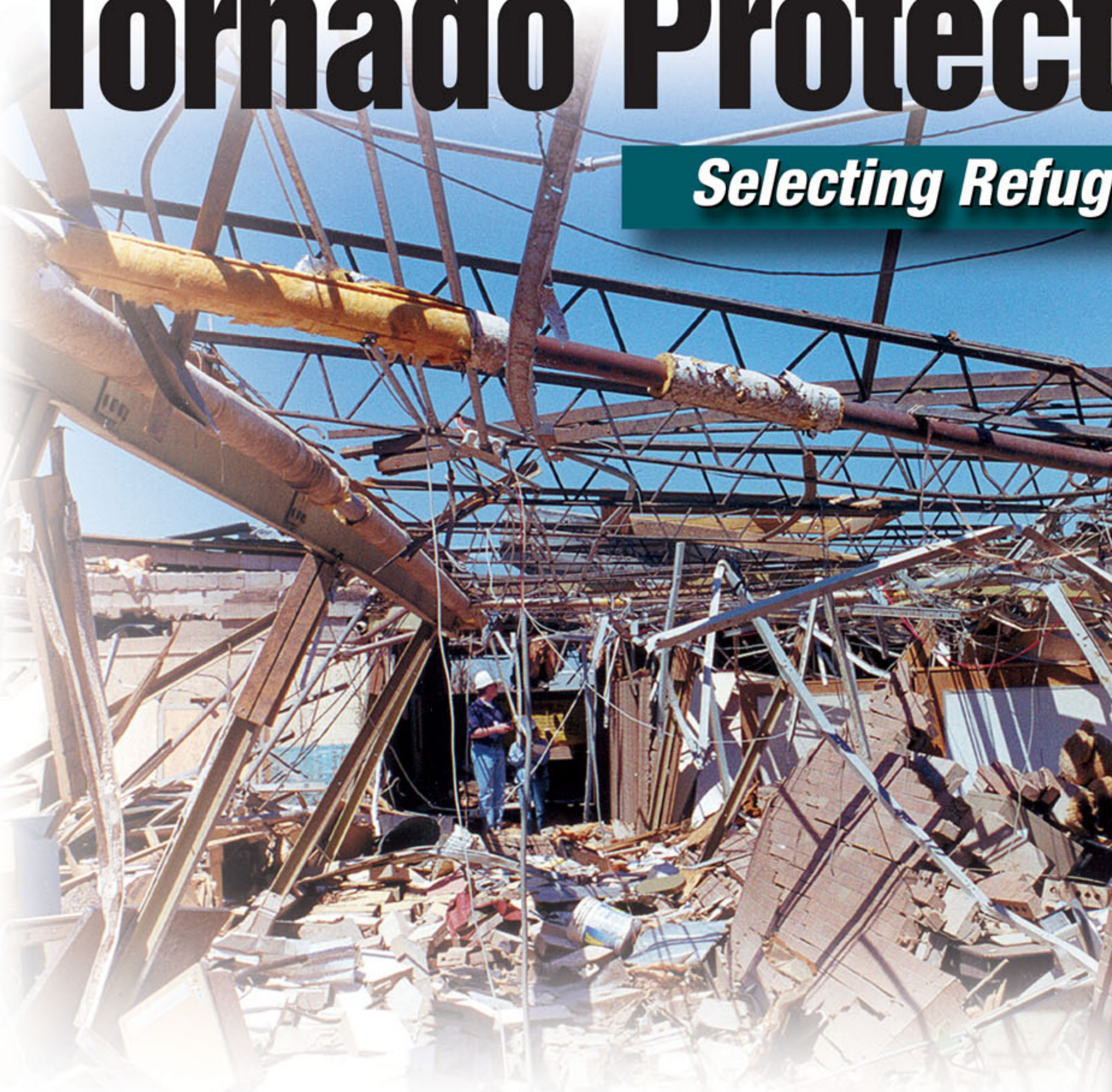
FEMA 431/*November 2003*

# Tornado Protection

## Selecting Refuge Areas in Buildings



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Florida Department of Community Affairs
Tallahassee, FL 32399-2100

## About the Cover

The large photograph on the cover shows the remains of a central corridor in the Kelly Elementary School, in Moore, Oklahoma. This extensive damage was caused by one of the tornadoes that struck Oklahoma and Kansas on May 3, 1999. The corridor walls, which consisted of lightweight steel frame members with masonry infill topped by clerestory windows, were unable to withstand the extreme loads caused by lateral and uplift wind forces. As indicated by the inset photograph, which shows a similar corridor in another school, this type of corridor construction is common and creates special challenges for building administrators and design professionals who must identify refuge areas in schools and other buildings.

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# Contents

# Foreword

Tornadoes cause heavy loss of life and property damage throughout much of the United States. Most schools and other public buildings include areas that offer some protection from this danger, and building administrators should know the locations of these areas.

This booklet presents case studies of three schools that were struck by tornadoes: Xenia Senior High School in Xenia, Ohio; St. Augustine Elementary School in Kalamazoo, Michigan; and Kelly Elementary School in Moore, Oklahoma, which were struck on April 3, 1974; May 13, 1980; and May 3, 1999, respectively. The resulting damage to these schools was examined by teams of structural engineers, building scientists, engineering and architectural faculties, building administrators, and representatives of the architectural firms that designed the buildings. From these and other examinations, guidance has been developed for selecting the safest areas in existing buildings – areas that may offer protection if a tornado strikes – referred to in this booklet as the *best available refuge areas*.

The guidance presented in this booklet is intended primarily to help building administrators, architects, and engineers select the best available refuge areas in existing schools. Building administrators, architects, and engineers are encouraged to apply this guidance so that the number of injuries and deaths will be minimized if a tornado strikes an occupied school.

For the design of shelters in schools yet to be constructed, refer to FEMA publication 361, *Design and Construction of Community Shelters*.

# Introduction

## What Are "Best Available Refuge Areas"?

The term ***best available refuge areas*** refers to areas in an existing building that have been deemed by a qualified architect or engineer to likely offer the greatest safety for building occupants during a tornado. It is important to note that, because these areas were not specifically designed as tornado shelters, their occupants may be injured or killed during a tornado. However, people in the best available refuge areas are less likely to be injured or killed than people in other areas of a building.

The likelihood that a tornado will strike a building is a matter of probability. Tornado damage to buildings is predictable. Administrators of schools and other public buildings should have a risk analysis performed to determine the likelihood that a tornado will occur and the potential severity of the event. If a building is determined to be at sufficient risk, the safest areas of the building – areas that may offer protection if a tornado strikes – should be identified. This booklet refers to such areas as the ***best available refuge areas***. In many buildings, the best available refuge areas are large enough to accommodate the number of people who normally occupy the building. A qualified architect or structural engineer should assess an existing building and identify the best available refuge areas.

This booklet presents information that will aid qualified architects and engineers in the identification of the best available refuge areas in existing buildings. Architects and engineers who are designing tornado shelters within new buildings may also find this booklet useful, but should refer to *Design and Construction Guidance for Community Shelters* (FEMA 361) for more detailed information. FEMA 361 includes design criteria, information about the performance of specific construction materials under wind and debris impact loads, and examples of construction plans and costs.

The Wind Engineering Research Center at Texas Tech University provided much of the substance of this booklet. Dr. Kishor Mehta of the Center assisted in the preparation and review of the material. Invaluable assistance was provided by the architects and engineers of the buildings presented as case studies and by the school administrators.

# Tornado Profile

The National Weather Service defines a tornado as a violently rotating column of air pendant from a thunderstorm cloud that touches the ground.

From a local perspective, a tornado is the most destructive of all atmospheric-generated phenomena. In an average year, a little more than 800 tornadoes hit various parts of the United States, though the number has varied from 500 to 1,400 in a given year. More tornadoes are recorded in the months of May and June than in any other month (Figure 1-1). Figure 1-2 shows the geographic distribution of tornadoes in the United States.

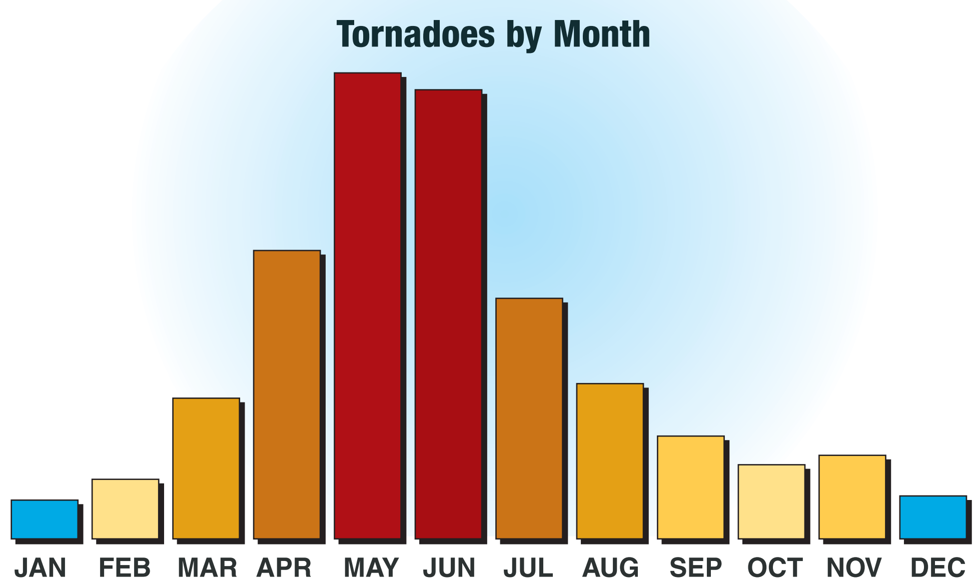
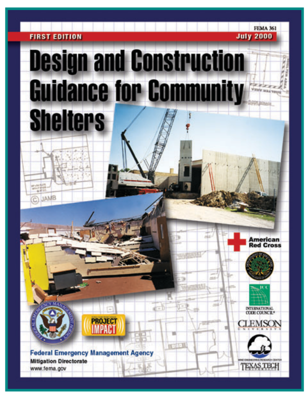



***Figure 1-1 Tornado occurrence by month in the United States.***

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## Determining Tornado Risk

Detailed guidance for determining the magnitude of the tornado risk in a specific area of the United States is presented in FEMA publication 361, *Design and Construction Guidance for Community Shelters* (for more information, see the section of this booklet titled **Information Sources**).

