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).
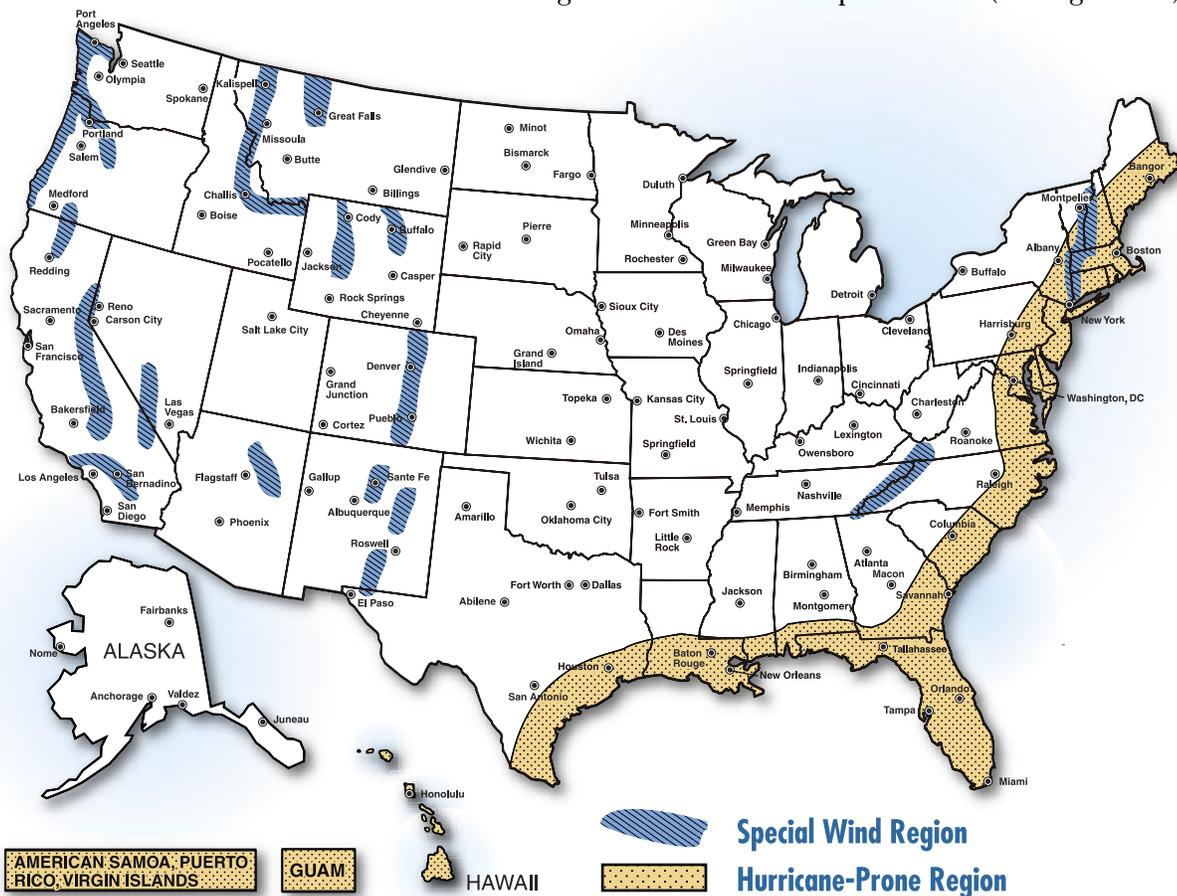

Figure 6-1   Hurricane-prone regions and special wind regions

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)

Number of Recorded F3, F4, & F5 Tornadoes per 3,700 Sq. Mi.

	< 1
	1 - 5
	6 - 15
	16 - 25
	> 25

Based on NOAA, Storm Prediction Center Statistics
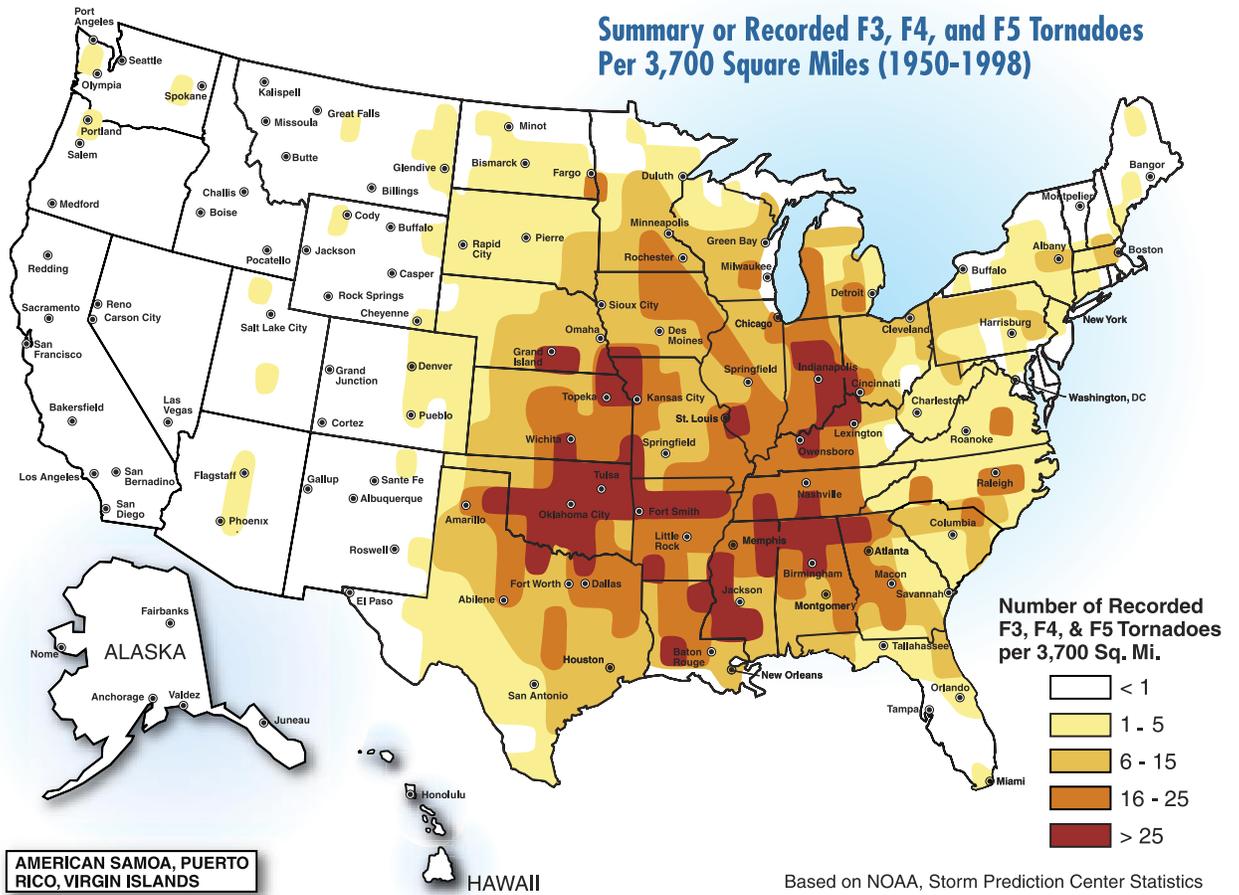
Figure 6-2   Tornado occurrence in the United States based on historical data

SOURCE: FEMA 361, *DESIGN AND CONSTRUCTION GUIDANCE FOR COMMUNITY SHELTERS*, 2000
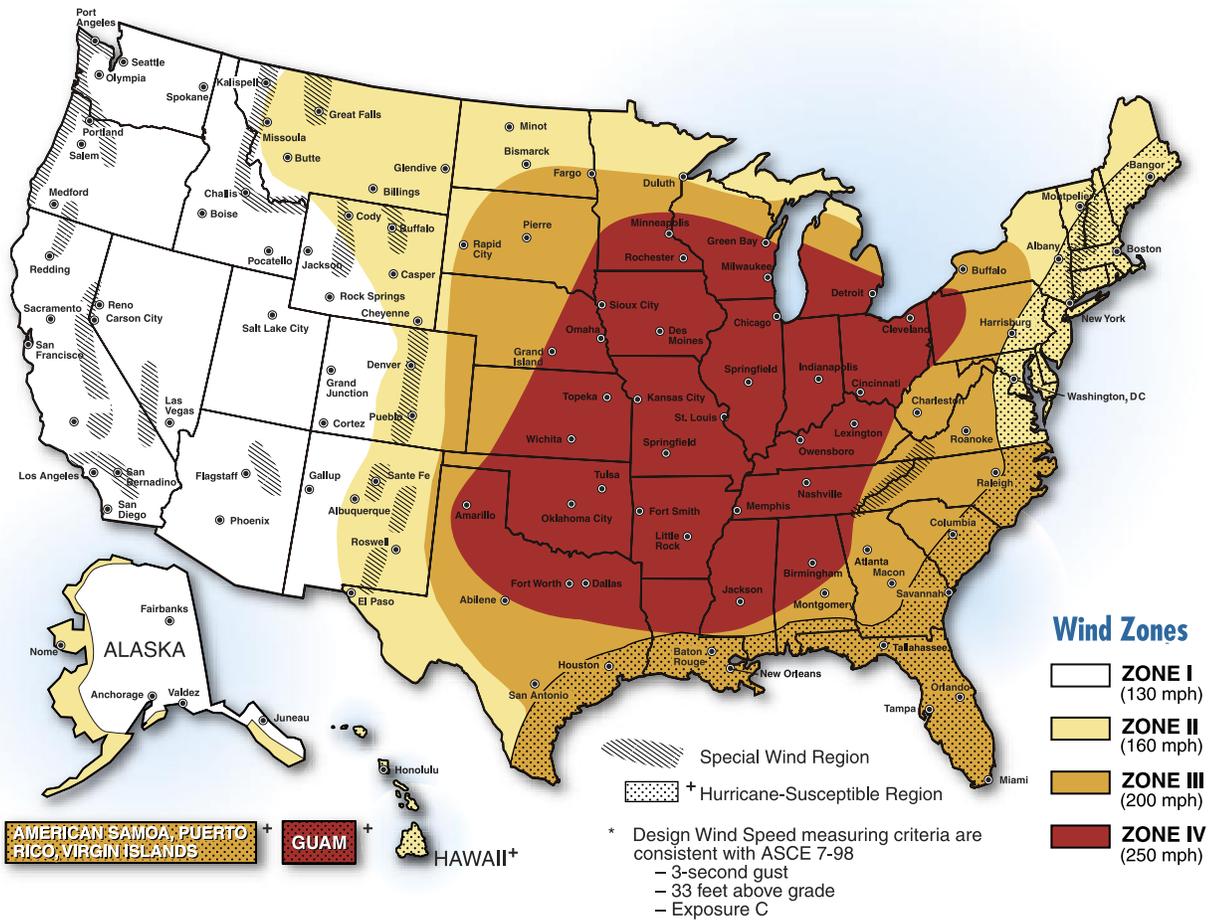
Figure 6-3   Design wind speeds for community tornado shelters

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.
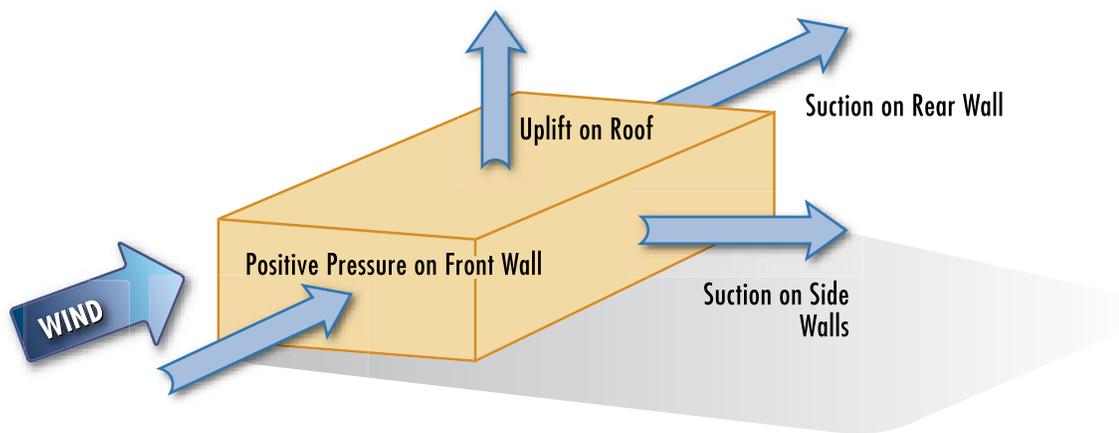

