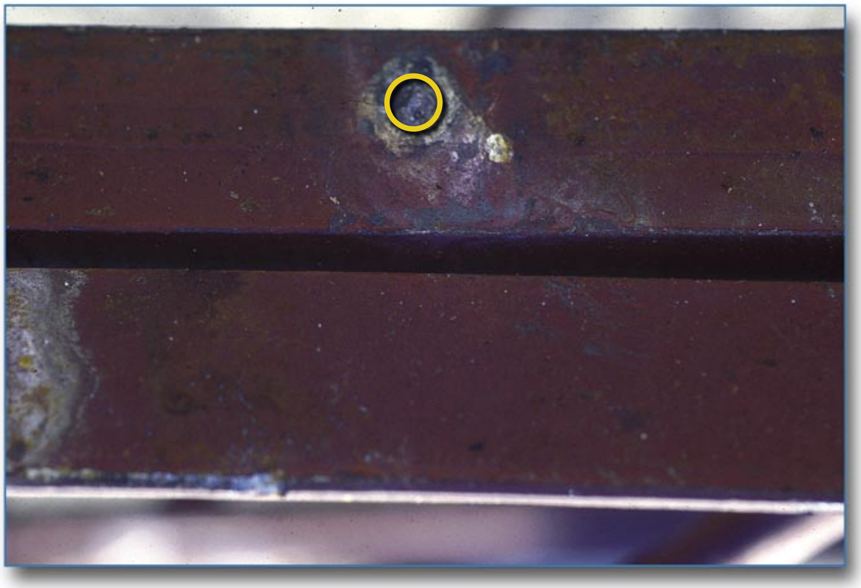

Figure 6-21
View of a steel joist after the metal decking blew away

Figure 6-22
View of another weld near the weld shown in Figure 6-21

- For attachment of wood sheathed roof decks, specify screws, or ring-shank or screw-shank nails in the corner regions of the roof. Where the basic wind speed is greater than 90 mph, also specify these types of fasteners for the perimeter regions of the roof.

- For precast concrete decks, design the deck connections to resist the design uplift loads (the dead load of the deck itself is often inadequate to resist the uplift load; see Figure 6-23).

Figure 6-23
Portions of this waffled precast concrete roof deck were blown off. Bolts had been installed to provide uplift resistance; however, anchor plates and nuts had not been installed. Without the anchor plates, the dead load of the deck was inadequate to resist the wind uplift load.

Figure 6-24
Several of the precast twin-Tee roof and wall panels collapsed. The connection between the roof and wall panels provided very little uplift load resistance. This roof panel lifted because of combined effects of wind uplift and pretension.

- For precast Tee decks, design the reinforcing to accommodate the uplift loads in addition to the gravity loads. Otherwise, large uplift forces can cause Tee failure due to the Tee's own prestress forces after the uplift load exceeds the dead load of the Tee (see Figure 6-24).

- For schools that have mechanically attached single-ply or modified bitumen membranes, refer to the decking recommendations presented in the National Research Council of Canada, Institute for Research in Construction, *Wind Design Guide for Mechanically Attached Flexible Membrane Roofs*, B1049, 2004.

- If an FMG-rated roof assembly is specified, the roof deck also needs to comply with the FMG criteria.

6.10 EXTERIOR DOORS

This section addresses primary and secondary egress doors, sectional (garage) doors, and rolling doors. See Section 6.15.3 for schools located in hurricane-prone regions.

6.10.1 Loads and Resistance

The IBC requires that the door assembly (i.e., door, hardware, frame, and frame attachment to the wall) be of sufficient strength to resist the positive and negative design wind pressure. Architects should specify that doors comply with wind load testing in accordance with ASTM E 1233. Architects should also specifically design the attachment of the door frame to the wall (e.g., specify the type, size, and spacing of frame fasteners).

See Section 6.15.3 for schools located in hurricane-prone regions.

6.10.2 Durability

Where corrosion is problematic, anodized aluminum or galvanized doors and frames, and stainless steel frame anchors and hardware are recommended.

6.10.3 Exit Door Hardware

For primary swinging entry/exit doors, exit door hardware is recommended to minimize the possibility of the doors being pulled open by wind suction. Exit hardware with top and bottom rods offers greater securement than exit hardware that latches at the jamb.

6.10.4 Water Infiltration

When heavy rain accompanies high winds (e.g., thunderstorms, tropical storms, and hurricanes), it can cause wind-driven water infiltration problems (the magnitude of the problem increases with the wind speed). Leakage can occur between the door and frame, and frame and wall, and water can be driven between the threshold and door. When the basic wind speed is greater than 120 mph, because of the very high design wind pressures and numerous opportunities for leakage path development, some leakage should be anticipated when design wind speed conditions are approached. To minimize infiltration, the following are recommended:

- ❍ **Vestibule.** Designing a vestibule is a method to account for the infiltration problem. With this approach, both the inner and outer doors can be equipped with weatherstripping, and the vestibule itself can be designed to tolerate water. For example, water-resistant finishes (e.g., concrete or tile) can be specified and the floor can be equipped with a drain.

- ❍ **Door swing.** With respect to weatherstripping, out-swinging doors offer an advantage compared to in-swinging doors. With out-swinging doors, the weatherstripping is located on the interior side of the door, where it is less susceptible to degradation. Also, some interlocking weatherstripping assemblies are available for out-swinging doors.

Another challenge with doors is successful integration between the door frame and wall. See Section 6.13.3 for discussion of this juncture.