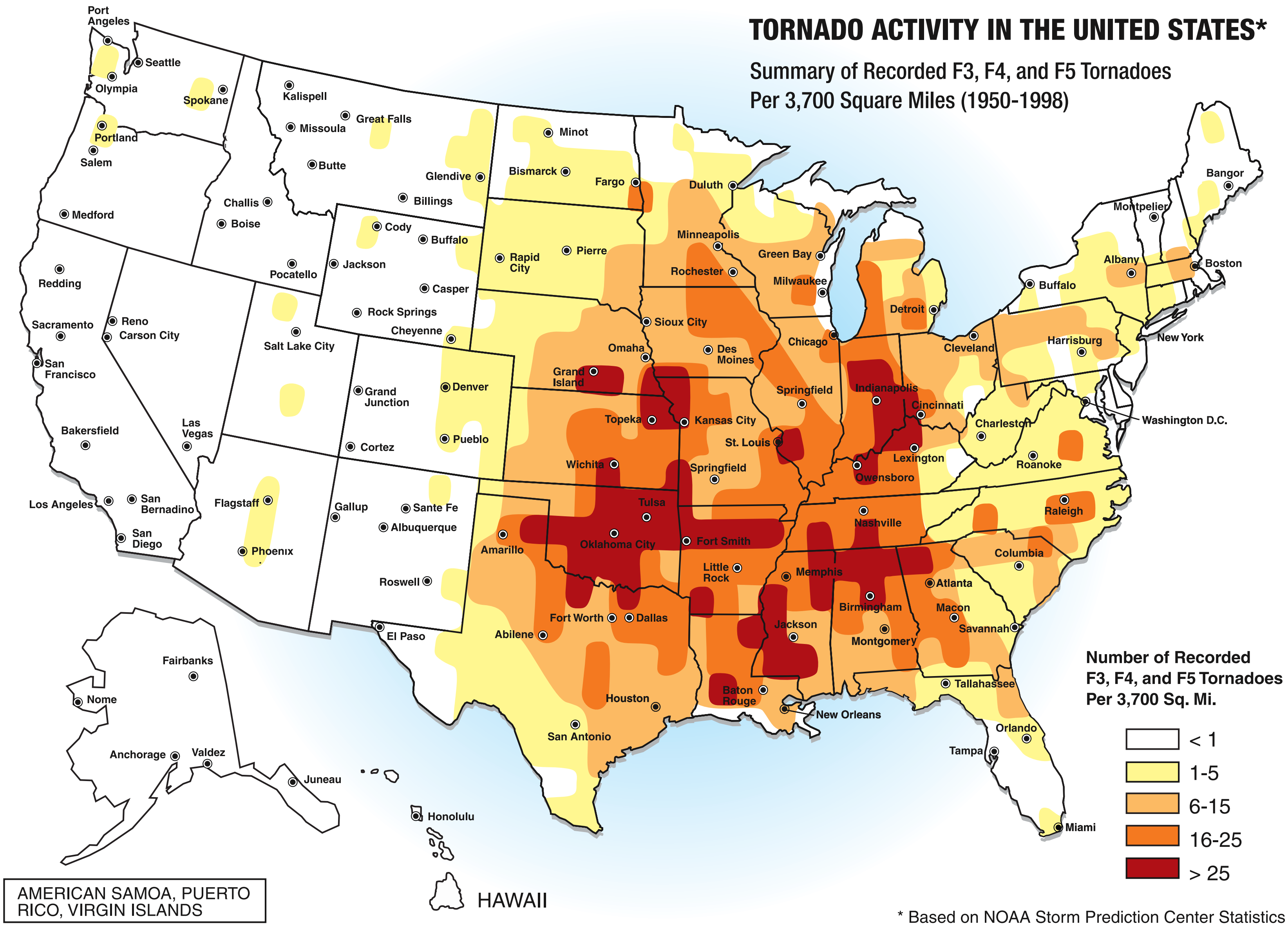


*Figure 1-2 Tornado occurrence in the United States based on historical data.*

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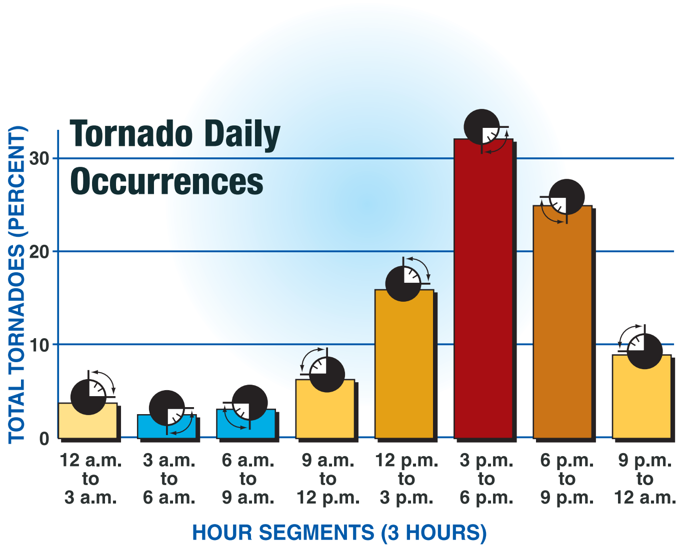


*Figure 1-3 Tornado occurrence by time of day.*

# Tornado Characteristics

The **time of day** when tornadoes are most likely to occur is the mid-afternoon, between 3:00 p.m. and 6:00 p.m. (Figure 1-3). Occasionally, severe tornadoes have been recorded in the early morning or late evening.

The **direction of movement** is predominantly from the southwest to the northeast. However, tornadoes have been known to move in any direction along with the parent thunderstorms.

The **length of path** averages 5 miles, but some tornado paths have exceeded 100 miles.

The **width of path** averages 300 to 400 yards, but may reach up to 1 mile.

The **travel speed (translational)** averages 25 to 40 miles per hour (mph), but speeds from 5 to 60 mph have been recorded.


**F0 Light:**
Some damage can be seen to poorly maintained roofs. Unsecured lightweight objects, such as trash cans, are displaced.

**F1 Moderate:**
Minor damage to roofs occurs, and windows are broken. Larger and heavier objects become displaced. Minor damage to trees and landscaping can be observed.

**F2 Considerable:**
Roofs are damaged. Manufactured homes, on nonpermanent foundations, can be shifted off their foundations. Trees and landscaping either snap or are blown over. Medium-sized debris becomes airborne, damaging other structures.

**F3 Severe:**
Roofs and some walls, especially unreinforced masonry, are torn from structures. Small ancillary buildings are often destroyed. Manufactured homes on nonpermanent foundations can be overturned. Some trees are uprooted.

**F4 Devastating:**
Well constructed homes, as well as manufactured homes, are destroyed. Some structures are lifted off their foundations. Automobile-sized debris is displaced and often tumbles. Trees are frequently uprooted and blown over.

**F5 Incredible:**
Strong frame houses and engineered buildings are lifted from their foundations or are significantly damaged or destroyed. Automobile-sized debris is moved significant distances. Trees are uprooted and splintered.

***Figure 1-4 The Fujita Tornado Damage Scale.***

The **rotational speed** is assumed to be symmetrical. The maximum rotational velocity occurs at the edge of the tornado core. The speed reduces rapidly as the distance from the edge increases.

The **intensity of damage** from a tornado is related to wind speed, windborne debris, and type of construction. The atmospheric pressure drop in the center of a tornado does not destroy buildings, because pressures inside and outside of buildings equalize through broken windows and doors or through openings that result when sections of the roof are removed.

Tornadoes are rated by the National Weather Service according to the tornado damage scale developed by Dr. Theodore Fujita, a professor of meteorology. Ratings vary from F0, for light damage, to F5, for total destruction of a building (Figure 1-4). Ninety percent of the tornadoes recorded over the past 45 years have been categorized as F0, F1, or F2 (Figure 1-5).

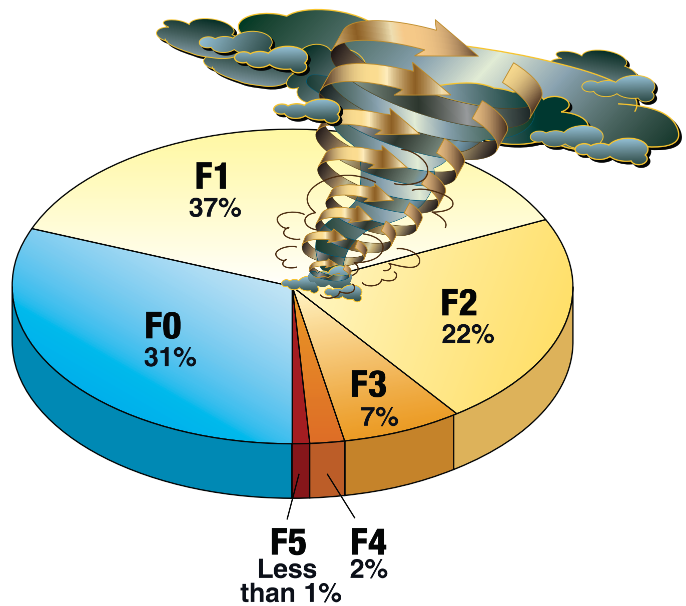


***Figure 1-5***
***Percentage of recorded tornadoes by Fujita Tornado Damage Scale ranking.***

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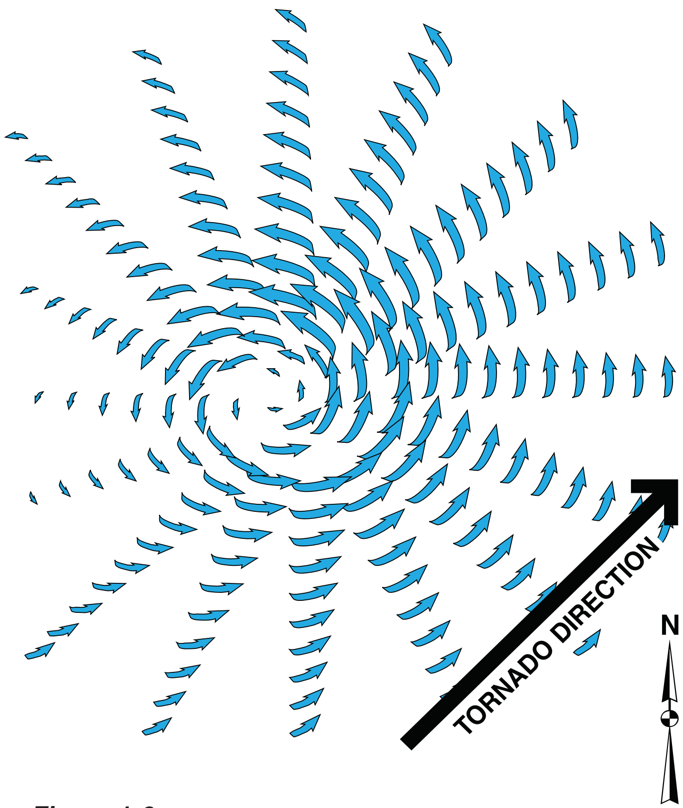


***Figure 1-6***
***Typical tornado rotation.***

**Rotation** is generally counterclockwise in the northern hemisphere (Figure 1-6). About 10 percent of tornadoes have been known to rotate clockwise.

**Wind speed** is the sum of rotational speed and translational speed. The rotational speed decreases as the distance from the center of a tornado increases. With a counterclockwise rotation, the wind speed on the right side of the tornado is higher because the translational speed adds to the rotational speed.

Because of the unpredictability of tornado paths and the destruction of commonly used instruments, direct measurements of wind speeds have not been made in tornadoes. Rather, wind speeds are judged from the intensity of damage to buildings. Engineering assessment of damage puts the maximum wind speed at 200 mph in most destructive tornadoes, and the speed is not likely to exceed 250 mph near ground level.

# Effects of High Winds

In buildings hit by tornadoes, the threat to life is due to a combination of effects that occur at almost the same time. To understand the tornado damage that can occur in a building, the following must be considered:

- wind-induced forces
- changes in atmospheric pressure
- debris impact

## Wind Effects on Buildings

The wind speeds generated by some tornadoes are so great that designing for these extreme winds is beyond the scope of building codes and engineering standards. Most buildings that have received some engineering attention, such as schools, and that are built in accordance with sound construction practices can usually withstand wind speeds specified by building codes. Meeting these code-specified wind speeds can provide sufficient resistance to tornadic winds if the building is located on the outer edge of the tornado vortex. In addition, if a portion of the building is built to a higher tornado design standard, then both building and occupant survival are improved.

Wind creates inward- and outward-acting pressures on building surfaces, depending on the orientation of the surface (e.g., flat, vertical, low-slope). As the wind moves over and around the building, the outward-acting pressure increases as the building geometry forces the wind to change direction. These pressure increases create uplift on parts of the building, forcing the building apart if it is too weak to resist the wind loads. When wind forces its way inside or creates an opening by breaking a window or penetrating the roof or walls, the pressures on the building increase even more. Figure 2-1 shows how wind affects both an enclosed building and a building with openings.

Heavy building materials (e.g., reinforced masonry or concrete) that are well tied to all other building components often survive extreme winds. The weight of these materials helps resist uplift and lateral loads, and heavy materials often stop windborne debris that can increase damage to the building. However, heavy concrete roof panels and heavy masonry walls that are not adequately connected or reinforced have failed during severe winds. Lightweight roofing and siding materials such as gravel, insulation, shingles, roofing membranes, and brick veneer can also be a problem.