Figure 6-4
Schematic of wind-induced pressures on a building

[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

Section

Plan
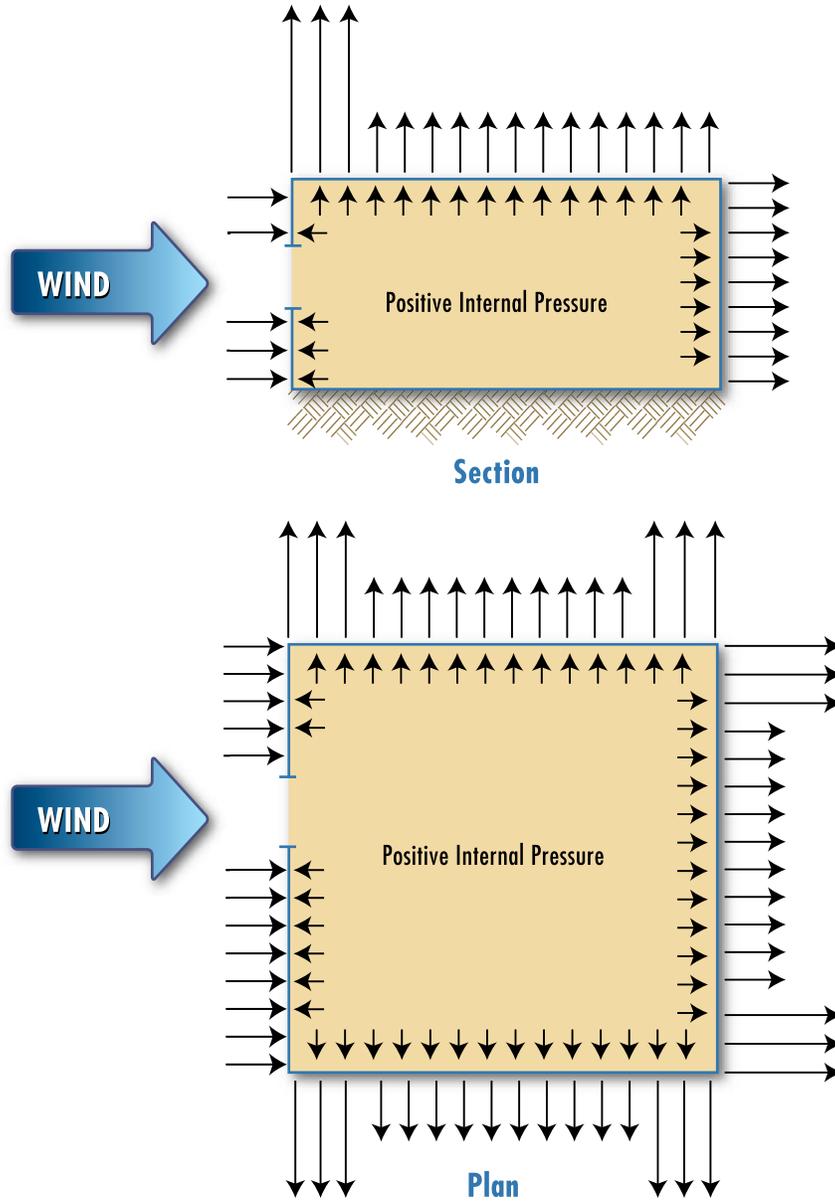
NOTE: Arrows indicate direction and magnitude of applied force.

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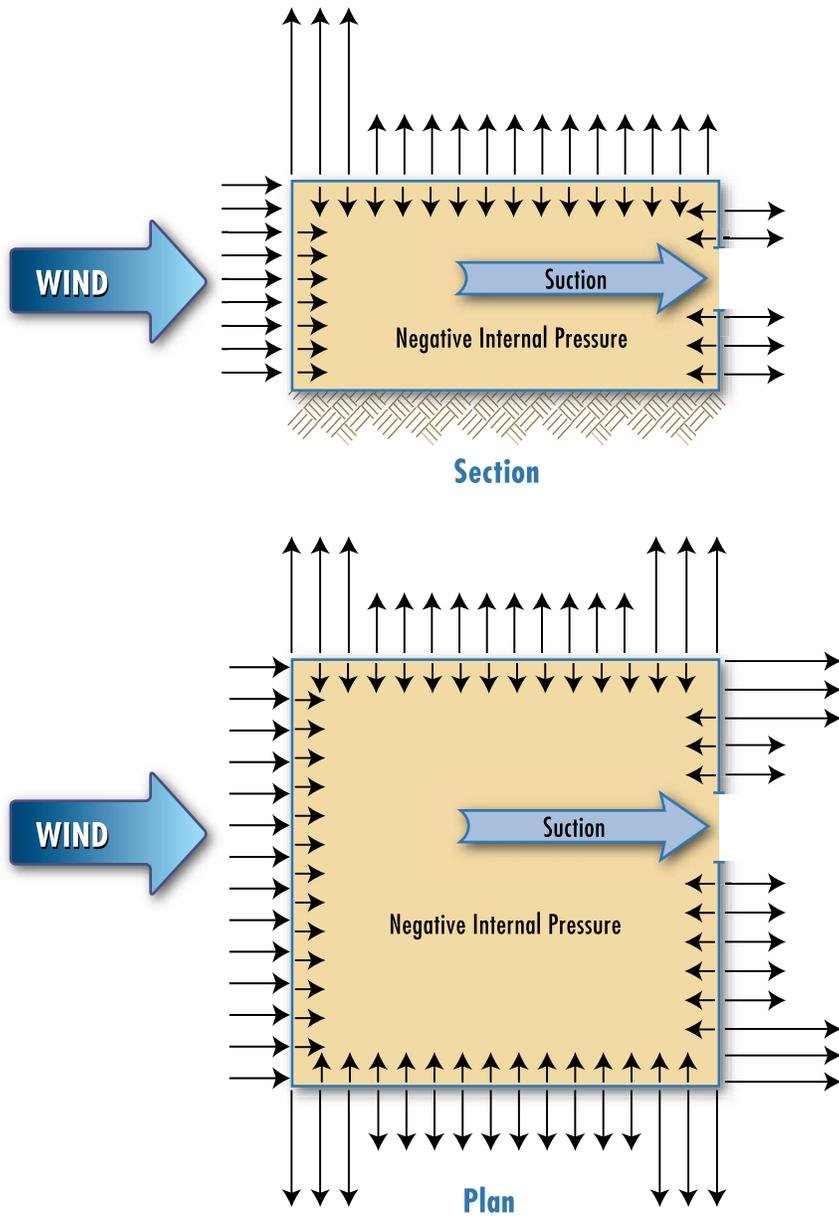
Figure 6-6
Schematic of internal
pressure condition
when the dominant
opening is in the
leeward wall

Section

Plan

NOTE: Arrows indicate direction and magnitude of applied force.

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.

−24 psf

−37 psf

−15 psf

Flat or gable, up to 7° roof slope, no overhang

−20 psf

+15 psf

−16 psf

−20 psf

−27 psf at perimeter, corners, and ridge line

−15 psf

Gable, >27° to 45° roof slope, overhang all sides

−46 psf at corners

−23 psf at hip and ridge lines

−27 psf at perimeter

−13 psf

Hip or gable, 7° to 27° roof slope, overhang all sides
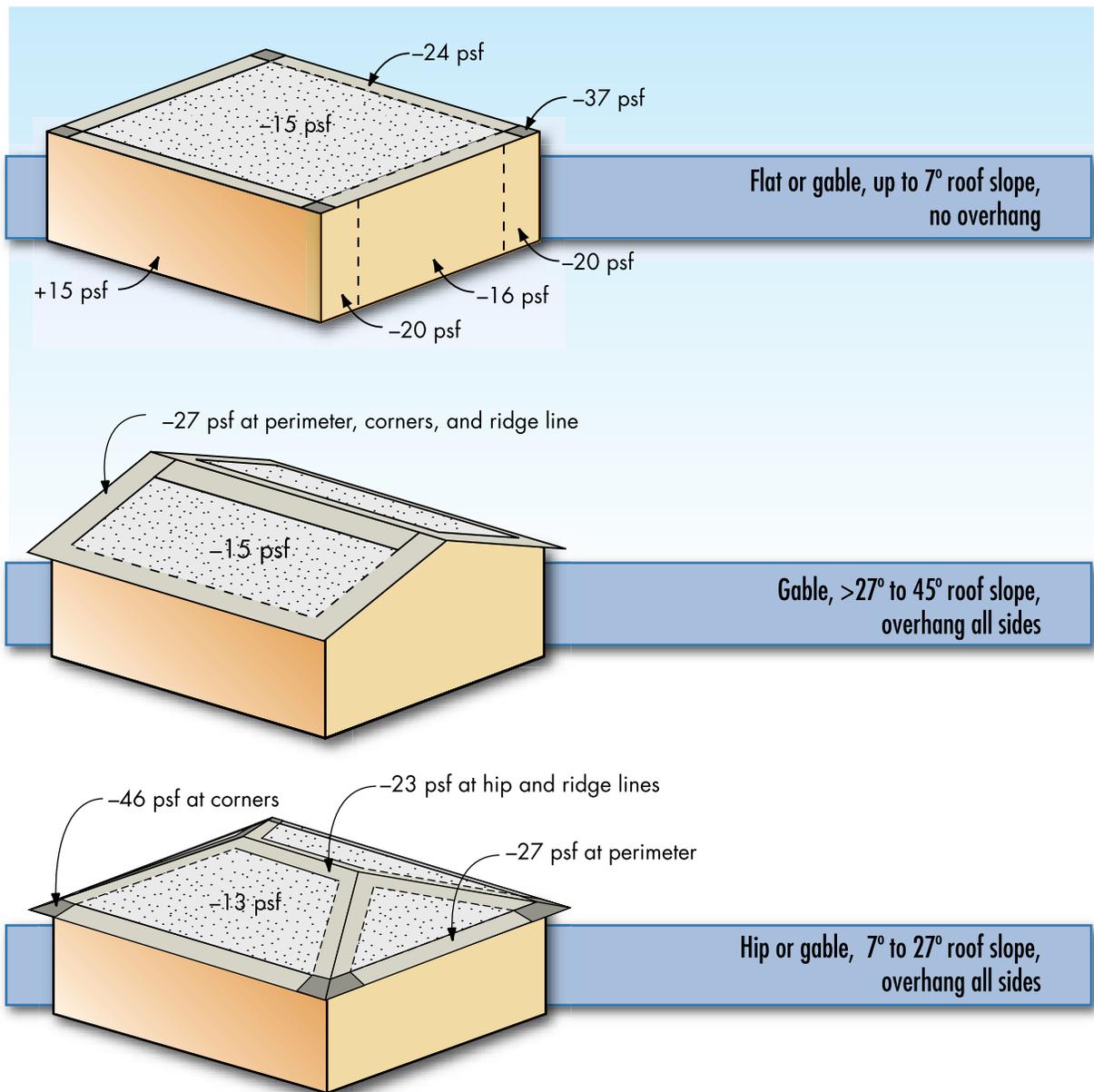
NOTE: Design pressures all assume an enclosed building with the same basic wind speed of 90 mph, exposure B, and 30' roof height.

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.

MAKING SCHOOLS SAFE AGAINST WINDS

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.

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).

❍ **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.

❍ **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

MAKING SCHOOLS SAFE AGAINST WINDS

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

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).

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-

> 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.

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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.

[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 docu-
ments. For structural elements, the designer of record typically
accounts for load resistance by indicating the material, size,
spacing, and connection of elements. For nonstructural ele-
ments, 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 ex-
terior-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.

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.

> **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.

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

NOTE: Roof covering not shown for clarity.

Metal roof decking screwed to joists

Steel joist welded to base plate

Grouted base plate with 2 hooked anchor bolts

A single bond beam will be adequate in most cases. Use a double bond beam when large wall openings are present.