Building shapes that "catch" the wind, such as overhangs, canopies, and eaves, tend to fail and become "sails" in extreme winds. Flat roofs can be lifted off when the wind flows over them and increases the uplift pressure at the corners and edges of the roofs.

# Atmospheric Pressure Changes

Initially, the pressure outside a building during a tornado is very low compared to the pressure inside. In most buildings, however, there is enough air leakage through building component connections to equalize these pressures. Also, windborne debris is likely to break windows and allow wind to enter.

The explosion of buildings during a tornado due to atmospheric pressure differences is a myth. In reality, the combination of internal pressure and outward pull on the building from suction pressure has caused building failures that have forced the walls outward and given the building the appearance of having exploded. During an event, doors and windows should remain closed on all sides of the building in order to minimize the entry of wind into the building.

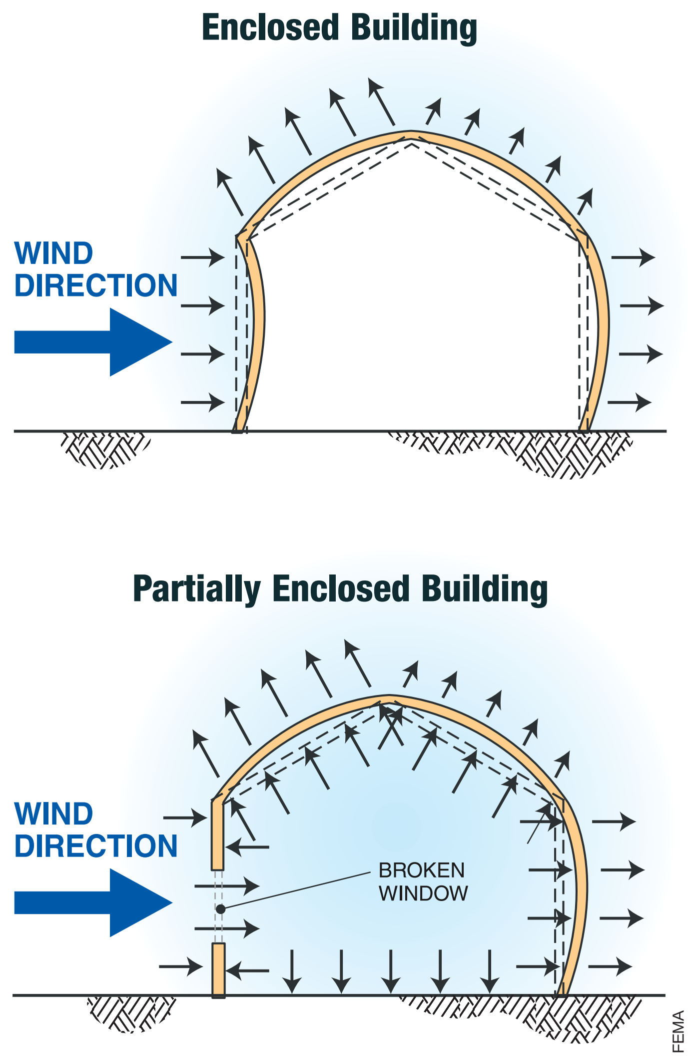


***Figure 2-1***
***Effects of wind on a fully enclosed building and on a building with openings.***

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***Figure 2-2***
***Example of damage from a windborne missile. A 2-inch by 6-inch board penetrated a refrigerator.***

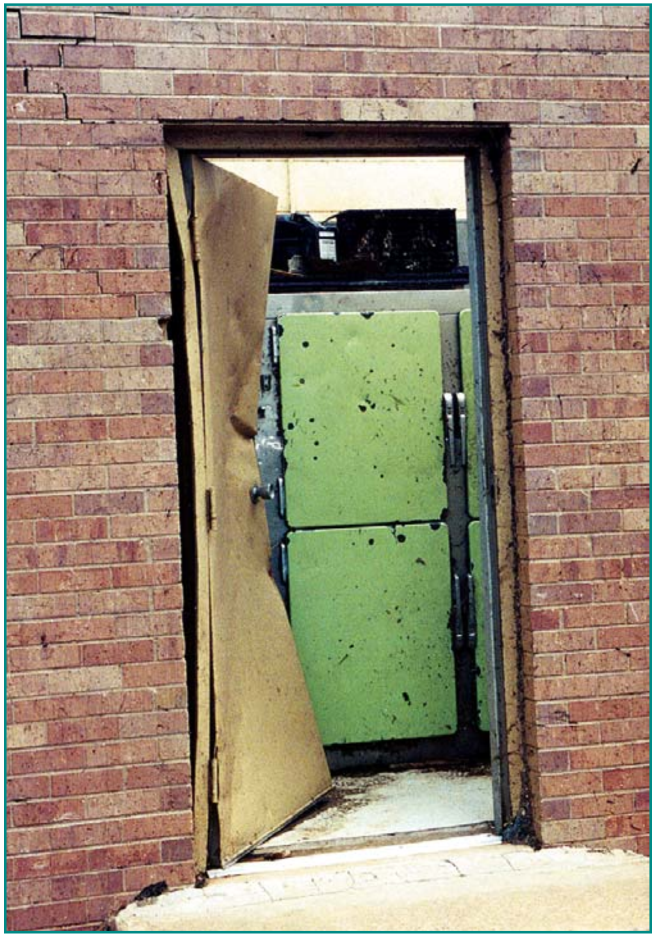

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***Figure 2-3***
***Example of severe damage from a windborne missile. This metal door was pushed inward by the impact of a heavy object.***

# Debris Impact

The extreme winds in tornadoes pick up and carry debris from damaged buildings and objects located in the path of the winds (see Figures 2-2 and 2-3). Even heavy, massive objects such as cars, tractor trailers, and buses can be moved by extreme winds and cause collateral damage to buildings. Light objects become flying debris, or missiles, that can penetrate doors, walls, and roofs; heavier objects can roll and cause crushing-type damage.

Missiles can travel vertically as well as horizontally (see Figure 2-4). Therefore, shelters and refuge areas should provide protection overhead as well as on the side. Building walls and roofs can be designed to withstand the impacts of these missiles. Protection can be provided at the exterior building wall, or interior barriers can be constructed to provide protection for a smaller area within the building.


***Figure 2-4***
***Example of damage from windborne missiles. Medium and small missiles penetrating through the roof of a high school. The missile protruding from the roof in the foreground is a double 2-inch by 6-inch wood board. The portion sticking out of the roof is 13 feet long. This missile penetrated a ballasted ethylene propylene diene monomer (EPDM) membrane, approximately 3 inches of polyisocyanurate roof insulation, and the steel roof deck. The missile lying on the roof just beyond it is a 2-inch by 10-inch, 16-foot-long wood board. The missile protruding from the roof in the background is a 2-inch by 6-inch, 16-foot-long wood board.***

# Selecting Refuge Areas

Wind effects on buildings have been studied sufficiently to predict which building elements are most likely to successfully resist the extreme wind pressures caused by tornadoes and which are most likely to fail. Sufficient material testing and design work has been performed for large shelters to develop a refuge area selection guide for any building in which such areas are needed. Many buildings contain a small interior area or areas that could serve as the best available refuge area or possibly be converted or reinforced for refuge area use.

The selection of refuge areas in existing buildings is discussed in Chapter 4. For more information about refuge areas and shelter design, refer to FEMA publication 361, *Design and Construction Guidance for Community Shelters* (see sidebar on page 11).

# Case Studies

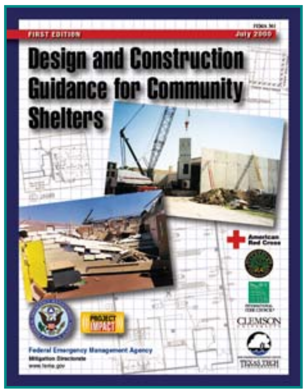
A large number of schools have been destroyed or heavily damaged by tornadoes, and there have been many injuries and deaths. The three school buildings presented as case studies in this booklet were selected for the following reasons:

- All were hit by different, but intense storms.
- The three structures varied in size, age, and type of construction.
- All were designed by different architects and engineers to national building codes.
- All had to be partially or totally destroyed later because of the extent of the tornado damage.

The building damage was examined by teams of structural engineers, building scientists, specially trained members of engineering and architectural faculties and firms, building administrators, and representatives of the architectural firms that designed the buildings.

The determination of the best available refuge areas in the three buildings (shown on floor plans presented later in this chapter) was based on three sources of information, in the following order of importance:

- persons who were in each building during the tornado
- building examinations by engineers and architects
- aerial photographs taken shortly after the storms

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### Guidance for Refuge Area Selection

Detailed evaluation checklists for selecting the best available refuge areas in existing buildings and guidance for designing and constructing shelters are presented in FEMA publication 361, *Design and Construction Guidance for Community Shelters* (for more information, see the section of this booklet titled **Information Sources**).

The identified refuge areas in these buildings are the best that were available in each of the three buildings when the storms occurred.

These case studies are presented here with two goals:

- to help building designers and administrators locate accurately the parts of a building that would likely be left standing after a tornado—before the tornado strikes
- to help architects and engineers design buildings that offer occupants excellent tornado protection

# Xenia Senior High School

## Xenia, Ohio

| | |
|---|---|
| **Building population:** | **1,450, including staff** |
| | **12 students, 3 staff in building during tornado** |
| **Tornado direction:** | **From southwest** |
| **Damage intensity:** | **F5** |
| **Time:** | **4:45 p.m.** |
| **Date:** | **April 3, 1974** |

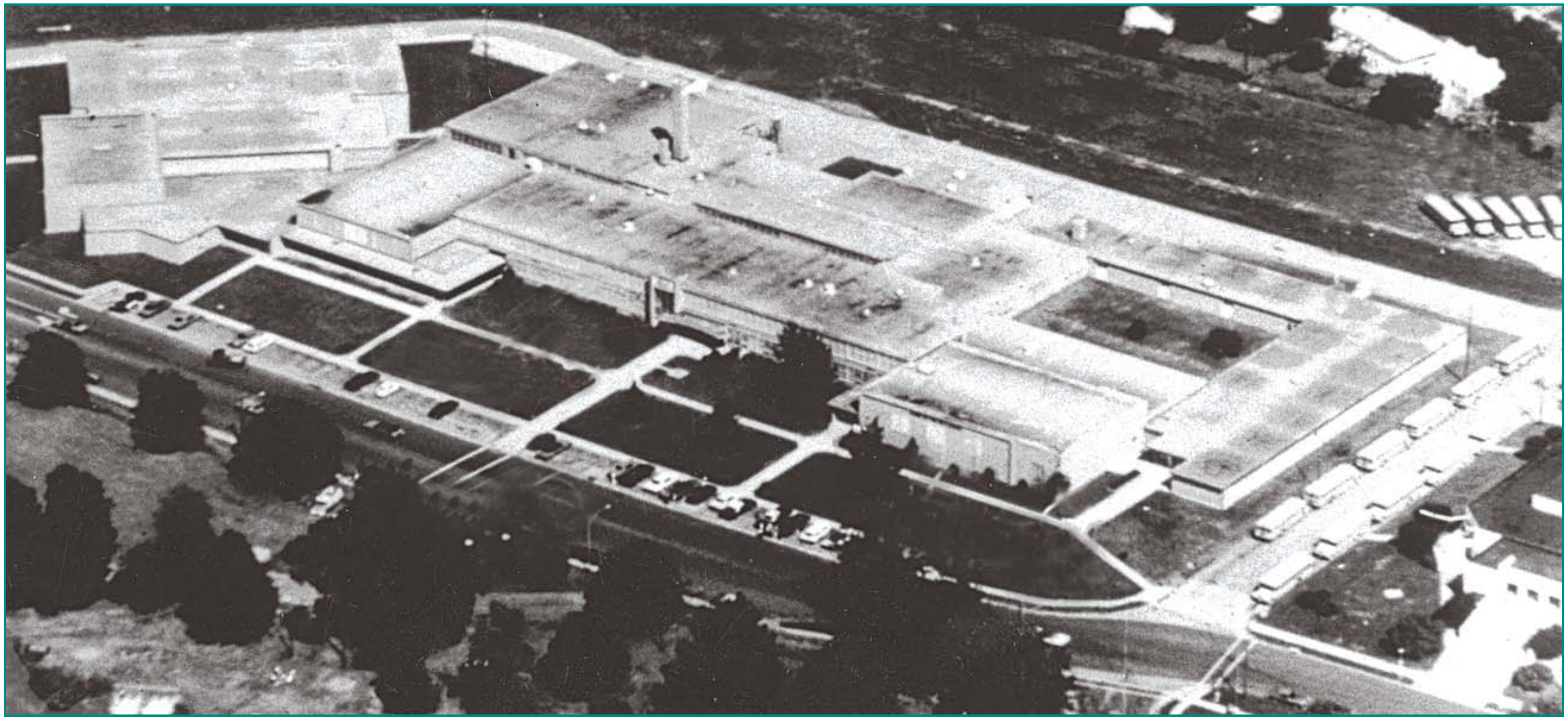

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***Figure 3-1 Xenia Senior High School, Xenia, Ohio.***

Xenia Senior High School (Figure 3-1) was a two-story, slab-on-grade building without a basement located on the north side of Xenia, Ohio. It faced Shawnee Park to the west.