2 horizontal bars

Vertical reinforcement

Horizontal joint reinforcing every other course

Connection of CMU Wall to Roof Structure

Overlap for reinforcing steel determined on uplift and lateral windloads

Vertical reinforcement

Lap splice in accordance with masonry code

Grade

Slab on grade

Foundation

Hook vertical bars in foundation

Connection of CMU Wall to Foundation

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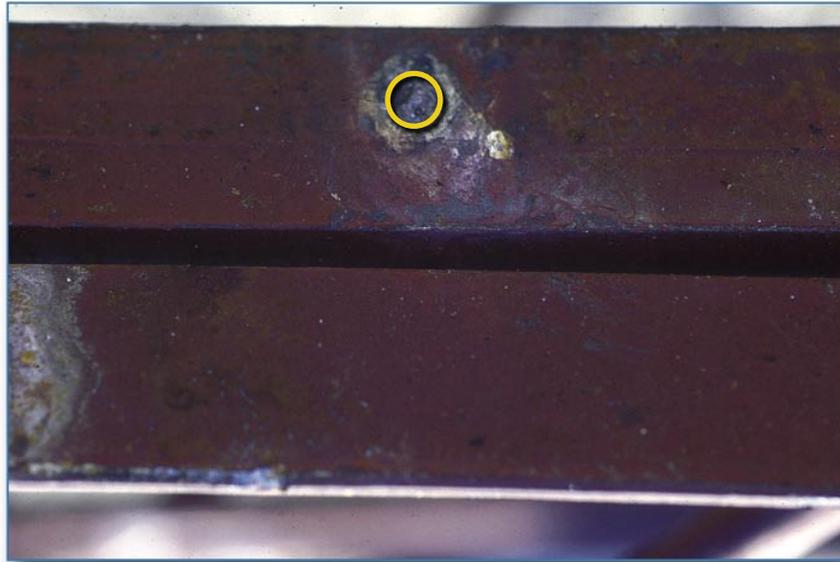
Figure 6-22
View of another weld near the weld shown in Figure 6-21

❍ 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.

ASTM E 2112 (*Standard Practice for Installation of Exterior Windows, Doors and Skylights*) provides information pertaining to installation of doors, including the use of sill pan flashings with end dams and rear legs (see Figure 6-25). It is recommended that designers use E 2112 as a design resource.

Figure 6-25
Door sill pan flashing with end dams, rear leg, and turned-down front leg
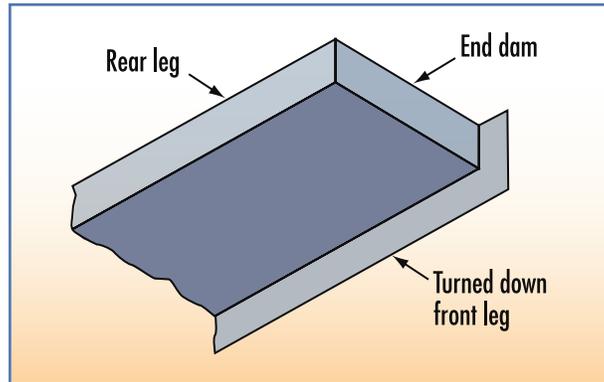
6.10.5 Weatherstripping

A variety of pre-manufactured weatherstripping components are available, including drips, door shoes and bottoms, thresholds, and jamb/head weatherstripping. A few examples of weatherstripping options are:

❍ **Drip.** These are intended to shed water away from the opening between the frame and door head, and the opening between the door bottom and the threshold (see Figures 6-26 and 6-27). Alternatively, a door sweep can be specified (see Figure 6-28); however, for high-traffic doors, periodic replacement of the neoprene will be necessary.

Figure 6-26
Drip at door head and drip with hook at head

SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL*, 2000
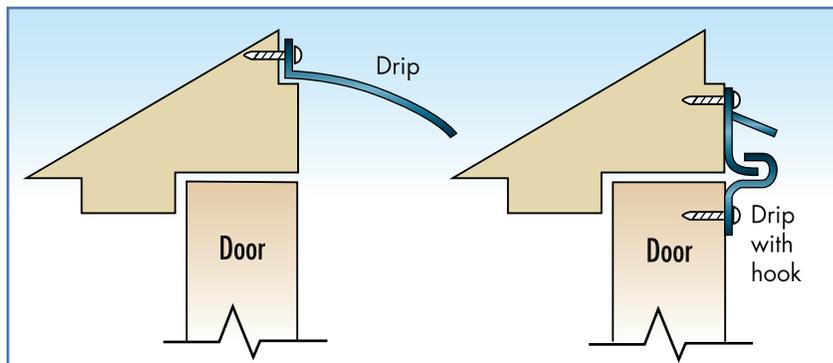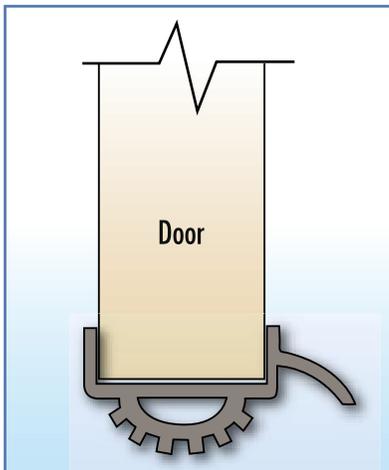
Figure 6-27
Door shoe with drip and vinyl seal
SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL*, 2000
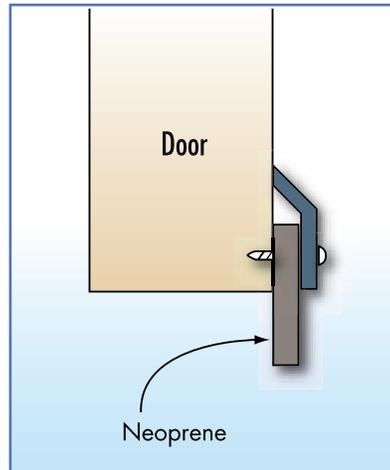
Figure 6-28
Neoprene door bottom sweep
SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL*, 2000

❏ **Door shoes and bottoms.** These are intended to minimize the gap between the door and threshold. Figure 6-27 illustrates a door shoe that incorporates a drip. Figure 6-29 illustrates an automatic door bottom. Door bottoms can be surface-mounted or mortised. For high-traffic doors, periodic replacement of the neoprene will be necessary.
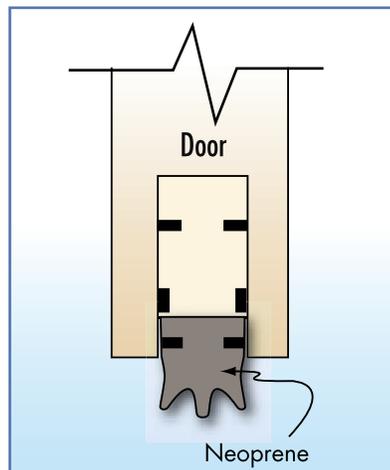
Figure 6-29
Automatic door bottom
SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL*, 2000

❏ **Thresholds.** These are available to suit a variety of conditions. Thresholds with vertical offsets offer enhanced resistance to wind-driven water infiltration. However, where Americans with Disabilities Act (ADA)-compliant thresholds are required, or at high-traffic doors, the offset is limited. However, at other doors, high offsets are preferred.

Thresholds can be interlocked with the door (see Figure 6-30) or thresholds can have a stop and seal (see Figure 6-31). In some instances, the threshold is set directly on the floor. Where this is appropriate, specify setting the threshold in butyl sealant to avoid water infiltration between the threshold and floor. In other instances, the threshold is set on a pan flashing as discussed in Section 6.10.4. If the threshold has weep holes, specify that the weep holes should not be obstructed (see Figure 6-30).

Figure 6-30
Interlocking threshold with drain pan

SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL, 2000*

The threshold should be set in butyl sealant. If a drain pan exists underneath the threshold, weep holes must not be blocked with sealant or debris.
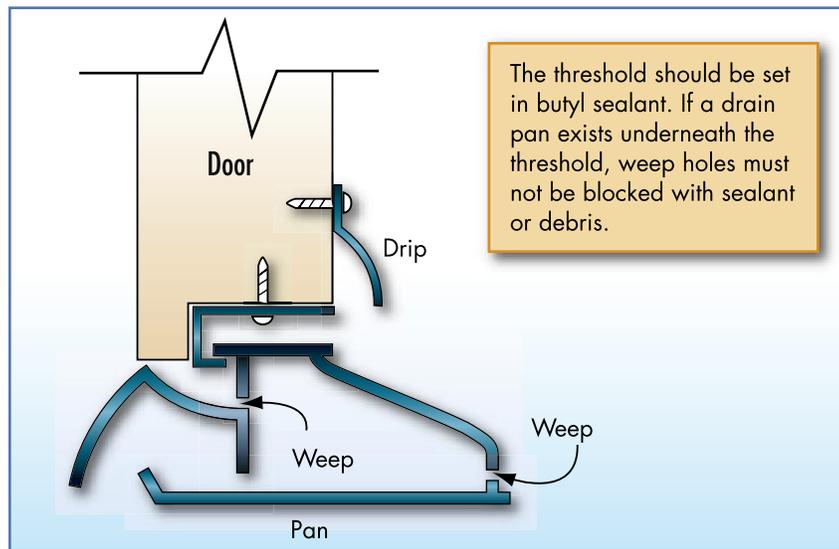
Figure 6-31
Threshold with stop and seal

SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL, 2000*

The threshold should be set in butyl sealant. If a drain pan exists underneath the threshold, weep holes must not be blocked with sealant or debris.
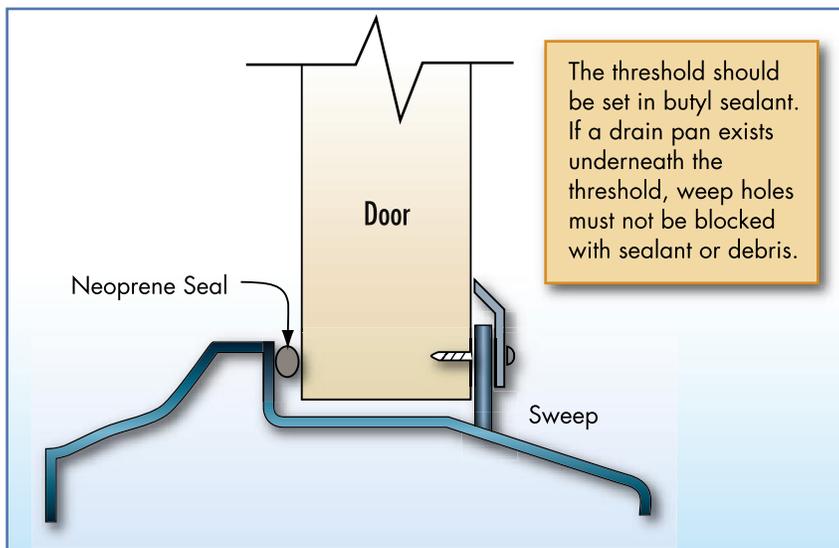
❍ **Adjustable jamb/head weatherstripping.** This type of jamb/head weatherstripping is recommended because these units have wide sponge neoprene that offers good contact with the door (see Figure 6-32). The adjustment feature also helps ensure good contact, provided the proper adjustment is maintained.

❍ **Meeting stile.** At the meeting stile of pairs of doors, an overlapping astragal weatherstripping offers greater protection than weatherstripping that does not overlap.


Door

Adjustable Jamb Weatherstrip
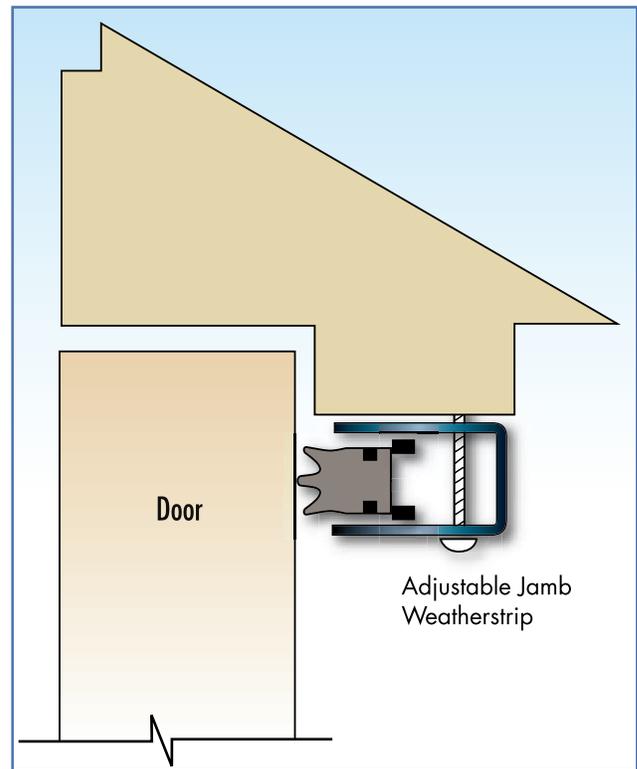
Figure 6-32   Adjustable jamb/head weatherstripping

SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL*, 2000

6.11 NON-LOAD BEARING WALLS, WALL COVERINGS, SOFFITS, AND UNDERSIDE OF ELEVATED FLOORS

This section addresses exterior non-load bearing walls and provides guidance for interior non-load bearing masonry walls. Exterior wall coverings and soffits, as well as the underside of elevated floors, are also discussed.