The massive tornado hit 1 hour and 45 minutes after school dismissal. It was spotted by a student who was leaving the school. She alerted drama students who were rehearsing in the auditorium. The students ran and dove for shelter in a nearby corridor.

The tornado passed directly over the school. Two school buses came to rest on the stage where the students had been rehearsing. Some of the students were treated for injuries at a nearby hospital.

The building was found to be unsafe to enter and was demolished.

## Construction

The construction types varied among the main parts of the school—original building, three additions (A, B, and C):

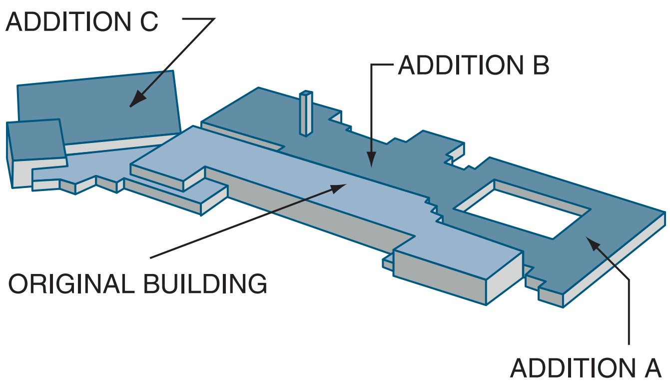
Original building and addition B: Lightweight steel frame, open-web steel joists, 2-inch gypsum roof deck.

Addition A: Loadbearing masonry walls, hollow-core precast concrete roof planks.

Addition C: Precast concrete frame, concrete double-tee floor/roof beams.

Girls' gym: Loadbearing masonry wall, precast concrete tee beams.

Auditorium and boys' gym: Loadbearing masonry walls, steel trusses.




## Tornado Damage

The tornado passed directly over the school, engulfing the entire building and the adjacent fieldhouse to the south (Figure 3-2).

The enclosure walls failed on the west and south sides, allowing the winds to enter the building. The roofs collapsed over the three large spans—the auditorium, the boys' gym, and the girls' gym. The lightweight roof over the original two-story building was torn off by the extreme winds.

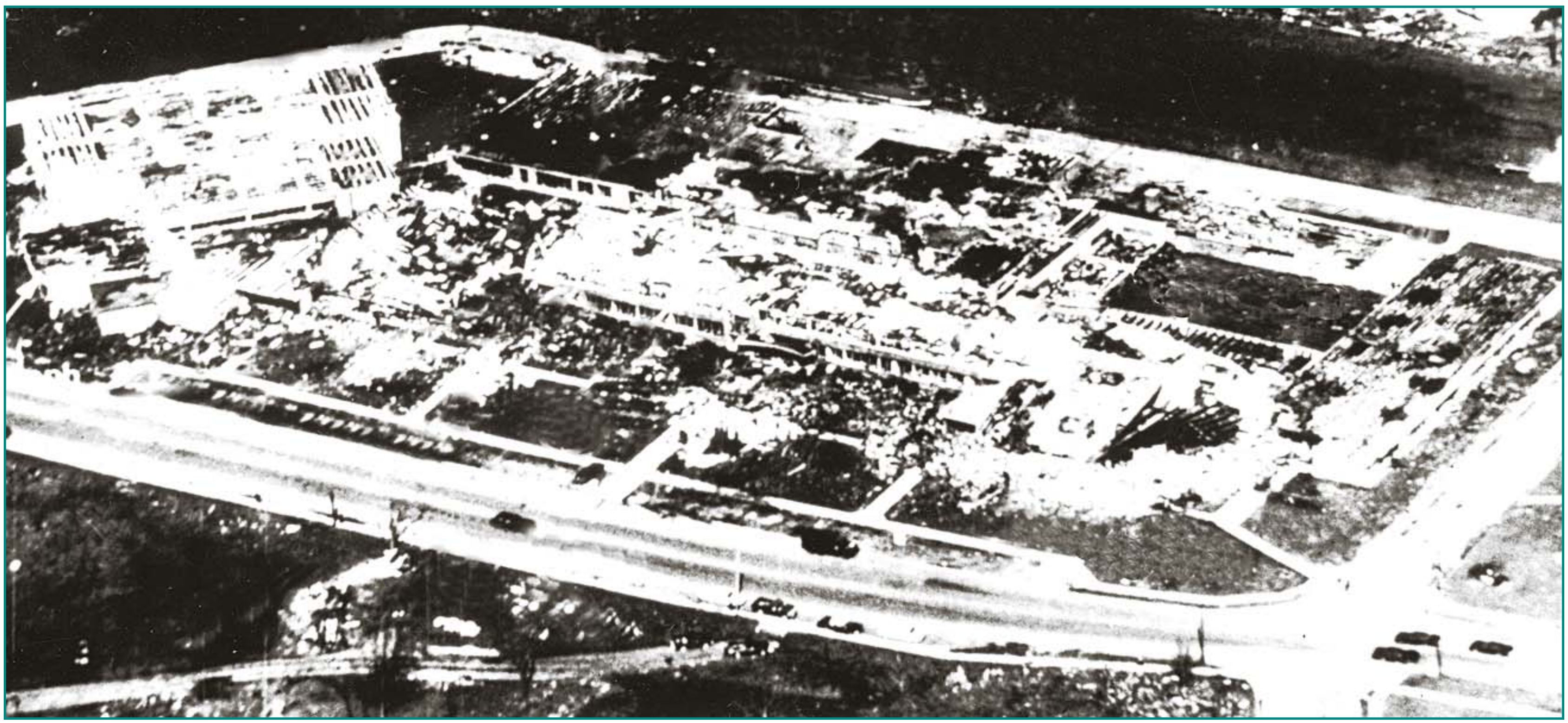


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***Figure 3-2 Xenia Senior High School, Xenia, Ohio.***

## Hazardous Elements

All **windows** on the west and south sides were blown into the interior. The high single-story, **loadbearing masonry walls** of the **long-span** rooms failed, allowing the roofs to fall in. The unbaffled west entrances allowed the east-west corridors to become **wind tunnels**.

Debris from nearby houses, vehicles, and Shawnee Park became **missiles**, many of which hit and entered the school. The 46-foot-high **masonry chimney collapsed**. A non-loadbearing second-floor wall on the north side **collapsed** onto a lower roof.

## Protective Elements

The only portion of the original building that offered refuge was the **lowest floor** (first floor). The completely **interior spaces** remained intact, especially the **smaller spaces**. Most of the corridors that were perpendicular to the storm path offered considerable protection (Figures 3-3 and 3-4).

The **concrete structural frame** of addition C remained intact. As a result, interior portions of the second floor provided refuge for some custodians.

The **heavy concrete roof** remained in place, wherever the supports were rigid frames. It also remained intact in addition A, with its loadbearing walls.

The **concrete block interior partitions** stopped incoming missiles from reaching adjacent interior spaces.

As a result of combinations of the above protective elements, extensive refuge space existed in scattered locations throughout the building (Figure 3-4).

### Selecting Refuge Areas

An understanding of the effects of **hazardous** and **protective elements** allows the best available refuge areas in an existing building to be identified. The checklists in FEMA publication 361 should be used to confirm that the selected refuge areas are the best available.


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***Figure 3-3***
***Surviving interior hallway. This is an example of the type of area that may provide refuge for building occupants during a tornado.***

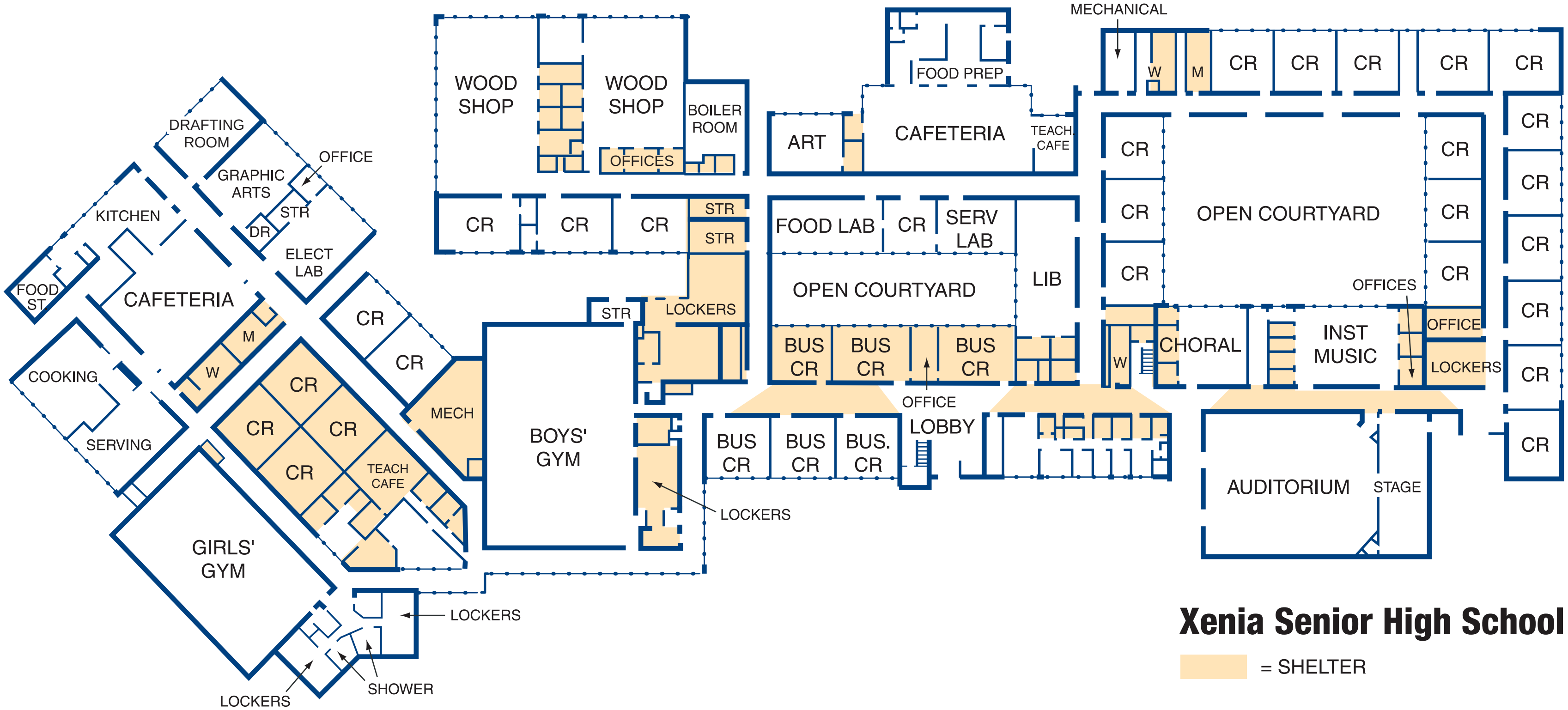


***Figure 3-4 Best available refuge areas in Xenia Senior High School.***

## Comments

"The cast had just done the big dance number from the show. They had done a sloppy job and I was just getting ready to tell them to do it again when a girl yelled, 'Hey, you want to see a tornado? There's a funnel cloud outside.' I came very close to telling everyone to forget it and do the dance again. That would have been a fatal mistake.