See Section 6.15.4 for schools located in hurricane-prone regions.

6.11.1 Loads and Resistance

The IBC requires that exterior non-load bearing walls, wall coverings, and soffits (see Figure 6-33) have sufficient strength to resist the positive and negative design wind pressure. Architects should specify that wall coverings and soffits comply with wind load testing in accordance with ASTM E 1233.

Depending upon wind direction, soffits can experience either positive or negative pressure. Besides the cost of repairing damaged soffits, wind-borne soffit debris can cause property damage and injuries.

Figure 6-33
This suspended metal soffit was not designed for upward-acting wind pressure.

Particular care should be given to the design and construction of exterior non-load bearing walls constructed of masonry. Although these walls are not intended to carry gravity loads, they must be designed to resist the positive and negative wind loads in order to avoid collapse. Because of their great weight, when these types of walls collapse, they represent a severe risk to life as shown in Figure 6-14.

Special consideration should also be given to interior non-load bearing masonry walls. Although these walls are not required by building codes to be designed to resist wind loads, if glazing is broken, the interior walls could be subjected to significant load as the school rapidly becomes fully pressurized. To avoid occupant injury (see Figure 6-34), it is recommended that interior non-load bearing masonry walls that are adjacent to student areas be designed to accommodate loads exerted by a design wind event, using the partially enclosed pressure coefficient. By doing so, wall collapse may be prevented if the building envelope is breached. This recommen-

dation is applicable to schools in tornado-prone areas that do not have shelter space designed in accordance with FEMA 361, to schools located in areas with a basic wind speed greater than 120 mph, and to schools that will be used for hurricane shelters.

Figure 6-34
The interior walls of this classroom wing were constructed of unreinforced CMU.

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

6.11.2 Durability

Where corrosion is problematic, stainless steel fasteners are recommended for wall and soffit systems. For other components (e.g., furring, blocking, struts, and hangars), the following are recommended: nonferrous components (such as wood), stainless steel, or steel with a minimum of G-90 hot-dipped galvanized coating. In addition, if air can freely circulate in a cavity (e.g., above a soffit), access panels are recommended so components within the cavity can be periodically observed for corrosion.

6.11.3 Wall Coverings

There are a variety of exterior wall covering options. Brick veneer, exterior insulation finish systems (EIFS), metal wall panels, and aluminum and vinyl siding have often exhibited poor wind performance. Veneers (such as ceramic tile and stucco) over concrete

and cement-fiber panels and siding have also blown off. Blow-off of wood siding and panels is rare.

Figure 6-35 shows brick veneer that was blown off. The bricks were attached to the back-up wall with corrugated metal ties. All of the following failure modes are commonly found in the vicinity of this type of common failure: 1) The nails pull out of the studs (smooth shank nails are typically used, hence they have limited withdrawal resistance; 2) The ties do not extend far enough into the mortar joint (i.e., the tie is not long enough); 3) Although the ties make contact with the mortar, they are not well-bonded to it; 4) The ties are spaced too far apart; and 5) The ties provide essentially no resistance to compression. Hence, when a great amount of positive pressure is applied to the bricks, the brick joints flex. This flexing weakens the mortar joint. Walls that have not had bricks blown away have been found to be capable of being deflected with hand pressure. Although they look sound, in this condition they are very vulnerable to failure. Good reliable wind performance of brick veneer is very demanding on the designer and applicator.

Figure 6-35
Failure of brick veneer

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

MAKING SCHOOLS SAFE AGAINST WINDS

Figure 6-36 shows EIFS blow-off. In this case, the expanded polystyrene (EPS) was attached to gypsum board, which was attached to metal studs. The gypsum board detached from the studs, which is a common EIFS failure mode. When the gypsum board on the exterior side of the studs is blown away, it is common for gypsum board on the interior side to also be blown off. This then allows the school to become fully pressurized and allows entrance of wind-driven rain. Other common failure modes include separation of the EPS from its substrate and separation of the synthetic stucco from the EPS. Good reliable wind performance of EIFS is very demanding on the designer and applicator. Maintenance of EIFS and associated sealant joints is also demanding in order to minimize reduction of EIFS' wind resistance due to water infiltration.

Figure 6-36
EIFS blow-off near a wall corner. At one area, the metal fascia was also blown in.

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

Another issue associated with EIFS is the potential for misdiagnosis of the wall system. EIFS is sometimes mistaken to be a concrete wall. If school personnel believed that an EIFS wall covering was a concrete wall and sought shelter from a tornado, instead of being protected by several inches of concrete, only two layers of gypsum board (i.e., one layer on each side of the studs) and a layer of EPS would be between the occupants and windborne debris. The debris could easily penetrate such a wall.

EIFS can also be applied over concrete or CMU. In this scenario, the concrete or CMU could provide adequate missile protection provided it was thick enough and adequately reinforced. However, with this wall construction, there is still risk of blow-off of the EIFS. As discussed in Section 6.15.4, if the concrete or CMU is left exposed, there is no covering to be blown off.

Wind performance of metal wall panels is highly variable. Performance depends upon strength of the specified panel (which is a function of material, panel profile, panel width and whether or not the panel is a composite) and the adequacy of the attachment (which can either be by concealed clips or exposed fasteners). A common problem is excessive spacing between clips/fasteners. Clip/fastener spacing should be specified, along with the specific type and size of fastener to be used. Figures 6-13 and 6-43 illustrate metal wall panel problems.

To minimize water infiltration at metal wall panel joints, it is recommended that sealant tape be specified at sidelaps when the basic wind speed is in excess of 90 mph. However, end laps should be left unsealed so that moisture behind the panels can wick out. End laps should be a minimum of 3 inches (4 inches where the basic wind speed is greater than 120 mph) to avoid wind-driven rain infiltration. At the base of the wall, a 3-inch (4-inch) flashing should also be detailed, or the panels should be detailed to over-lap with the slab or other components by a minimum of 3 inches (4 inches).

Vinyl siding blow-off is typically caused by nails spaced too far apart and/or the use of vinyl siding that has inadequate wind-resistance. Vinyl siding is available with enhanced wind resistance features, such as an enhanced nailing hem, greater interlocking area, and greater thickness.

Secondary Protection. Almost all wall coverings permit the passage of some water past the exterior surface of the covering, particularly when rain is wind-driven. Hence, most wall coverings should be considered as water-shedding, rather than as water-

MAKING SCHOOLS SAFE AGAINST WINDS

proofing coverings. To avoid moisture related problems, it is recommended that a secondary line of protection with a moisture barrier (such as housewrap or asphalt-saturated felt) and flashings around door and window openings be provided. Designers should specify that horizontal laps of the moisture barrier be installed so that water is allowed to drain from the wall (i.e., the top sheet should lap over the bottom sheet so that water running down the sheets remains on their outer surface). The bottom of the moisture barrier needs to be detailed to allow drainage.

In areas that frequently experience strong winds, enhanced flashing details are recommended. Enhancements include use of flashings that have extra-long flanges, and use of sealant and tapes. Flashing design should recognize that wind-driven water can be pushed vertically. The height to which water can be pushed increases with wind speed. Water can also migrate vertically and horizontally by capillary action between layers of materials (e.g., between a flashing flange and housewrap). It is recommended that designers attempt to determine what type of flashing details have successfully been used in the area where the school will be constructed.

If EIFS is specified, it is strongly recommended that it be designed with a drainage system that allows for dissipation of water leaks.

6.11.4 Underside of Elevated Floors

If sheathing is applied to the underside of joists or trusses elevated on piles (e.g., to protect insulation installed between the joists/trusses), its attachment should be specified in order to avoid blow-off. Stainless steel or hot-dip galvanized nails or screws are recommended. ASCE 7 does not provide guidance for load determination.

6.12 ROOF SYSTEMS

Because roof covering damage has historically been the most frequent and costly type of wind damage, special attention needs to be given to roof system design.

Code Requirements. The IBC requires load resistance of the roof assembly to be evaluated by one of the test methods listed in IBC's Chapter 15. Architects are cautioned that designs that deviate from the tested assembly (either with material substitutions or change in thickness or arrangement) may adversely affect the wind performance of the assembly. The IBC does not specify a minimum safety factor. However, for the roof system, a safety factor of two is recommended. (To apply the safety factor, divide the test load by two to determine the allowable design load. Conversely, multiply the design load by two to determine the minimum required test resistance.)

For metal panel systems, the IBC requires test methods UL 580 or ASTM E 1592. It is recommended that architects specify use of E 1592 because it is more likely to give a better representation of the system's uplift performance capability.

Load Resistance. Specifying load resistance is commonly done by specifying a Factory Mutual Research (FMR) rating, such as Factory Mutual (FM) 1-75. The first number ("1") indicates that the roof assembly passed the FMR tests for a Class 1 fire rating. The second number ("75") indicates the uplift resistance in psf that the assembly achieved during testing. Applying a safety factor of two to this example, this assembly would be suitable where the design uplift load is 37.5 psf.

As previously discussed, because of building aerodynamics, the highest uplift load occurs at roof corners. The perimeter has a somewhat lower load; the field of the roof has the lowest load. FMG *Data Sheets* are formatted so that a roof assembly can be selected for the field of the roof. That assembly is then adjusted to meet the higher loads in the perimeter and corners by increasing the number of fasteners or decreasing the spacing of adhesive ribbons by a required amount; however, this assumes that the failure is the result of the pulling-out of the fastener from the deck, or that failure is in the vicinity of the fastener plate, which may not be the case. Also, the increased number of fasteners required by FM may not be sufficient to comply with

the perimeter and corner loads derived from the building code. Therefore, if FM resistance data are specified, it is prudent for the architect to separately specify the resistance for the field of the roof (1-75 in the example above), the perimeter (1-130), and the corner (1-190).

Edge Flashings and Copings. Roof membrane blow-off is almost always a result of lifting and peeling of the metal edge flashing or coping, which serves to clamp down the membrane at the roof edge (see Figure 6-37). Therefore, it is important for the architect to carefully consider the design of metal edge flashings, copings, and the nailers to which they are attached. ANSI/SPRI ES-1, *Wind Design Standard for Edge Systems Used in Low Slope Roofing Systems* provides general design guidance, including a methodology for determining the outward-acting load on the vertical flange of the flashing/coping (ASCE 7 does not provide this guidance).

Figure 6-37
The metal edge flashing on this modified bitumen membrane roof was installed underneath the membrane, rather than on top of it and then stripped in. In this location, the edge flashing is unable to clamp the membrane down. At one area, the membrane was not sealed to the flashing (an ink pen was inserted into the opening prior to photographing). Wind can catch the opening and lift and peel the membrane.

A minimum safety factor of three for edge flashings, copings, and nailers is recommended for schools. ANSI/SPRI ES-1 also includes test methods for assessing flashing/coping resistance. For FMG-insured schools, FMR approved flashing should be used and *Data Sheet 1-49* should also be consulted.

The traditional edge flashing/coping attachment method relies on concealed cleats that can deform under wind load and lead to disengagement of the flashing/coping (see Figure 6-38) and subsequent lifting and peeling of the roof membrane (as shown in Figure 6-11). When a vertical flange disengages and lifts up (as shown in Figure 6-38), the edge flashing and membrane are very susceptible to failure. Normally, when a flange lifts such as shown in Figure 6-38, the failure continues to propagate and the metal edge flashing and roof membrane blow off.

Figure 6-38
This metal edge flashing had a continuous cleat, but the flashing disengaged from the cleat and the vertical flange lifted up. However, the horizontal flange of the flashing did not lift.

Storm-damage research has revealed that, in lieu of cleat attachment, use of exposed fasteners to attach the vertical flanges of copings and edge flashings has been found to be a very effective and reliable attachment method (see Figure 6-39).