"Instead, I jumped off the stage and told everyone to follow me so that we could get a view of it. We ran out the front doors of the school nearest the auditorium. It looked like a lot of dirt or smoke swirling around. We couldn't see anything that looked like a clearly defined funnel cloud. We were looking out at the park across from the school. The mass of wind, dirt, and debris was everywhere. I would say between 100 and 200 yards away. Cars parked in front of the school started to bounce around a bit from the force of the winds. It was really beyond belief.

"Someone said we'd better take cover, so we turned around and ran from the hallway we were in into the center hall that ran north and south. Before we could reach the center hall, the lights went out.

"I only opened my eyes a couple of times. When I did, I saw large pieces of dirt and wood flying through the air. Lockers clanged open and shut, and several sections of lockers were actually pulled from the wall and thrown onto the floor. One section barely missed some of my students when it came out of the wall.

"I was sitting directly across from one of the restrooms, and a metal door kept flying open and shut constantly during the time that the tornado was on us. That was my greatest fear."

**English/Drama Teacher**

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***Figure 3-5***
***Loss of lightweight roof over the original two-story building.***

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***Figure 3-6***
***Collapsed hollow-core precast roof panels in the classroom area.***

*"I was watching the sky, and the lightning seemed to get worse. The minutes went by, and it at first had been going vertically, and slowly it started to go on angles.*

*"The black cloud looked like it was about 2 miles away from the school. As I watched, the lightning came concentrated into the middle of the cloud and began going on angles until it was horizontal.*

*"For a few seconds, I didn't know that the shrinking cloud was forming a tornado funnel. The funnel was a whitish-grey color more in the shape of a column than it was a funnel. I realized it was a tornado when I saw air currents begin to swirl. At first I was not afraid. Instead, I was fascinated that you could really see air currents in it.*

*"I went to the main office to get the principal, but the office was locked and everyone was gone. Just as I started to move, the drama cast started to rehearse a song in the auditorium*

*"I walked down the aisle past 24 rows of seats to one of my friends in the second row and said, 'Hi Paul, have you ever seen a tornado?' He said 'Ya' and put his arm up on the back of a chair like he's getting ready for a long conversation. I said 'Neat, there's one across the street.' He looked up at me. Then they all stood up and started to walk out. They got about halfway out and started running.*

*"All the kids were yelling, 'Hey, neat, look at that' and things like that. All of a sudden everyone was dead silent for about 4 seconds. Then everyone started screaming and yelling at once. Julie yelled, 'Get to A-1.' I said, 'Get to the southwest corner.' Mr. Heath turned around and yelled, 'Go to the main hall.' So all the cast started to rush out of the doors and promptly got stuck, so they had to wait and go slow and go out one or two at a time."*

**Student (spotter)**

*"When we were warned about the tornado, we all ran to the door to look at it. I was about the last one to arrive there, and I stood there very long until someone yelled from around the corner to get over there. The last thing I saw the tornado doing was picking up my car which was parked out on the street.*

*"I then ran around the corner and found everyone already lying along each side of the wall and some around the corner. I then ran to the intersection of the two halls and laid alongside the wall.*

*"When it was all over, I was buried from the waist down in little pieces of gravel, boards, and a lot of water from the lake across the street in the park."*

**Student**

*"The first place I ran to was this little cubbyhole right in front of the girls' restroom door. If I had stayed there, I would have been splattered across the hall, because it blew so hard it almost came off its hinges. For some reason, which I cannot account for, I dived across the hall right after the lights went out and got to the other side of the hall just as the front doors were breaking.*

*"I kept my eyes open, which was stupid on my part. I was looking down at the floor rather than out and I could see big chunks of wood and debris flying down the hall by my feet. It was incredible."*

**Student**

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***Figure 3-7***
***Collapsed gymnasium walls and roof, where open-web roof joists were supported on unreinforced masonry walls.***

# St. Augustine Elementary School and Gymnasium

## Kalamazoo, Michigan

| | |
|---|---|
| **Building population:** | **Approximately 400, including staff**<br>**One staff person in the building during tornado** |
| **Tornado direction:** | **From west** |
| **Damage intensity:** | **F2-F3** |
| **Time:** | **4:09 p.m.** |
| **Date:** | **May 13, 1980** |

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***Figure 3-8 St. Augustine Elementary School, Kalamazoo, Michigan.***

# St. Augustine Elementary School Building

The St. Augustine Elementary School was a two-story, 17-classroom building constructed in 1964. Classes had been dismissed when the tornado struck. Only the facility engineer remained in the building. He took refuge in a janitor's closet on the first floor and escaped injury.

## Construction

The structural system consisted of 3-foot-wide masonry piers constructed of 8-inch concrete masonry units and 4-inch face bricks. The piers were 8.7 feet apart. Steel beam lintels spanned the window openings between the piers. Steel open-web joists at 2 feet on center supported the 1.5-inch steel roof deck, which was welded to joists. The top chords of the joists were extended to provide a 2-foot overhang.

## Tornado Damage

The tornado winds lifted part of the roof and collapsed the second-floor piers in one wing of the school building (Figures 3-8, 3-9, and 3-10). The wind and windborne debris blew in most of the windows, and windborne debris was found in the classrooms (Figure 3-11). The exterior solid-core wood doors stayed in place and kept the debris out. Wired glass windows near the exterior doors remained intact. The interior doors to the classrooms remained in place although the hinges were damaged. The school was damaged to an extent where demolition was required.

## Hazardous Elements

The structural system of **unreinforced masonry piers** collapsed and almost one-third of the second-floor **lightweight roof structure** was lifted. Roof removal occurred over the classrooms as well as over the corridor. Most of the **skylights** in the corridors were removed by wind or broken by windborne debris. Almost all the **windows** on both floors were broken. Windborne debris and broken glass were found in the classrooms.

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***Figure 3-9***
***Collapsed second floor of St. Augustine Elementary School building.***

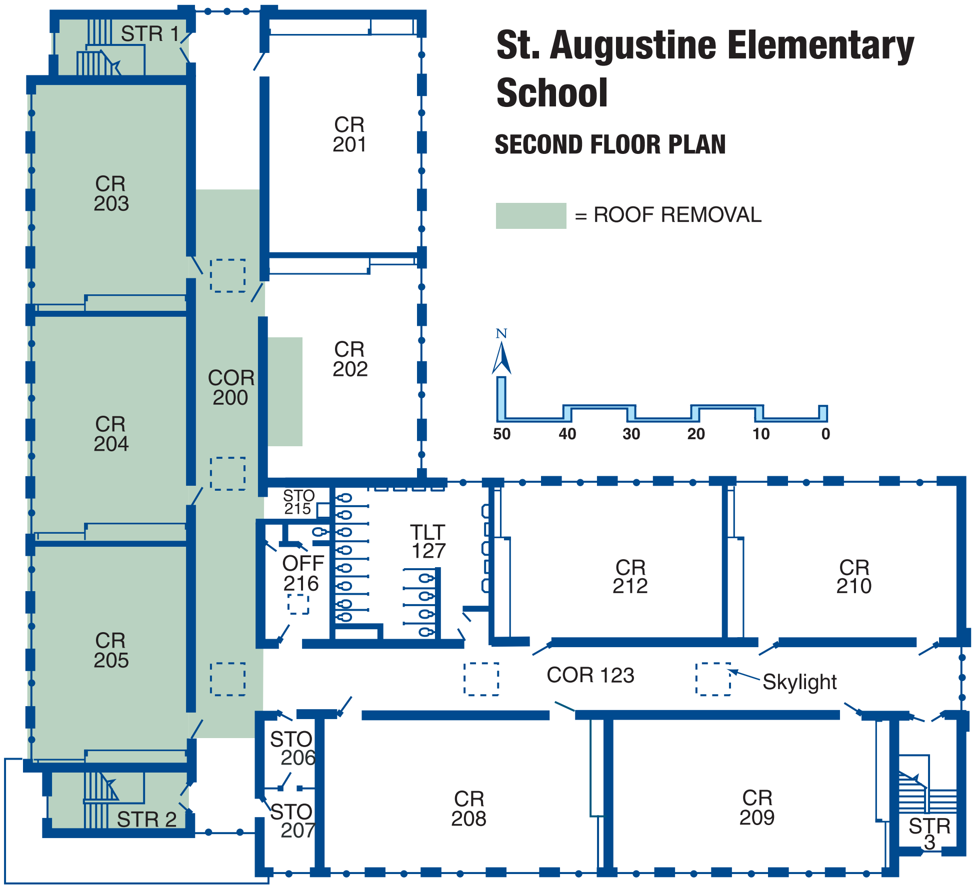
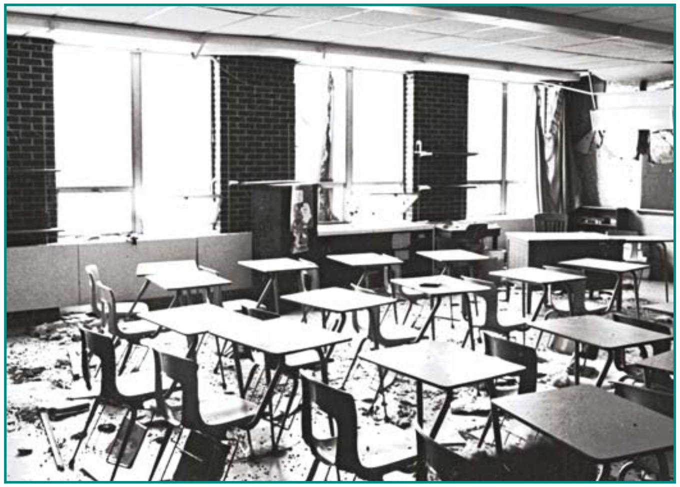



*Figure 3-10*
*Floor plan of second floor of St. Augustine Elementary School showing locations of roof removal.*

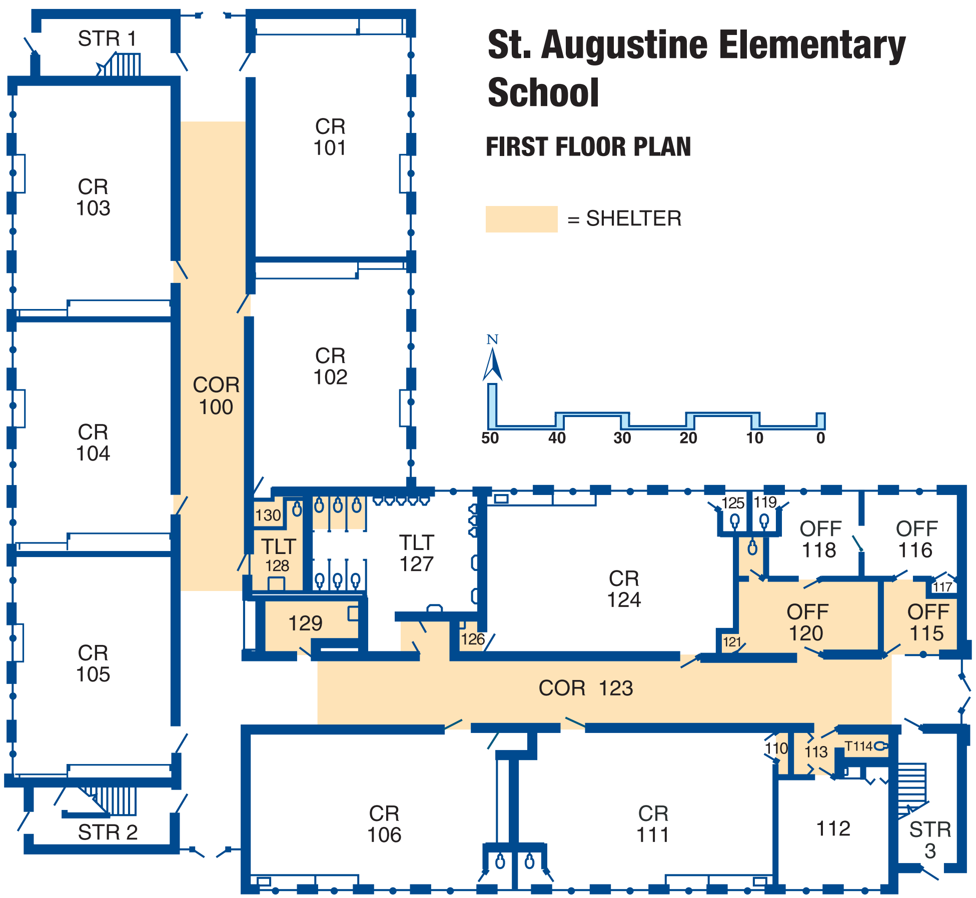


WERC, TEXAS TECH UNIVERSITY

*Figure 3-11*
*Broken windows and debris in classroom of St. Augustine Elementary School building.*

## Protective Elements

The structural system of the first floor remained intact. The exterior **solid-core wood doors** stayed in place and kept the debris out. The interior walls and doors were able to prevent debris from entering the corridors. The corridors, offices, and toilet areas on the first floor, which had two or more walls to the exterior, would have protected the occupants from serious injury (Figure 3-12).