If cleats are used for attachment, it is recommended that a bar be placed over the roof membrane near the edge flashing/coping as illustrated in Figure 6-40. The purpose of the bar is to provide secondary protection against membrane lifting and peeling in the event that the edge flashing/coping fails. A robust bar specifically made for bar-over mechanically attached single-ply systems is recommended. The bar needs to be very well anchored to the parapet or deck. Depending upon design wind loads, a spacing

Figure 6-39
This coping was attached with ¼-inch diameter stainless steel concrete spikes at 12 inches on center. When the fastener is placed in wood, #14 stainless steel screws with stainless steel washers are recommended. Also, in the corner areas, the fasteners should be more closely spaced (the spacing will depend upon the design wind loads). ANSI/SPRI ES-1 provides guidance on fastener spacing and thickness of the coping/edge flashing.
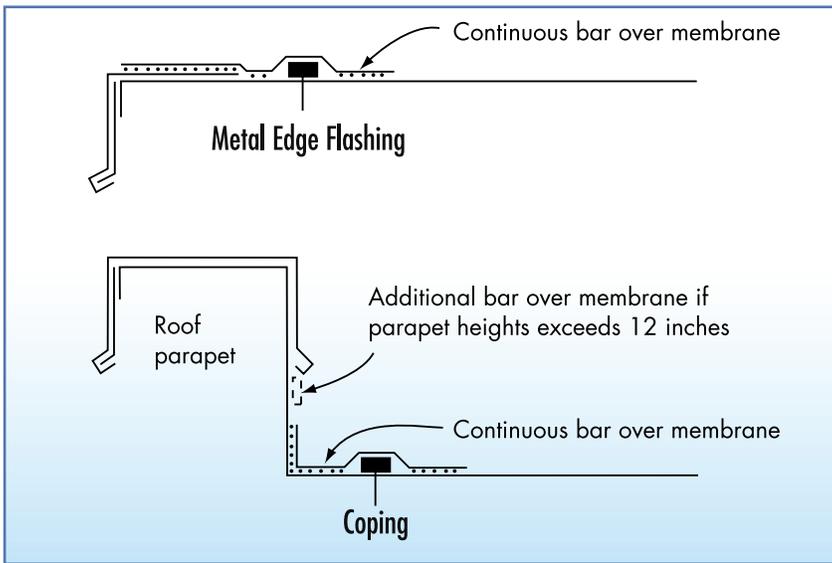
Figure 6-40
Continuous bar near the edge of edge flashing or coping. If the edge flashing or coping is blown off, the bar may prevent a catastrophic progressive failure.

SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL,* 2000

between 4 and 12 inches on center is recommended. A gap of a few inches should be left between each bar to allow for water flow across the membrane. After the bar is attached, it is stripped over with a stripping ply.

Gutters. Special design attention needs to be given to uplift attachment of gutters, particularly those in excess of 6 inches wide. Recommendations are provided in "Honing in on hangars," *Professional Roofing*, Thomas L. Smith, October 2002, pp. 32 (available on-line at www.nrca.net).

Roof System Performance. Storm-damage research has shown that sprayed polyurethane foam and liquid-applied roof systems are very reliable high-wind performers. If the substrate to which the foam or liquid-applied membrane was applied does not lift, it is highly unlikely that the sprayed polyurethane foam (SPF) or the liquid-applied membrane will blow-off. Both systems are also more tolerant of missiles than other systems. Built-up roofs (BURs) and modified bitumen systems have also demonstrated good wind performance provided the edge flashing/coping does not fail (edge flashing/coping failure is common). The exception is aggregate surfacing, which is prone to blow-off (see Figure 6-11). Modified bitumen adhered to a concrete deck has demonstrated excellent resistance to progressive peeling after blow-off of the metal edge flashing. Metal panel performance is highly variable. Some systems are very wind-resistant, while others are quite vulnerable.

Of the single-ply attachment methods, the paver-ballasted and fully adhered methods are the least problematic. Systems with aggregate ballast are prone to blow-off, unless care is taken in the design of the size of aggregate and the parapet height (see Figure 6-8). Performance of protected membrane roofs (PMRs) with factory-applied cementitious coating over insulation boards is highly variable. When these boards are installed over a loose-laid membrane, it is critical that an air retarder be incorporated to prevent the membrane from ballooning and disengaging the boards. ANSI/SPRI RP-4 (which is referenced in the IBC) provides wind guidance for ballasted systems using aggregate, pavers, and cementitious-coated boards.

The National Research Council of Canada, Institute for Research in Construction's *Wind Design Guide for Mechanically*

Attached Flexible Membrane Roofs, B1049 (2004) provides recommendations related to mechanically attached single-ply and modified bituminous systems. B1049 is a very comprehensive wind design guide and includes discussion of air retarders, which can be effective in reducing membrane flutter, in addition to their beneficial use in ballasted single-ply systems. When a mechanically attached system is specified, careful coordination with the structural engineer with respect to selection of deck type and thickness is important. If a steel deck is specified, it is critical to specify that the membrane fastener rows run perpendicular to the steel flanges in order to avoid overstressing attachment of the deck to the deck support structure (see Figures 6-41 and 6-42). In Figure 6-42, the flange with membrane fasteners carries essentially all of the uplift load because of the deck's inability to transfer any significant load to adjacent flanges. Hence, at the joists, the deck fasteners on either side of the flange with the membrane fasteners are the only connections to the joists that are carrying uplift load. Had the membrane fasteners shown in Figure 6-42 been run perpendicular to the deck flanges, each of the fasteners connecting the deck to the joists would have been carrying uplift load.

Figure 6-41
On this school, the fastener rows of the mechanically attached single-ply membrane ran parallel to the top flange of the steel deck. Hence, essentially all of the row's uplift load was transmitted to only two deck fasteners at each joist (as illustrated in Figure 6-42). Because the deck fasteners were overstressed, a portion of the deck blew off and the membrane progressively tore.

Figure 6-42
View of the underside
of a steel deck. The
mechanically attached
single-ply membrane
fastener rows ran parallel
to the top flange of the steel
deck.

Recommendations related to metal panels is provided in "Insights on Metal Roof Performance in High-wind Regions," *Professional Roofing*, Thomas L. Smith, February 1995, pp. 12 (available on-line at www.nrca.net).

Parapet Base Flashings. Loads on parapet base flashings were first introduced in the 2002 edition of ASCE 7. The loads on base flashings are greater than the loads on the roof covering if the parapet's exterior side is air-permeable. When base flashing is fully adhered, it has sufficient wind resistance in most cases. However, when base flashing is mechanically fastened, typical fastening patterns may be inadequate, depending upon design wind conditions (see Figure 6-43). Therefore, it is imperative that base flashing loads be calculated and attachments be designed to accommodate the loads. It is also important for designers to recognize and specify different attachment spacings in parapet corner regions versus regions between corners. Further discussion is provided in "Detailing ASCE 7's changes," *Professional Roofing,* Thomas L. Smith, July 2003, pp. 26 (available on-line at www.nrca.net).

Figure 6-43
The parapet on this school was sheathed with metal wall panels. The panels were fastened at 2 feet on center along their bottom edge, which was inadequate to resist the wind load.

Lightning Protection Systems. When not adequately integrated into a roof system, a lightning protection system can become detached from the roof during high winds. The detached system can damage the roof covering (see Figure 6-44). In addition, a detached system is no longer capable of providing lightning protection. Most manufacturers of lightning protection systems and most roofing manufacturers provide vague or inadequate details for securing a lightning protection system to a roof.

During prolonged high winds, repeated slashing of the membrane by loose conductors ("cables") and puncturing by air terminals can result in lifting and peeling of the membrane. It is, therefore, important to adequately design the attachment of the lightning protection system. Recommendations pertaining to wind-resistant design, and specification and installation of lightning protection systems are provided in "Integrating a Lightning Protection System in a Roof System," Thomas L. Smith, 12th International Roofing and Waterproofing Conference Proceedings (CD), National Roofing Contractors Association, 2002.

Steep-slope Coverings. For discussion and recommendations pertaining to steep-slope roof coverings, see FEMA 55, *Coastal Construction Manual*, Third Edition, 2000.

Figure 6-44

This air terminal ("lightning rod") was dislodged and whipped around during a windstorm. The single-ply membrane was punctured by the sharp tip in several locations.

SOURCE: FEMA, *BUILDING TO MINIMUM TYPHOON DAMAGE: DESIGN GUIDELINES FOR BUILDINGS*, JULY 1998

Hurricane-prone Regions. See Section 6.15.5 for schools in hurricane-prone regions.

Tornado-prone Regions. In order to reduce the number of wind-borne missiles, it is recommended that aggregate surfacings, pavers, tile, and slate not be specified on schools in tornado-prone regions (as defined in Section 6.7.1; see Figure 6-8).

6.13 WINDOWS AND SKYLIGHTS

This section addresses exterior windows and skylights. See Section 6.15.6 for schools located in hurricane-prone regions.

6.13.1 Loads and Resistance

The IBC requires the window, curtain wall, or skylight assembly (i.e., the glazing, frame, and frame attachment to the wall or roof) to have sufficient strength to resist the positive and negative design wind pressure (see Figure 6-45). Architects should specify that these assemblies comply with wind load testing in accordance with ASTM E 1233. It is important to specify an adequate load path and to check its continuity during submittal review.

In tornado-prone regions, some school districts may desire to have laminated glazing installed at exterior openings in order to provide wind-borne debris protection during weak tornadoes. Laminated glazing may also offer protection during strong tornadoes, but should not be relied upon for violent tornadoes. Further discussion is provided in Section 6.15.6.

6.13.2 Durability

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

6.13.3 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 at the glazing/frame interface, at the frame itself, or between the frame and wall. 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.

The challenge with windows and curtain walls is successful integration between these elements and the walls. To the extent possible, detailing of the interface between the wall and the window or curtain wall units should rely on sealants as the secondary line of defense against water infiltration, rather than making the sealant the primary protection.

When designing joints between walls and windows and curtain wall units, consider the shape of the sealant joint (i.e., a square joint is typically preferred) and the type of sealant to be specified. The sealant joint should be detailed so the sealant is able to bond on only two opposing surfaces (i.e., a backer rod or bond-breaker tape should be specified). For concealed sealants, butyl is recommended. For exposed sealants, polyurethane is recommended. During installation, cleanliness of the sealant substrate is important (particularly if polyurethane or silicone sealants are specified), as well as tooling of the sealant. ASTM E 2112 provides guidance on design of sealant joints, as well other information pertaining to installation of windows, including the use of sill pan flashings with end dams and rear legs (see Figure 6-46). It is recommended that designers use ASTM E 2112 as a design resource.

Figure 6-46
View of a typical window sill pan flashing with end dams and rear legs. Windows that do not have nailing flanges should typically be installed over a pan flashing.

SOURCE: ASTM E2112
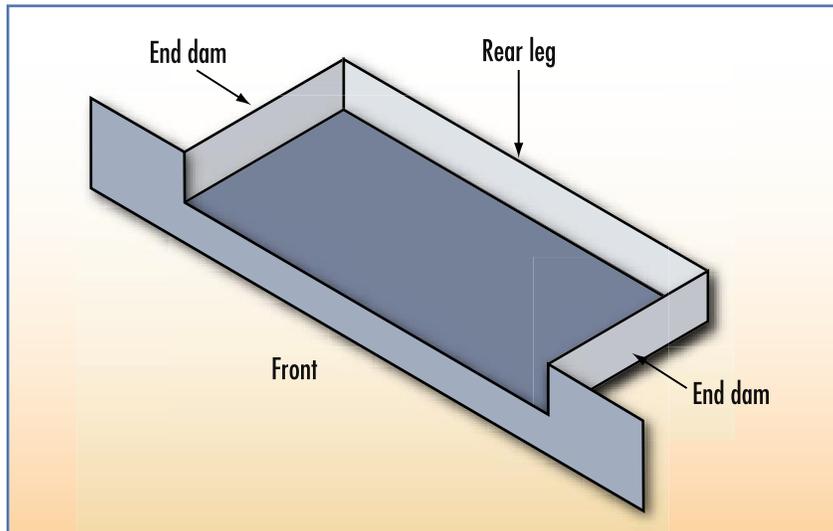
Sealant joints can be protected with a removable stop as illustrated in Figure 6-47. The stop protects the sealant from direct exposure to the weather and reduces the wind-driven rain demand on the sealant.
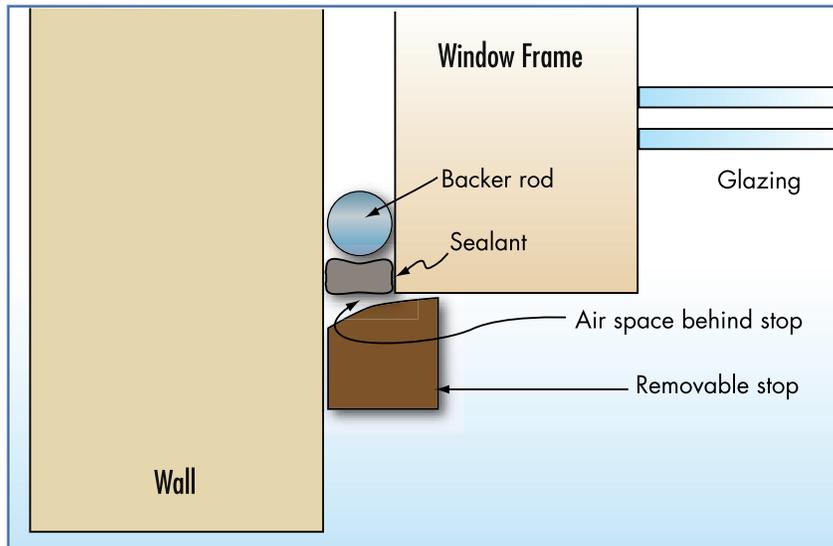
Figure 6-47
Protection of sealant with a stop. The stop retards weathering of the sealant and reduces the wind-driven rain demand on the sealant.

SOURCE: FEMA 55, *COASTAL CONSTRUCTION MANUAL*, 2000

Where water infiltration protection is particularly demanding and important, it is recommended that on-site water infiltration testing in accordance with ASTM E 1105 be specified.

6.14 EXTERIOR-MOUNTED MECHANICAL, ELECTRICAL, AND COMMUNICATIONS EQUIPMENT

Exterior-mounted mechanical (e.g., exhaust fans, HVAC units, relief air hoods, boiler stacks), electrical, and communications equipment (e.g., light fixtures, antennae, satellite dishes) are often damaged during high winds. Damaged equipment can impair the use of the school, the equipment can become missiles, and water can enter the facility where equipment was displaced (see Figures 6-19 and 6-48).

Problems typically relate to inadequate equipment anchorage, inadequate strength of the equipment itself, and corrosion.

Figure 6-48
The rooftop mechanical equipment on this school was blown over. The displaced equipment can puncture the roof membrane and, as in this case, rain can enter the school through the large opening that is no longer protected by the equipment.

6.14.1 Loads and Attachment

Rooftop Equipment. Criteria for determining loads on rooftop equipment were added to the 2002 edition of ASCE 7. A minimum safety factor of three is recommended for the design of equipment anchorage.

To anchor membrane fans, small HVAC units, and relief air hoods, the following minimum prescriptive attachment schedule is recommended:

❍ For curb-mounted units, specify #14 screws with gasketed washers.

❍ For curbs with sides less than 12 inches, specify one screw at each side of the curb.

❍ For curbs between 12 inches and 24 inches, specify two screws per side.

❍ For curbs between 24 inches and 36 inches, specify three screws per side.

❍ For units that have flanges attached directly to the roof, attachment with #14 pan-head screws is recommended. A minimum of two screws per side, with a maximum spacing of 12 inches on center is recommended.

Figure 6-49 illustrates the use of supplemental securement straps to anchor equipment. The supplemental attachment was marginal; the straps were too light and the fasteners used to secure them were corroded. This illustrates the validity of the supplemental securement, and it also illustrates the need to execute the securement with attention to detail. In lieu of one screw at each end of the strap, two side-by-side screws offer a stronger and more reliable connection (this of course requires a slightly wider strap).

Figure 6-49
This HVAC equipment had two supplemental securement straps. Both straps are still on this unit, but some of the other units on the roof had broken straps.

SOURCE: FEMA, *BUILDING TO MINIMUM TYPHOON DAMAGE: DESIGN GUIDELINES FOR BUILDINGS*, JULY 1998

Electrical and Communications Equipment. Damage to exterior-mounted electrical equipment is infrequent, in large part, because of the small size of most equipment (e.g., disconnect switches). Exceptions are communication masts (see Figure 6-50), surveillance cameras, service masts, and satellite dishes. These failures are typically caused by failure to perform wind load calculations and anchorage design. Service mast failure is typically caused by collapse of overhead power lines; this can be avoided by underground service. Where overhead service is provided, it is recommended that the service mast not penetrate the roof. Otherwise, a downed service line could pull the mast and rupture the roof membrane.

Figure 6-50
The communications mast on this school was pulled out of the deck, resulting in a progressive peeling failure of the fully adhered single-ply membrane. There are several exhaust fans in the background that were blown off their curbs, but were retained on the roof by the parapet.

SOURCE: FEMA, *BUILDING TO MINIMUM TYPHOON DAMAGE: DESIGN GUIDELINES FOR BUILDINGS*, JULY 1998

ASCE 7 provides load calculation criteria for trussed towers. The ASCE 7 criteria are consistent with ANSI/EIA/TIA-222-E. The ASCE 7 approach is a simplified procedure. The IBC allows use of either approach. ASCE 7 does not provide guidance for on-site power distribution poles nor for light fixture poles. However, the National Electrical Safety Code, ANSI/C2 provides guidance for determining wind loads on power poles. The AASHTO S*tandard Specification for Structural Support for Highway Signs, Luminaries and Traffic Signals* provides guidance for determining wind loads on light fixture poles.

See Section 6.8.1 regarding siting of light fixture poles, power poles, and electrical and communications towers.

6.14.2 Equipment Strength

It is common for equipment components such as fan cowlings and access panels to be blown off during storms. Design of these elements is the responsibility of the equipment manufacturer. Although poor equipment performance has been documented, manufacturers have not offered enhanced equipment for high-wind regions. Therefore, it is incumbent upon the architect/engineer to give special design attention to equipment strength.

Damage investigations have revealed that cable tie-downs have been effective in securing fan cowlings when a sufficiently strong cable and anchor details were used (see Figure 6-51). For fan cowlings less than 4 feet in diameter, 1/8-inch diameter stainless steel cables are recommended. For larger cowlings, use 3/16-inch diameter cables. When the basic wind speed is 120 mph or less, specify two cables. Where the basic wind speed is greater than 120 mph, specify four cables. (As an alternative to cables, heavy stainless steel straps could be screwed to the cowling and curb.) To minimize leakage potential at the anchor point, it is recommended that the cables be anchored to the equipment curb (rather than anchored to the roof deck). The attachment of the curb itself also needs to be designed and specified.

Figure 6-51
To overcome blow-off of the fan cowling, which is a common problem, this cowling was attached to the curb with cables. The curb needs to be adequately attached to carry the wind load exerted on the fan.

SOURCE: FEMA, *BUILDING TO MINIMUM TYPHOON DAMAGE: DESIGN GUIDELINES FOR BUILDINGS,* JULY 1998

To minimize blow-off of equipment access panels, job-site modification will typically be necessary (such as the attachment of hasps and locking devices such as a carabineer). The modification details will need to be tailored for the equipment, which may necessitate detail design after the equipment has been delivered to the job site. Alternatively, factored loads on the equipment could be specified, along with the requirement for the manufacturer to demonstrate compliance with the load requirement.

6.14.3 Durability

To avoid corrosion-induced blow-off, it is recommended that exterior-mounted mechanical, electrical, and communications equipment be nonferrous, stainless steel, or steel with minimum G-90 hot-dip galvanized coating for the equipment itself, equipment stands, anchors, and fasteners. When equipment with enhanced corrosion protection is not available, the designer should advise the school district that periodic equipment maintenance and inspection is particularly important to avoid advanced corrosion and subsequent equipment damage during a windstorm.

The recommendations given in Sections 6.8 through 6.14 are summarized in Table 6-1.

Table 6-1: Summation of Risk Reduction Design Methods

Site	See Section 6.8.1.
Exposure	Locate in Exposure B if possible. Avoid escarpments and upper half of hills.
Are there trees or poles?	Locate to avoid blow-down on school.
Site access	Minimum of two roads.
Are there, or will there eventually be portables?	Locate downwind of school.
General design issues	See Section 6.8.2
Calculate loads on MWFRS, building envelope and rooftop equipment	Use ASCE 7 or local building code, whichever procedure results in highest loads.
Determine load resistance via calculations and/or test data	Give load resistance criteria in contract documents, and clearly indicate load path continuity.
Durability	Give special attention to material selection and detailing to avoid problems due to corrosion, wood decay, and termite attack.
Rain penetration	Detail to minimize wind-driven rain penetration into the building envelope.

MAKING SCHOOLS SAFE AGAINST WINDS

Table 6-1: Summation of Risk Reduction Design Methods (continued)

Structural Systems (MWFRS)	See Section 6.9.
Is it a pre-engineered structural system?	Take special steps to ensure structure is not vulnerable to progressive collapse.
Are there exterior bearing walls?	Design as MWFRS and Components and Cladding. Reinforce CMU. Sufficiently connect precast concrete panels.
Roof decks	Concrete, steel, or wood sheathing is recommended. Attach steel decks with screws. Use special fasteners for wood sheathing. Anchor precast concrete to resist uplift load. For precast Tees, design reinforcing to resist uplift. If FMG-rated assembly, deck must comply with FMG criteria. If mechanically attached roof membrane, refer to recommendations in National Research Council of Canada, *Institute for Research in Construction, Wind Design Guide for Mechanically Attached Flexible Membrane Roofs*, B1049, 2004.
Exterior Doors and Non-Load Bearing Exterior Walls	See Section 6.10 and 6.11.
Door, frame and frame fasteners	Resist positive and negative design load, verified by ASTM E 1233 testing. Specify type, size, and spacing of frame fasteners.
Water infiltration	Consider vestibules, door swing, weatherstripping. Refer to ASTM E 2112 for design guidance.
Are there exterior non-load bearing walls, wall coverings, soffits, or elevated floors?	See Section 6.11.
Load resistance	Resist positive and negative design load, verified by ASTM E 1233 testing. Design as Components and Cladding.
Secondary protection	Provide moisture barrier underneath wall coverings that are water-shedding.
Roof Systems	See Section 6.12.
Testing	Avoid designs that deviate from a tested assembly. If deviation is evident, perform rational analysis. For metal panel systems, test per ASTM E 1592.
Edge flashings and copings	Follow ANSI/SPRI ES-1. Use a safety factor of three. Consider face-fasteners (Figure 6-39). Consider continuous bars (Figure 6-40).
System selection	Select systems that offer high reliability, commensurate with the wind-regime where the school is located.
Are there parapet base flashings?	Calculate loads and resistance. This is particularly important if base flashing is mechanically attached.
Is there a lightning protection system?	Design and specify anchorage to the roof.
Is there a steep-slope roof system?	See *Coastal Construction Manual*, Third Edition, FEMA 55, 2000.

Table 6-1: Summation of Risk Reduction Design Methods (continued)

Windows and Skylights	**See Section 6.13.**
Glazing, frame, and frame fasteners	Resist positive and negative design load, verified by ASTM E 1233 testing. Specify type, size, and spacing of frame fasteners.
Water infiltration	Carefully design juncture between walls and windows/curtain walls. Avoid relying on sealant as the first line of defense. Refer to ASTM E 2112 for design guidance. Where infiltration is demanding, consider on-site water infiltration testing per ASTM E 1105.
Exterior-mounted Mechanical, Electrical, and Communications Equipment	**See Section 6.14.**
Load resistance	Specify anchorage of all rooftop and wall-mounted equipment. Use a safety factor of three for rooftop equipment anchorage.
Equipment strength	Specify cable tie-downs for fan cowlings. Specify hasps and locking devises for equipment access panels.
Electrical service mast	Avoid penetration through the roof.
After Completion of Contract Documents	
Peer review	Consider peer review. See Section 6.8.3.
Submittals	Ensure required submittals are submitted and that they include the necessary information. Verify that each submittal demonstrates development of a load path through the system and into its supporting element. See Section 6.8.4.
Field observations	Analyze design to determine which elements are critical to ensuring high-wind performance. Determine observation frequency of critical elements. See Section 6.8.4.
Post-occupancy inspections, maintenance, and repair	Advise the school administration of the importance of periodic inspections, special inspections after unusually high winds, maintenance, and timely repair. See Section 6.8.5.

6.15 SCHOOLS LOCATED IN HURRICANE-PRONE REGIONS

The IBC, through ASCE 7, prescribes that exterior glazing in schools in wind-borne debris regions be provided with wind-borne debris protection (either by use of laminated glass or shutters, as discussed in Section 6.15.6). Schools in hurricane-prone regions also have to be designed for a 100-year mean recurrence interval wind event if they are to be used as shelters. These are the only hurricane-related requirements currently in the IBC. These requirements do not provide adequate protection to occupants in a school during a hurricane, because the missile requirements only pertain to glazing. Hence, a code-compliant school can be designed, yet still allow the entrance of missiles through the roof or walls. To account for this deficiency, recommendations are given below regarding missile penetration through exterior walls and the roof. For a more conservative hurricane shelter, refer to FEMA 361.

Publication 4496 by the American Red Cross (ARC) provides information regarding assessing existing buildings for use as hurricane shelters. Unless a school has been specifically designed for use as a shelter, it should only be used as a last resort and only if the school meets the criteria given in ARC 4496.

Schools located in hurricane-prone regions should receive special design attention because of the unique characteristics of this type of windstorm. In addition to being capable of delivering very high winds, hurricanes can cause strong winds for many hours, which can eventually lead to fatigue failure. The direction of the wind can also change, thereby increasing the probability that the wind will approach the school at the most critical angle. Hurricanes also typically generate a large amount of missiles, which can be very damaging to schools and cause injury or death.