## Selecting Refuge Areas

An understanding of the effects of **hazardous** and **protective elements** allows the best available refuge areas in an existing building to be identified. The checklists in FEMA publication 361 should be used to confirm that the selected refuge areas are the best available.

***Figure 3-12***
***Best available refuge areas in the St. Augustine Elementary School building.***

## St. Augustine Elementary School Gymnasium

An 80-foot by 100-foot, 23-foot-high gymnasium building was adjacent to the school building.

### Construction

The structural system consisted of loadbearing masonry walls constructed of 12-inch concrete masonry units and 4-inch face brick. The walls were not reinforced in the vertical direction. The roof structure consisted of long-span steel joists spanning 80 feet between the walls and spaced 6 feet apart. The steel roof deck was connected to the joists with puddle welds.

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***Figure 3-13 St. Augustine Elementary School Gymnasium, Kalamazoo, Michigan.***

### Tornado Damage

The building was destroyed (Figures 3-13 and 3-14). The loadbearing west wall collapsed inward, and the east wall fell outward. The roof fell in the building when the walls collapsed.

### Hazardous Elements

**Slender unreinforced masonry walls** and **long-span** roof structure.

### Protective Elements

None

## Observations: School Building and Gymnasium

The unreinforced masonry walls combined with the lightweight roof structure in the building as well as the gymnasium building were vulnerable to collapse in windstorms. Gymnasium buildings are not considered suitable for occupant protection because they usually include tall walls and long-span roofs. Lightweight roof structures that are not adequately anchored can be lifted in windstorms. Except in violent (F4 and F5) tornadoes, the lower floor (in two-story or higher buildings) generally provides good protection for occupants when there are two or more walls between the refuge area and the outside.

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***Figure 3-14***
***Collapsed St. Augustine Elementary School Gymnasium building.***

# Kelly Elementary School

## Moore, Oklahoma

**Building population: 490, including staff**

| | |
|---|---|
| **Tornado direction:** | **From southwest** |
| **Damage intensity:** | **F4** |
| **Time:** | **7:25 p.m.** |
| **Date:** | **May 3, 1999** |

CLEVELAND COUNTY, OK

***Figure 3-15 Kelly Elementary School, Moore, Oklahoma.***

The Kelly Elementary School was a one-story slab-on-grade building, without a basement, located in Moore, Oklahoma.

The tornado hit after school hours and passed just to the north of the site. Damage to the school building was both severe and extensive (Figure 3-15). As discussed in the Lessons Learned section in this case study, the remaining structure was demolished and the school was rebuilt. The new school includes structural elements designed to provide increased wind resistance.

## Construction

Three basic wall types were used in the construction of the school:

- reinforced masonry
- unreinforced masonry topped by reinforced bond beams
- lightweight steel frame with masonry infill

The roof system consisted of open-web steel roof joists, metal decking, and a built-up roof. Wall and roof construction of this type is common to many schools in the United States.

Hall corridors were the designated areas of refuge (see Figure 3-16). The corridor walls were of lightweight steel frame with masonry infill. The infill extended to a height of approximately 7 feet. Above this height were clerestory windows that extended to the tops of the walls. Had the halls been occupied during the tornado, many injuries and deaths would have occurred (see Figure 3-20, later in this chapter).

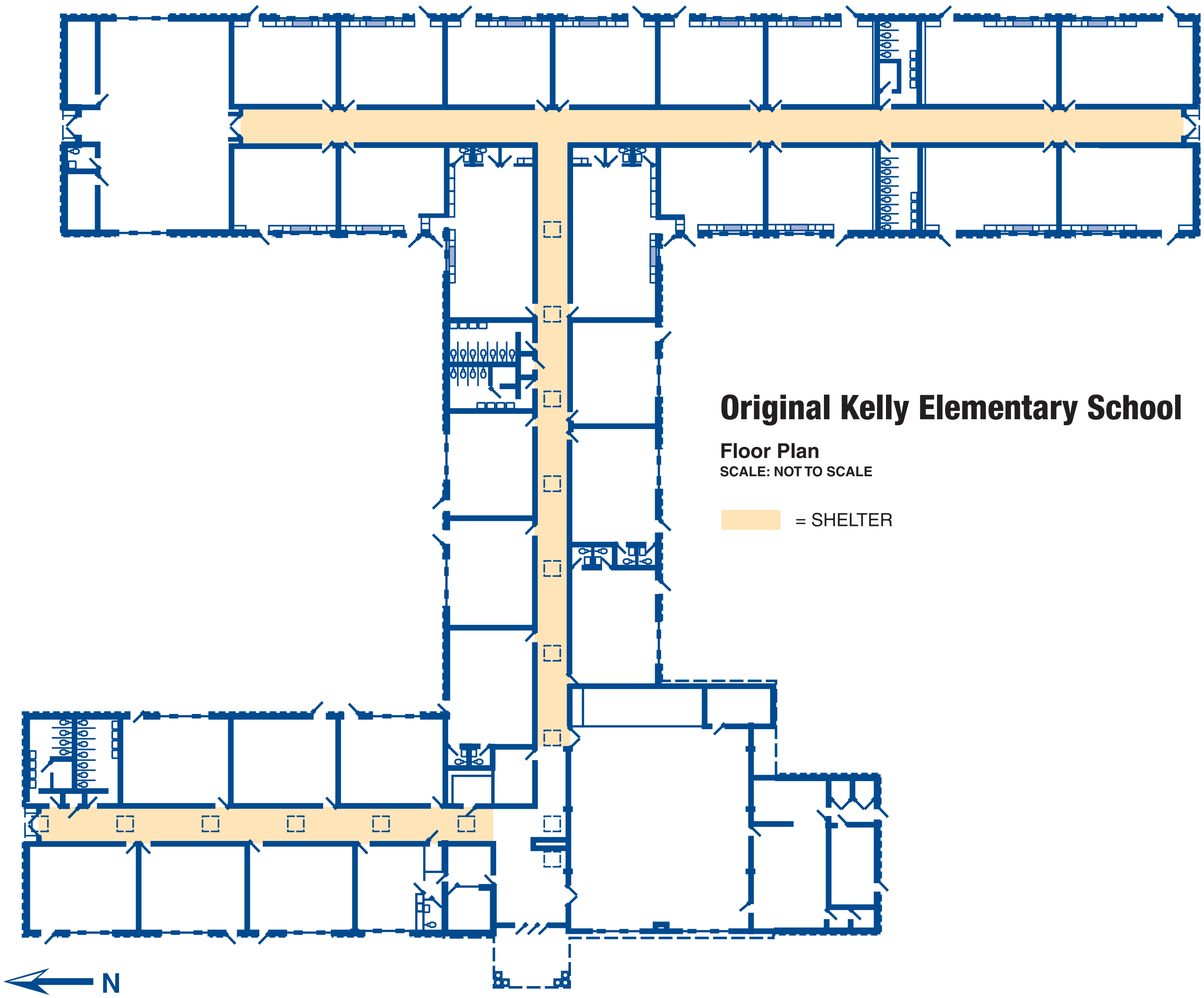


*Figure 3-16 Designated refuge areas in the original Kelly Elementary School.*

## Tornado Damage

Wall and roof structures, including those of designated areas of refuge, failed under the combination of uplift and lateral loads caused by the tornado winds. Connections between bond beams, joists, and walls were adequate for gravity loads, but could not resist the high uplift loads caused by the wind.

Unreinforced masonry walls failed when the roof system was lifted or removed by tornado winds (Figures 3-17, 3-18, and 3-19). Figures 3-17 and 3-19 show failed interior and exterior walls, respectively. Figure 3-18 shows the separation of the reinforced bond beam (indicated by circles) from the upper part of a corridor wall. The inclusion of clerestory windows in some corridor walls contributed to their failure under loads imposed by tornado winds (Figure 3-20).

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***Figure 3-17***
***Interior and exterior unreinforced masonry walls were damaged when reinforced bond beams failed.***

FEMA

***Figure 3-18***
***Corridor area. Separation of reinforced bond beam (indicated by circles) from supporting wall.***

FEMA

***Figure 3-19***
***Collapsed roof structure and exterior wall.***

FEMA

***Figure 3-20***
***Failed interior corridor walls. These walls consisted of unreinforced brick masonry infill between steel-frame members. The brick masonry extended to a height of approximately 7 feet. Clerestory windows extended from the top of the masonry to the tops of the walls.***

Inspection of the roof damage revealed that the roof decking failed at the points where it was welded to the tops of the steel trusses. Although the spacing of the welds appeared to be consistent with standard practice, the welds were not strong enough to resist the wind uplift forces (Figure 3-21).

Damage was also caused by the impact of windborne missiles. Figure 2-3, in Chapter 2, shows a steel door that appeared to have been opened by the impact of a heavy object. This door led into an area where the roof was missing. The opening created by this breached door may have allowed wind to enter the building and create internal pressure that increased the load on the building envelope. Figure 3-22 shows damage to a laminated glass window hit by a table.

FEMA

***Figure 3-21***
***Failed roof structure showing broken welds between metal roof deck and tops of joists (upper circle) and lack of vertical reinforcement (bottom circle).***

FEMA

***Figure 3-22***
***Impact performance of laminated glass. The corner of a table penetrated this laminated glass window, but the glass remained in its frame.***

## Hazardous Elements

Walls with **clerestory windows**, such as the corridor walls of the designated areas of refuge, have limited capacity to resist lateral forces.

**Unreinforced masonry** walls failed when the reinforced bond beams at the tops of the walls failed.

**Welds** between the roof decking at the tops of the metal joists failed because they were **not strong enough to resist the uplift**.

**Unprotected doors and windows** can be breached by windborne missiles. The resulting openings allow wind to enter the building, where it causes increased pressures on the building envelope.

## Protective Elements

None

## Lessons Learned

Because the damage to Kelly Elementary School was so great, the school was demolished and completely rebuilt. The new building, although constructed on the same footprint, incorporated several structural improvements specifically designed to provide improved resistance to extreme winds and create refuge areas for the school's occupants. As in the original building, the central corridors of the three wings are the designated refuge areas (Figures 3-23 and 3-24).