For schools in hurricane-prone regions that will be used for a hurricane shelter and/or for emergency response after a storm, the following design parameters are recommended (these

recommendations are in addition to the recommendations previously given in Sections 6.8 through 6.14):

1. During the design phase, the architect should determine from the school district whether or not the school will be designated or used as a shelter or emergency response facility. The school should only be used for a shelter if it was designed for that purpose.

2. For schools in coastal Alaska and other areas that experience frequent high wind events (such as parts of Colorado), several of the following recommendations are also applicable to these schools, with the exception of the wind-borne debris recommendations.

6.15.1 Design Loads

For the importance factor, use a value of 1.15.

6.15.2 Structural Systems

Because of the exceptionally good wind performance that reinforced cast-in-place concrete structures offer, a reinforced concrete roof deck and reinforced concrete and/or reinforced and fully grouted CMU exterior walls are recommended.

In order to achieve enhanced missile resistance, the following roof decks are recommended, in descending order of preference: cast-in-place concrete, precast concrete, and concrete topping over steel decking. For exterior walls, the following are recommended: 6-inch (minimum) thick concrete reinforced with #4 rebars at 12 inches on center each way, or 8-inch (minimum) thick fully grouted CMU reinforced with #4 rebars in each cell.

6.15.3 Exterior Doors

For glazing in doors, see the recommendations in Section 6.15.6.

Although the ASCE-7 wind-borne debris provisions only apply to glazing within a portion of hurricane-prone regions, it is recommended that all schools that will be used for evacuation shelters within the entire hurricane-prone region comply with the following recommendation: To minimize the potential of missiles penetrating exterior doors and striking people within the school, it is recommended that doors without glazing and the unglazed portions of doors with glazing be designed to resist the missile loads specified in ASTM E 1996 and that they be tested in accordance with ASTM E 1886. The test assembly should include the door, door frame and hardware. Further information on missile resistance of doors is found in FEMA 361, *Design and Construction Guidance for Community Shelters.*

6.15.4 Non-load Bearing Walls, Wall Coverings, and Soffits

In order to achieve enhanced missile resistance, the following types of exterior walls are recommended: reinforced cast-in-place concrete, or reinforced and fully grouted CMU.

To minimize long-term problems with non-load bearing walls, wall coverings, and soffits, it is recommended that non-load bearing exterior walls, wall coverings, and soffits be avoided to the extent possible. Reinforced concrete or CMU offers greater reliability (i.e., they have no coverings that can be blown off).

6.15.5 Roof Systems

The following types of roof systems are recommended on schools in hurricane-prone regions because they are more likely to avoid water infiltration if the roof is hit by wind-borne debris. Also, the following systems are less likely to become sources of wind-borne debris:

❍ In tropical climates where insulation is not needed above the roof deck: 1) liquid-applied membrane over cast-in-place concrete deck, or 2) modified bitumen membrane torched directly to cast-in-place concrete deck.

❍ Install a secondary membrane over a concrete deck (if another type of deck is specified, a cover board may be needed over the deck). Seal the secondary membrane at perimeters and penetrations. Specify a minimum 2-inch thick rigid insulation and a layer of 5/8-inch thick glass mat gypsum roof board over the secondary membrane to absorb missile energy. If the primary membrane is punctured during a storm, the secondary membrane should provide watertight protection unless the roof is hit with missiles of very high energy. A modified bitumen membrane is recommended for the primary membrane because of its enhanced resistance to puncture by small missiles.

❍ For an SPF roof system over a concrete deck, specify that the foam be a minimum of 3 inches thick to avoid missile penetration through the entire layer of foam.

❍ For a PMR, it is recommended that pavers weighing a minimum of 22 psf be specified. In addition, base flashings should be protected with metal. Parapets are recommended at roof edges. The parapet should be at least 3 feet high or higher if so indicated by ANSI/SPRI RP-4. Note: If the basic wind speed exceeds 130 mph, a PMR is not recommended on schools in hurricane-prone regions.

❍ For structural metal roof panels with concealed clips, it is recommended that mechanically seamed ribs spaced at 12 inches on center over a concrete deck be specified. If a steel deck is specified, specify a self-adhering modified bitumen membrane and 3-inch thick rigid insulation, followed by the metal panels installed on wood nailers. At the self-adhering membrane laps, specify metal strips over the deck where the laps do not occur over the deck ribs, or specify a suitable cover board between the deck and self-adhering membrane. If the metal panels are punctured during a storm, the secondary membrane should provide watertight protection unless the roof is hit with missiles of very high energy. Note: Architectural metal panels are not recommended on schools in hurricane-prone regions.

In order to avoid the possibility of roofing debris blowing off and striking people arriving at the school during the storm, the following types of roof coverings are not recommended: aggregate surfacings (either on BUR [shown in Figure 6-11], single-plies [shown in Figure 6-8] or SPF), lightweight concrete pavers, cementitious-coated insulation boards, slate, and tile (see Figure 6-52). Wind-borne debris from heavy roof coverings such as tiles have great potential to cause serious injury to people arriving at a school during a hurricane or other high wind event.

Figure 6-52
These wire-tied tiles were installed over a concrete deck. They were attached with stainless steel clips at the perimeter rows and all of the tiles had tail hooks. Adhesive was also used between the tail and head of the tiles.

SOURCE: FEMA, *BUILDING TO MINIMUM TYPHOON DAMAGE: DESIGN GUIDELINES FOR BUILDINGS*, JULY 1998

Because mechanically attached and air-pressure equalized single-ply membrane systems are susceptible to massive progressive failure after missile impact (see Figure 6-53), these systems are not recommended on schools in hurricane-prone regions. Fully adhered single-ply membranes are also very vulnerable to missiles (see Figure 6-54); therefore, they also are not recommended unless they are ballasted with pavers.

Figure 6-53
At this school, a missile struck the fully adhered low-sloped roof (see arrow) and slid into the steep-sloped reinforced mechanically attached single-ply membrane. A large area of the mechanically attached membrane was blown away due to progressive membrane tearing.

Figure 6-54
This fully adhered single-ply membrane was struck by a large number of missiles during a hurricane.

6.15.6 Windows and Skylights

ASCE 7 requires the use of impact-resistant glazing (i.e., laminated glass) or shutters in wind-borne debris regions. ASCE 7 refers to ASTM E 1996 for missile loads and to ASTM E 1886 for the test method to be used to demonstrate compliance with the E

1996 load criteria. In addition to testing for impact resistance, the window unit is subjected to pressure cycling after missile impact to evaluate whether or not the window can still resist wind loads.

If wind-borne debris glazing protection is provided by shutters, the glazing is still required by ASCE 7 to meet the positive and negative design air pressures.

For those schools that desire to provide blast-resistant glazing, the windows and glazed doors can be designed to accommodate wind pressure, missile loads, and blast pressure. However, the window and door units need to be tested for missile loads and cyclic air pressure, as well as for blast. A unit that meets blast criteria will not necessarily meet the E 1996 and E 1886 criteria, and vice versa.

With the advent of building codes requiring glazing protection in wind-borne debris regions, a variety of shutter designs have entered the market. Figure 6-55 illustrates an effective shutter. A metal track was permanently mounted to the wall above and below the window frame. Upon notification of an approaching hurricane, the metal shutter panels were inserted into the frame and locked into position with wing nuts.

Figure 6-55
View of a metal shutter designed to provide missile protection for windows

Shutters typically have a lower initial cost than laminated glass. However, unless the shutter is permanently anchored to the school (e.g., an accordion shutter), space will be needed to store the shutters. Also, when a hurricane is forecast, costs will also be incurred each time shutters are installed and removed afterward. To avoid the difficulty of installing shutters on upper-level glazing, motorized shutters could be specified, although laminated glass may be more economical in these locations.

6.15.7 Emergency Power

Schools intended for use as shelters and/or emergency response after a storm should be equipped with an emergency generator.

6.15.8 Construction Contract Administration

It is important for the school district to obtain the services of a professional contractor who will execute the work described in the contract documents in a diligent and technically proficient manner.

The frequency of field observations and extent of special inspections and testing should be greater than those employed on schools that are not designated as shelters.

6.15.9 Periodic Inspections, Maintenance, and Repair

The recommendations previously given for periodic and post-storm inspections, maintenance, and repair are critically important for schools used as shelters and emergency response after a storm because, if failure occurs, the risk of injury or death to occupants is great, and the needed continued operation of the school would be jeopardized.

The recommendations given in Section 6.15 are summarized in Table 6-2. These recommendations are in addition to those given in Sections 6.8 to 6.14, as summarized in Table 6-1.

Table 6-2: Summation of Design of Schools Used for Hurricane Shelters and/or for Emergency Response After a Storm

For wind-load calculations	Use an importance factor of 1.15.
Structural system	Reinforced cast-in-place concrete is recommended. If roof deck is not cast-in-place, pre-cast concrete or concrete topping over steel decking is recommended.
Exterior walls	Reinforced concrete or fully grouted and reinforced CMU is recommended, without wall coverings other than paint.
Exterior doors	Designed and tested to resist missiles.
Roof covering	Avoid aggregate surfacings, lightweight concrete pavers, cementitious-coated insulation boards, slate and tile. Avoid single-ply membranes unless ballasted with heavy pavers. Design a roof covering that can accommodate missiles – see Section 6.15.5.
Exterior windows and skylights	Laminated glass or shutters designed and tested to resist missiles. If equipped with shutters, glazing is still required to resist wind pressure loads.
Emergency power	School equipped with an emergency generator.
Construction contract administration	Construction executed by professional contractor and subcontractors. More frequent field observations, special inspections and testing.
Periodic inspections, maintenance, and repair	After construction, diligent periodic inspections and special inspections after storms. Diligent maintenance and prompt execution of needed repairs.
Is enhanced occupant protection sheltering desired?	For a more conservative hurricane shelter, refer to FEMA 361, *Design and Construction Guidance for Community Shelters*.

6.16 DESIGN FOR TORNADO SHELTERS

Tornado risk assessment and tornado-prone regions were discussed in Section 6.7 and the cost of tornado shelters was discussed in Section 6.5.2. Following up on those discussions, strong and violent tornadoes produce wind speeds that are substantially greater than those delivered by the strongest hurricanes; hence, the wind pressures that these tornadoes exert on buildings is tremendous and far exceed the minimum pressures required by building codes. In addition, strong and violent tornadoes can generate very powerful missiles (see Figure 6-56), including vehicles. The missile sticking out of the roof in the foreground of Figure 6-56 is a double 2-inch by 6-inch. The portion sticking out of the roof is 13 feet long. It penetrated a ballasted ethylene propylene diene monomer (EPDM) membrane and approximately 3 inches of polyisocyanurate roof insulation and the steel roof deck. The missile laying on the roof just beyond is 2 inches by 10 inches by 16 feet long.

Missile loads that are used for the design of tornado shelters are significantly greater than the missile loads used for the design of glazing protection in wind-borne debris regions of hurricane-prone regions.

Figure 6-56
A violent tornado passed by this high school and showered the roof with missiles.

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

As discussed in Section 6.5.2, FEMA 361, *Design and Construction Guidance for Community Shelters*, includes software for assessing the benefit/cost ratio of incorporating specially designed tornado shelters within schools. In addition, it includes comprehensive information regarding the design of shelters. If shelter design is contemplated, use of FEMA 361 is recommended.

Existing Schools without Tornado Shelters. Where the number of recorded F3, F4, and F5 tornadoes per 3,700 square miles is one or greater (see Figure 6-2), if the school does not have a tornado shelter, the best available refuge areas should be identified. FEMA 431, *Tornado Protection, Selecting Refuge Areas in Buildings* provides useful information for school administrators, and for architects and engineers who perform evaluations of existing schools.

To minimize deaths and injuries of students, faculty, and other occupants, it is critically important that the best available refuge areas be pre-identified by a qualified architect/engineer.[8] Once identified, those areas need to be clearly marked so that occupants can quickly seek refuge. Don't wait for the arrival of a tornado on the school grounds to try to find the best available refuge areas; by that time, it is too late. If refuge areas have not been pre-identified, occupants can easily take cover in areas that can become death traps (see Figure 6-57).

When a true shelter is desired for a school that does not have one, retrofitting a shelter within the school can be very expensive. An economical alternative is an addition to the existing school that can function as a shelter as well as serve another purpose. This approach works well for smaller schools, but, for a very large school, construction of two or more shelter additions should be considered in order to reduce the time it takes to reach the shelter (often there is ample warning time, but sometimes an approaching tornado is not noticed until a couple of minutes before it strikes).