The creation of refuge areas in the new school involved, among other improvements, the design and construction of stronger loadbearing walls, roofs, roof-to-wall connections, and wall-to-foundation connections. Figure 3-25 is a typical cross-section of the top of a safe area (corridor) wall in the new school. As shown in this figure, the wall is constructed of reinforced concrete masonry. Note the continuous, closely spaced (8 inches on center) vertical reinforcement bars, fully grouted block cells, 6-inch-thick reinforced concrete

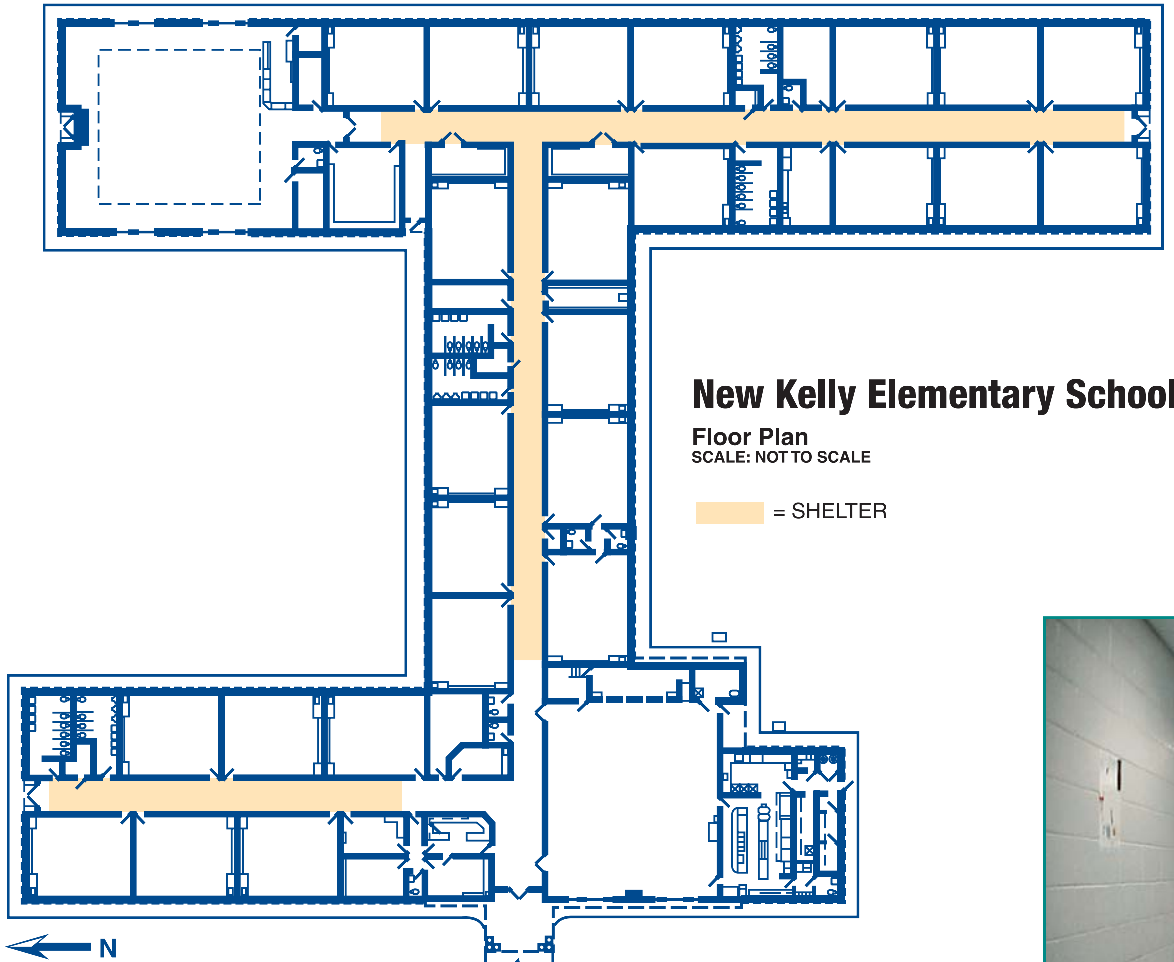



*Figure 3-23*
*Designated refuge areas in the reconstructed Kelly Elementary School.*

CITY OF MOORE, OK

*Figure 3-24*
*Corridor (designated safe area) in reconstructed Kelly Elementary School.*

roof slab, and strong connection between the roof slab and wall. The new ceilings over the corridors are constructed of poured reinforced concrete, which will provide nearly ultimate resistance to winds and damaging missiles.

Figure 3-26 is a typical cross-section of the bottom of a safe area wall. Note that the wall is securely tied to the floor slab with L-shaped reinforcing bars placed 24 inches on center. As shown in Figures 3-23 and 3-24, the corridor walls do not include the clerestory windows that increased the vulnerability of the corridor walls in the original school building.

The improvements discussed here are designed to prevent the types of damage to interior corridor walls and roofs shown previously in Figures 3-17, 3-18, 3-20, and 3-21. The reconstruction of the Kelly Elementary School is a good example of how refuge areas can be incorporated into new construction.

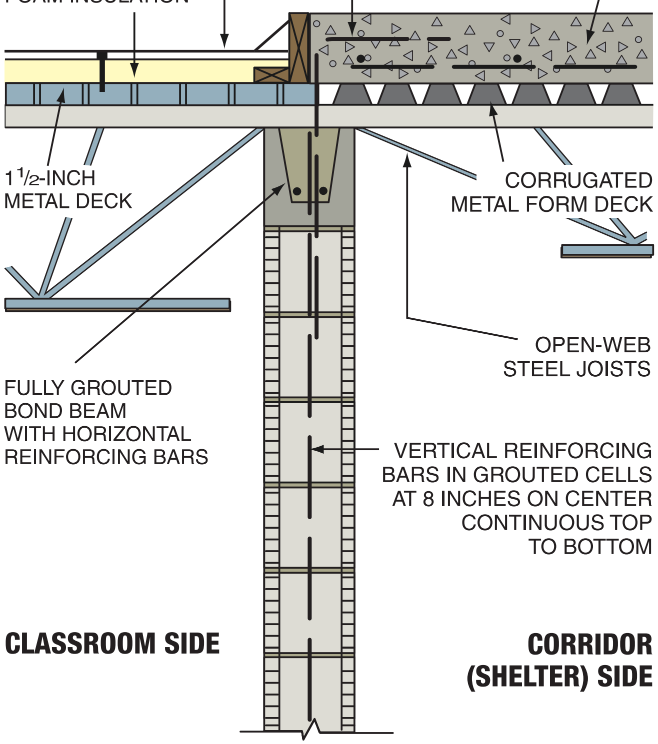



***Figure 3-25***

***Typical cross-section of top of safe area wall in the reconstructed Kelly Elementary School.***

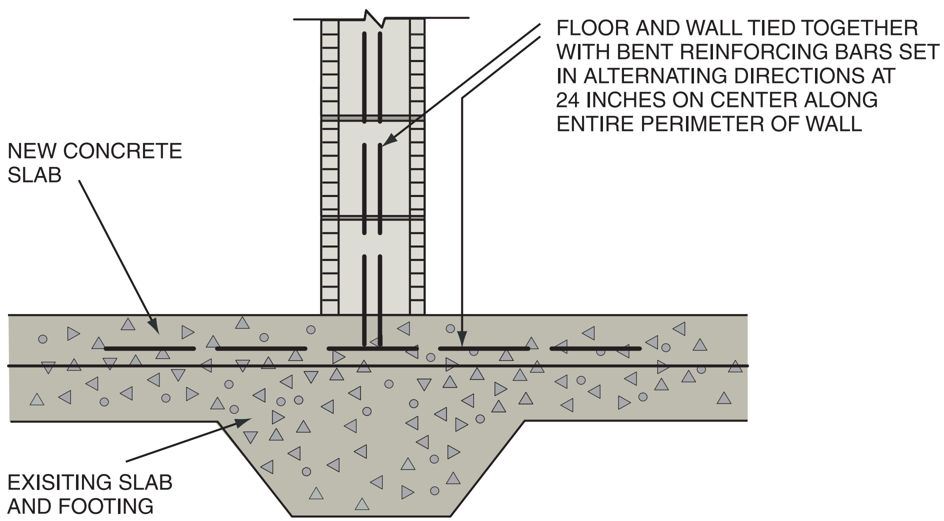



***Figure 3-26***

***Typical cross-section of bottom of safe area wall in the reconstructed Kelly Elementary School.***

# Selection Procedure

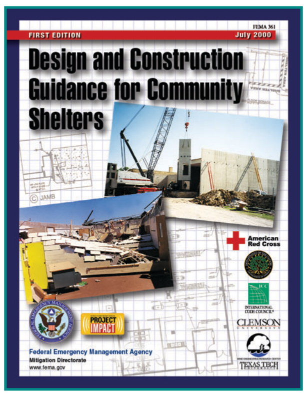
The procedure presented in this chapter is designed to assist in a systematic review of a building for the purpose of selecting the areas within the building that are likely to be the most resistant to tornadoes, referred to in this booklet as the **best available refuge areas.** When used for refuge during tornadoes, these areas do not guarantee safety; they are, however, the safest areas available for building occupants. This selection procedure does **not** apply to structures such as lightweight modular houses and offices and relocatable classrooms. Such structures are presumed to fail, and **they must be evacuated**.

Most buildings, unless specifically designed as shelters, will sustain catastrophic damage if they take a direct hit from a Violent Tornado (i.e., a tornado ranked F4 or F5 on the Fujita Tornado Damage Scale—see Chapter 1). Because the maximum wind speeds associated with a Violent Tornado greatly exceed the wind speeds that the buildings were designed to withstand, complete destruction will usually occur during these extremely rare events.

In reality, most tornadoes do not produce the winds of a Violent Tornado, and some areas of many buildings can survive these lesser events without catastrophic damage or collapse. Placing building occupants in the **best available refuge areas** within a building greatly reduces the risk of injury or death. However, unless the refuge area was designed as a shelter, its occupants are vulnerable to injury or death.

Selecting the **best available refuge areas** involves three main steps:

- **determining how much refuge area space is required** to house building occupants

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## Guidance for Refuge Area Selection

Detailed evaluation checklists for selecting the best available refuge areas in existing buildings and guidance for designing and constructing shelters are presented in FEMA 361, *Design and Construction Guidance for Community Shelters* (for more information, see the section of this booklet titled **Information Sources.**)

- **reviewing construction drawings and inspecting the building** to identify the strongest portion(s) of the building
- **assessing the site** to identify potential tree, pole, and tower fall-down and windborne missiles

Determining the required refuge area space and assessing the site are relatively straightforward tasks that can be completed by many people. The drawing review and building inspections are more technical in nature. Qualified structural engineers or architects should be consulted for those tasks.

# Determine the Required Amount of Refuge Area Space

Refuge areas must be large enough to provide space for all occupants who may be in the building when a tornado strikes. In schools, space must be provided for all students and faculty, maintenance and custodial workers, and any parents or other visitors who may be present.

Refuge area space requirements vary according to the age of the occupants and any special needs they may have. FEMA publication 361, *Design and Construction Guidance for Community Shelters*, recommends that shelter space determinations be based on the following guidelines:

| | |
|---|---|
| Children Under 10 | 5 square feet per person[1] |
| Adults, Standing | 5 square feet per person |
| Adults, Seated | 6 square feet per person |
| Wheelchair Users | 10 square feet per person |
| Bedridden Children or Adults | 30 square feet per person |

[1] Previous editions of this booklet recommended 3 square feet per person for small children.

## Example Calculation of Required Refuge Area Space

Consider an elementary school that has 560 students, 2 of whom use wheelchairs; 28 faculty members; and 3 custodial and maintenance workers. Calculating the required refuge area space involves identifying all groups of occupants and their refuge space needs:

| | |
|---|---|
| 558 Children @ 5 sq ft each | = 2,790 sq ft |
| 31 Adults @ 6 sq ft each | = 186 sq ft |
| 2 Wheelchair users @ 10 sq ft each | = 20 sq ft |
| | **Total = 2,996 sq ft** |

In this instance, the required refuge area space could be provided by a total of 375 feet of 8-foot-wide corridor or by a combination of smaller areas.