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[8] It should be realized that, unless the refuge area was specifically designed as a tornado shelter, occupants in a "best available refuge area" are vulnerable to injury or death.

Figure 6-57

View of an elementary school corridor after passage of a violent tornado. Although corridors sometimes offer protection, they can be death traps as illustrated in this figure (fortunately the school was not occupied when it was struck).

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

Portable Classrooms. Portable classrooms should not be occupied during times when a tornado watch has been issued by the National Weather Service (a watch means that conditions are favorable for tornado development). Do not wait for issuance of a tornado warning (i.e., a tornado has been spotted) by the National Weather Service to seek refuge in the main school building. If a tornado is nearby, students could be caught outdoors.

The recommendations given in Section 6.16 are summarized in Table 6-3 .

Table 6-3: Summation of Design for Tornado Shelters

Proposed New School	
1. Is proposed school in a tornado-prone region: yes or no? If yes, go to step 2.	See Section 6.7.1 for decision analysis.
2. If yes, perform benefit/cost analysis to assist in deciding whether or not to incorporate a shelter(s) within the school.	See FEMA 361, *Design and Construction Guidance for Community Shelters*, benefit/cost analysis.
3. Perform steps 1 and 2 prior to setting project budget.	If sheltering is not considered until after setting the budget, funds may not be available.
4. It is decided to incorporate a shelter(s).	Refer to FEMA 361, *Design and Construction Guidance for Community Shelters*, for design guidance.

MAKING SCHOOLS SAFE AGAINST WINDS

Table 6-3: Summation of Design for Tornado Shelters (continued)

Existing schools without specifically designed tornado shelters	
1. If 1 or more F3-F5 tornadoes per 3,700 square miles, pre-identify best available refuge areas.	See Figure 6-2 for history frequency and FEMA 431, *Tornado Protection, Selecting Refuge Areas in Buildings* for identification guidance.
2. If 1 or more F3-F5 tornadoes per 3,700 square miles, consider incorporating a shelter(s) within a new building addition(s).	See FEMA 361, *Design and Construction Guidance for Community Shelters*, for benefit/cost analysis and design guidance.

6.17 REMEDIAL WORK ON EXISTING SCHOOLS

Section 6.6.1 discussed prioritizing and Section 6.6.2 discussed cost. Following up on those discussions, many existing schools need building envelope component strengthening or structural strengthening. The need for this work is due either to deterioration over time and/or inadequate facility strength at the time the school was built.

It is prudent for school districts to have their existing facilities evaluated. This also applies to recently constructed schools that are located in an area where the basic wind speed is greater than 90 mph (peak gust), and those schools that will be used for emergency response after a storm and schools that will be used for a hurricane shelter.

For new schools, areas of concern would typically be the building envelope and exterior-mounted mechanical, electrical, and communications equipment. By identifying weaknesses and prioritizing and executing the work, many failures can be averted. A proactive approach can save significant sums of money and decrease the number of instances when schools are impaired or immobilized after a storm.

For roofs with weak metal edge flashing or coping attachment, face-attachment of the edge flashing/coping (as shown in Figure 6-39) is a cost-effective approach to greatly improve wind-resistance of the roof system. Fastening rooftop equip-

ment to curbs is a cost-effective approach to avoid the type of problems shown in Figure 6-19.

During planned roof covering replacement, by tearing off the existing roof covering rather than re-covering, there is the opportunity to evaluate the structural integrity of the deck and deck attachment and upgrade its attachment if necessary. Many older decks are poorly attached (Figure 6-58); hence, if their attachment is not upgraded, blow-off of the deck and the new roof covering could occur. The two deck panels shown in Figure 6-58 blew away because their attachment to the roof structure was inadequate. An SPF roof covering was over the deck panels that blew away because of the characteristics of this type of covering, membrane propagation failure did not occur, as would have been the case with built-up, modified bitumen, or single-ply roof membranes. Cementitious wood-fiber decks were commonly used on schools built in the 1950s and 1960s. Decks constructed during that era typically had very limited uplift resistance due to weak connections to the support structure.

Design guidance pertaining to existing decks is presented in "*Uplift Resistance of Existing Roof Decks: Recommendations for Enhanced Attachment During Reroofing Work,*" RCI Interface, Thomas L. Smith, January 2003, pp. 14.

Figure 6-58
This school had a cementitious wood-fiber deck (commonly referred to by the proprietary name "Tectum").

Weak non-load bearing masonry walls, poorly connected precast concrete panels, long-span structures (e.g., at gyms) with limited uplift resistance, and weak glass curtain walls are common problems with many older schools. Although the technical solutions to these problems are not difficult, the cost of the remedial work is normally quite expensive. If remediation funds are not available, it is important to minimize the risk of injury and death by evacuating areas that have this type of construction when winds above 60 mph are forecast.

For schools located in wind-borne debris regions, if the exterior glazing is not missile-resistant, equipping the openings with shutters is a cost-effective approach to provide protection.

The recommendations given in Section 6.17 are summarized in Table 6-4.

Table 6-4: Summation of Remedial Work on Existing Schools

Perform district-wide assessment of all schools	Evaluate all hazards. Prioritize the various schools and the work items at each school. Life-safety items are first priority; property damage and school interruption are second priority. See Section 6.6.1.
Are there weak non-load bearing masonry walls, weak curtain walls, poorly connected precast concrete panels, or weak long-span roof structures?	If strength is inadequate to resist winds that are likely to occur while the school is occupied (such as strong thunderstorms), implement remedial work.
Are edge flashings or copings inadequately attached?	Face-attach the vertical flanges. See Figure 6-39.
Are rooftop equipment units unanchored or poorly anchored?	Add screws or bolts to anchor equipment to curbs. Add cables to secure fan cowlings. Add latches to secure equipment access panels. See Section 6.14.
Are roof deck or roof structure connections weak?	During planned roof covering replacement, remove roof covering and strengthen attachment of deck and/or roof structure. See Section 6.12.
If the school is in a wind-borne debris region, does exterior glazing have protection (via laminated glass or shutters)?	Even if the school will not be used as a shelter, equip with shutters to avoid interior wind and water damage. For more conservative protection, consider the wind-borne debris region to include areas where the basic wind speed is equal to or greater to 110 mph (100 mph if the school is located within 1 mile of the coast).
Will the school be used as a hurricane evacuation shelter and/or for emergency response after a storm?	To the extent reasonably possible, upgrade the school so that it complies with the provisions in Section 6.15.
Is the school located in a tornado-prone area?	See Section 6.16.

6.18 REFERENCES AND SOURCES OF ADDITIONAL INFORMATION

American Institute of Architects, *Buildings at Risk: Wind Design Basics for Practicing Architects*, 1997.

Federal Emergency Management Agency, *Building Performance: Hurricane Andrew in Florida*, FEMA FIA-22, Washington, DC, December 1992.

Federal Emergency Management Agency, *Building Performance: Hurricane Iniki in Hawaii*, FEMA FIA-23, Washington, DC, January 1993.

Federal Emergency Management Agency, *Corrosion Protection for Metal Connectors in Coastal Areas*, FEMA Technical Bulletin 8-96, Washington, DC, August 1996.

Federal Emergency Management Agency, *Typhoon Paka: Observations and Recommendations on Building Performance and Electrical Power Distribution System*, Guam, U.S.A., FEMA-1193-DR-GU, Washington, DC, March 1998.

Federal Emergency Management Agency, *Hurricane Georges in Puerto Rico*, FEMA 339, Washington, DC, March 1999.

Federal Emergency Management Agency, *Oklahoma and Kansas Midwest Tornadoes of May 3, 1999*, FEMA 342, Washington, DC, October 1999.

Federal Emergency Management Agency, *Coastal Construction Manual*, Third Edition, FEMA 55, Washington, DC, 2000.

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Federal Emergency Management Agency, *Primer to Design Safe School Projects in Case of Terrorist Attacks*, FEMA 428, Washington, DC, October 2003.

Federal Emergency Management Agency, *Tornado Protection, Selecting Safe Areas in Buildings,* FEMA 431, Washington, DC, October 2003.

National Research Council of Canada, Institute for Research in Construction, *Wind Design Guide for Mechanically Attached Flexible Membrane Roofs,* B1049, 2004.

Rousseau, M.Z., *Facts and Fictions of Rain-Screen Walls,* Construction Canada, 1990, pp. 40.

Smith, Thomas L., "Insights on Metal Roof Performance in High-wind Regions," *Professional Roofing,* February 1995, pp. 12 (available on-line at www.nrca.net).

Smith, Thomas L., "Integrating a Lightning Protection System in a Roof System," 12th International Roofing and Waterproofing Conference Proceedings (CD), National Roofing Contractors Association, 2002.

Smith, Thomas L., "Honing in on hangars," *Professional Roofing,* October 2002, pp. 32 (available on-line at www.nrca.net).

Smith, Thomas L., "Uplift Resistance of Existing Roof Decks: Recommendations for Enhanced Attachment During Reroofing Work," *RCI Interface,* January 2003, pp. 14.

Smith, Thomas L., "Detailing ASCE 7's changes," *Professional Roofing,* July 2003, pp. 26 (available on-line at www.nrca.net).

6.19 GLOSSARY OF WIND TERMS

Basic wind speed. A 3-second gust speed at 33 feet above the ground in Exposure C.   (Exposure C is flat open terrain with scattered obstructions having heights generally less than 30 feet.) Note: Since 1995, ASCE 7 has used a 3-second peak gust measuring time. A 3-second peak gust is the maximum instantaneous speed with a duration of approximately 3 seconds. A 3-second peak gust speed could be associated with a given windstorm (e.g., a particular storm could have a 40-mile per hour peak gust speed), or a 3-second peak gust speed could be associated with a design-level event (e.g., the basic wind speed prescribed in ASCE 7).

Building, enclosed. A building that does not comply with the requirements for open or partially enclosed buildings.

Building, open. A building having each wall at least 80 percent open. This condition is expressed by an equation in ASCE 7.

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 percent, and

2. The total area of openings in a wall that receives positive external pressure exceeds 4 square feet or 1 percent 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 percent.

These conditions are expressed by equations in ASCE 7.

Building, regular shaped. A building having no unusual geometrical irregularity in spatial form.

Building, simple diaphragm. An enclosed or partially enclosed building in which wind loads are transmitted through floor and roof diaphragms to the vertical main wind-force resisting system.

Components and cladding. Elements of the building envelope that do not qualify as part of the main wind-force resisting system.

Escarpment. Also known as a scarp, with respect to topographic effects, a cliff or steep slope generally separating two levels or gently sloping areas.

Exposure. The characteristics of the ground roughness and surface irregularities in the vicinity of a building. ASCE 7 defines three exposure categories - Exposures B, C, and D.

Glazing. Glass or transparent or translucent plastic sheet used in windows, doors, and skylights.

Glazing, impact-resistant. Glazing that has been shown by an approved test method to withstand the impact of wind-borne missiles likely to be generated in wind-borne debris regions during design winds.

Hill. With respect to topographic effects, a land surface characterized by strong relief in any horizontal direction.

Hurricane-prone regions. Areas vulnerable to hurricanes; in the U.S. and its territories defined as:

1. The U.S. Atlantic Ocean and Gulf of Mexico coasts where the basic wind speed is greater than 90 miles per hour, and

2. Hawaii, Puerto Rico, Guam, U.S. Virgin Islands, and American Samoa.

Impact-resistant covering. A covering designed to protect glazing, which has been shown by an approved test method to withstand the impact of wind-borne missiles likely to be generated in wind-borne debris regions during design winds.

Importance factor, I. A factor that accounts for the degree of hazard to human life and damage to property. The importance factor adjusts the mean recurrence interval. Importance factors are given in ASCE 7.

Main wind-force resisting system. An assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface.

Mean roof height, h. The average of the roof eave height and the height to the highest point on the roof surface, except that, for roof angles of less than or equal to 10 degrees, the mean roof height shall be the roof eave height.

Missiles. Debris that became or could become ingested into the wind stream.

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. A door that is intended to be in the closed position during a windstorm would not be considered an opening. Glazed openings are also not typically considered an opening. However, if the building is located in a wind-borne debris region and the glazing is not impact-resistant or protected with an impact-resistant covering, the glazing is considered an opening.

Ridge. With respect to topographic effects, an elongated crest of a hill characterized by strong relief in two directions.

Wind-borne debris regions. Areas within hurricane-prone regions located:

1. Within 1 mile of the coastal mean high water line where the basic wind speed is equal to or greater than 110 mph and in Hawaii; or

2. In areas where the basic wind speed is equal to or greater than 120 mph.