### Why Are Individual Building Inspections Needed?

This section describes the role of different building elements in providing safety from extreme winds. However, individual buildings can vary considerably; therefore, individual building assessments based on the guidelines of FEMA publication 361 are always recommended. For example, although the lowest floors in a building are usually the safest, an individual evaluation of a school building may find that second-story areas are safest in a particular instance. Another example, shown previously, is the performance of Kelly Elementary School. Although interior corridors are often one of the safer areas, the corridors in Kelly Elementary School, as originally constructed, were unsafe during the F4 tornado that struck Moore, Oklahoma. An individual evaluation of Kelly Elementary School using the checklists in FEMA 361 would reveal these weaknesses.

In larger buildings, several dispersed refuge areas should be selected when possible so that travel times for building occupants are minimized. Keep in mind that building occupants with special needs, such as wheelchair users, may require additional time to reach the refuge area.

# Review Construction Drawings and Inspect the Building

As there are stronger and weaker tornadoes, there are stronger and weaker portions of any building. The construction drawing review and building inspection help identify the stronger areas that are most resistant to damage from high winds and windborne missiles.

Selecting the best available refuge areas involves predicting how a building may fail during an event that produces complex winds and unpredictable missiles. The failure modes in a building are numerous, complex, and progressive. The complex nature of tornadoes and the variations in as-built construction limit the effectiveness of even detailed engineering models in accurately predicting failure of an existing building. However, experience and subjective judgment can help identify areas that are less prone to failure during a tornado.

## Protective Elements

The **lowest floor** of a building is usually the safest. Upper floors receive the full strength of the winds. Occasionally, tornado funnels hover near the ground but hit only upper floors. **Belowground space** is almost always the safest location for a refuge area. If a building has only one floor and no basement, look for building elements that can improve the chances for occupant survival:

1. **Interior partitions** that provide the greatest protection are somewhat massive, fit tightly to the roof or floor structure above, and are securely connected to the floor or roof. Avoid interior partitions that contain windows.

2. **Short spans** on the roof (see sidebar) or floor structure are more likely to remain intact. This is because short spans limit the amount of uplift on connections caused by winds. Although short spans are best, small rooms, even those with walls that do not support the roof, may be the best available refuge areas. If the roof rises and then collapses, the interior walls may become supporting walls and thereby protect the occupants, although there is the risk that the walls will also collapse or be blown away.

3. Buildings with **rigid frames** usually remain intact. Buildings with heavy steel or reinforced concrete frames rigidly connected for lateral and vertical strength are superior to buildings that contain loadbearing walls. On the other hand, wood-framed construction used in residences and in light commercial buildings can be extremely vulnerable to damage from high winds. Wood-framed and pre-engineered metal buildings should not be used as tornado shelters.

4. **Poured-in-place reinforced concrete**, **fully grouted and reinforced masonry**, and **rigidly connected steel frames** are usually still in place after a tornado passes. However, in either type of construction, the floor or roof system must be securely connected to the supports. Gravity connection of the roof deck to the frame is inadequate. Generally, the heavier the floor or roof system, the more resistant it is to lifting and removal by extreme winds. Figure 4-1 shows typical fully grouted, reinforced masonry wall construction.

## Hazardous Elements

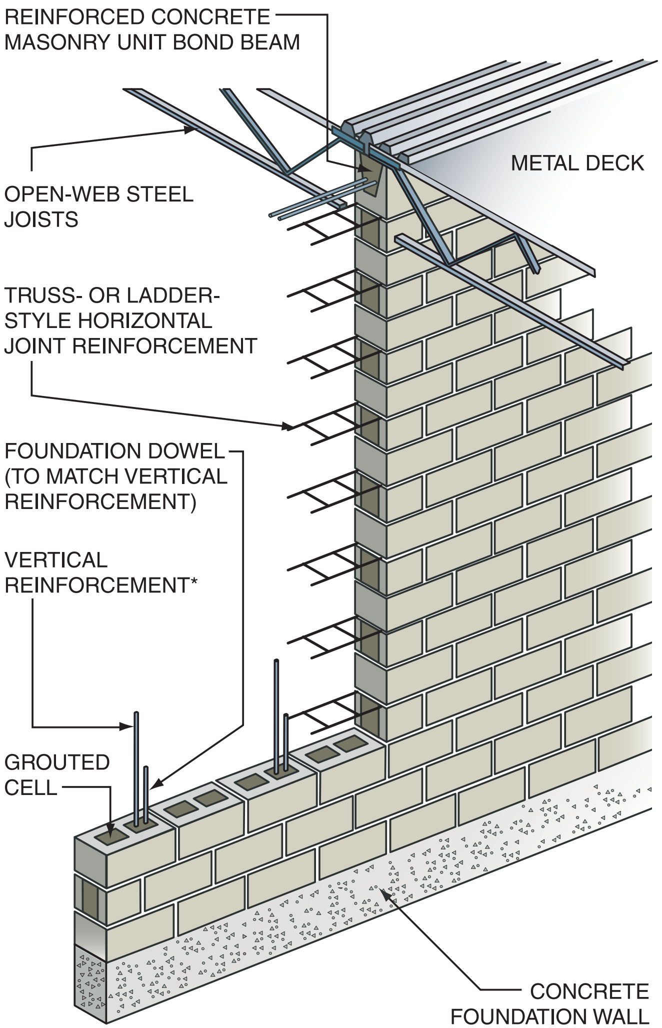
The following building elements seriously diminish occupant safety. Areas that contain these elements should not be used as refuge areas.

1. **Long-span roofs** are almost always found on rooms with high ceilings (e.g., gyms, auditoriums, music and multipurpose rooms). The exterior walls of such rooms are higher than typical one-story walls and often collapse under the forces imposed by tornado winds. Occasionally, high

### What is a Short-Span Roof?

No single number defines a "short span." The ability of any roof to resist wind uplift depends on several factors. The type of structural members used in the roof (e.g., steel joists vs. reinforced concrete frames), the weight of the roof (heavy for concrete decks vs. light for most metal decks), and the strength of the connections between the roof and the supporting structure all dictate how well a roof will resist high winds.

In FEMA publication 342, *Midwest Tornadoes of May 3, 1999*, FEMA's Building Performance Assessment Team recommended that rooms with roof spans longer than 40 feet not be used as refuge areas. Similarly, the Red Cross limits roof spans to 40 feet for hurricane shelters. The 40-foot criterion should be considered an absolute maximum unless an engineering analysis determines that the roof system is adequate. Preferably, best available refuge areas should have roof spans that are 25 feet or less.




* SPACING OF VERTICAL REINFORCING BARS IN MASONRY WALLS VARIES AND IS CONTROLLED BY FACTORS SUCH AS WALL HEIGHT, WALL WIDTH, AND DESIGN WIND SPEED.

***Figure 4-1***

***Typical fully grouted, reinforced masonry construction.***

walls collapse into a long-span room, and roofs that depend on the walls for support collapse. Building administrators must resist the temptation to gather many building occupants into a large space so that control will be easier. **Often these spaces incur maximum damage; if a large group of people is present, many deaths and injuries are likely to result.**

2. **Lightweight roofs** (e.g., steel deck, gypsum, lightweight insulating concrete, cement woodfiber, wood plank, and plywood) usually will be lifted and partially carried away while roof debris falls into the room below. The resulting opening then allows other flying debris to be thrown into the interior space. In addition, walls often collapse after loss of the roof deck.

3. **Heavier roofs** (e.g., precast concrete planks, channels, and tees) may be lifted, move slightly, and then fall. If supporting walls or other members have collapsed, the roof may fall onto the floor below, killing or seriously injuring anyone there. Cast-in-place concrete decks typically remain in place.

4. **Windows** are no match for the extreme winds or missiles of a tornado. Windows usually break into many jagged pieces and are blown into interior spaces. Even tempered glass will break, but usually into thousands of small, cube-like pieces. Windows in interior spaces also break, usually from missile impact. Acrylic or polycarbonate plastics are more resistant to impact than glass, but large panes may pop out, and the fumes given off when these materials burn can be toxic. Laminated glass can be quite effective, except when hit by very powerful missiles (see Figure 3-22, in Chapter 3). Windows at the ends of corridors are particularly dangerous because high winds can blow them down the corridor. (See window protection sidebar on page 42.)

5. **Wind tunnels** occur in **unprotected corridors** facing oncoming winds. In post-event damage inspections, debris marks have been found covering the full height of corridor walls, indicating that the winds occupied almost the entire volume of the corridor. If entrances are baffled with a solid, massive wall, this effect is much less serious.

6. **Loadbearing walls** are the sole support for floors or roofs above. If winds cause the supporting walls to fail, part or all of the roof or floors will collapse. In addition, walls often collapse after loss of the roof deck.

7. **Masonry construction** is not immune to wall collapse. Most masonry walls are **not vertically reinforced** and can fail when high horizontal forces such as those caused by winds or earthquakes occur. Masonry walls without vertical reinforcement are potentially hazardous. Such walls can also fail and create an additional hazard if the roof deck is lost.

# Assess the Site

Inspect the site and identify trees in excess of 6 inches in diameter, poles (e.g., light fixture poles, flag poles, power poles), masonry chimneys, and towers (e.g., electrical transmission and communication towers). Those trees, poles, chimneys, and towers that are close enough to fall on the building should be marked on a site plan. Accurately locate those trees, poles, chimneys, and towers and note the approximate height of each on the plan. (An example of a site plan is shown in the refuge area selection example presented later in this chapter.)

In selecting the best available refuge areas, plot the tree, pole, chimney, and tower fall-down areas on the building plan. The best available refuge area should not be located within or adjacent to the fall-down areas, because fall-down of trees, poles, chimneys, and towers can cause localized building collapse (see Figures 4-2 and 4-3). In addition to falling, these elements can also be blown a considerable distance (see Figure 4-4).

For most building locations, there will be many nearby sources of small and large windborne missiles. Missile examples include aggregate roof surfacing, rooftop HVAC equipment, components from nearby damaged buildings (e.g., roof decking, studs, joists, trusses, hot water heaters, kitchen appliances, building furnishings), tree limbs, trees, trash containers, propane tanks, poles,

### A Note About Window Protection

Many facilities in hurricane-prone areas have provisions to protect vulnerable windows from high winds and windborne debris. Most window protection methods are designed for wind speeds much lower than those associated with tornadoes. Also, some window protection devices, such as shutters and storm panels, need to be installed or closed to offer any benefit. With tornadoes, there will generally not be sufficient warning time for this to be accomplished. Consequently, any refuge area with large windows should be avoided.

An evaluation of potential refuge areas may include areas with doors that contain small windows. After an evaluation has been completed, areas that include such doors could still be considered the best available refuge areas despite the vulnerability of the glass. However, known problems should be addressed to the extent possible. Examples of corrective actions that could be taken include replacing any doors that contain windows, replacing the existing glazing with more impact-resistant glazing, and ensuring that the occupants of the refuge area are not in the path of any debris that could be generated by the failure of these small windows.

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***Figure 4-2***
***Two trees toppled by tornado winds damaged this house in Haysville, Kansas.***

FEMA

***Figure 4-3***
***Failure of brick chimney under tornado winds damaged the room of this house in Moore, Oklahoma.***

FEMA

*Figure 4-4*
***This power pole penetrated a window and extended several feet into the house after being blown 40 feet from its original location.***

automobiles, buses, and trucks. Missiles can be propelled horizontally and vertically (see Figures 2-2, 2-3, 2-4, and 4-5). Therefore, in selecting the best available refuge areas, it is typically prudent to assume that the building being evaluated will be bombarded with both small and large missiles, traveling horizontally and vertically.

# Example of Refuge Area Selection Process

The following example illustrates the methodology for assessing refuge area needs and identifying the best available refuge areas.

## General

The example facility is a single-story elementary school built in the early 1990s. In layout, design, and construction, it is typical of many schools in

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*Figure 4-5*
***This photograph illustrates the importance of overhead protection in refuge areas. The missile shown here fell nearly straight down.***

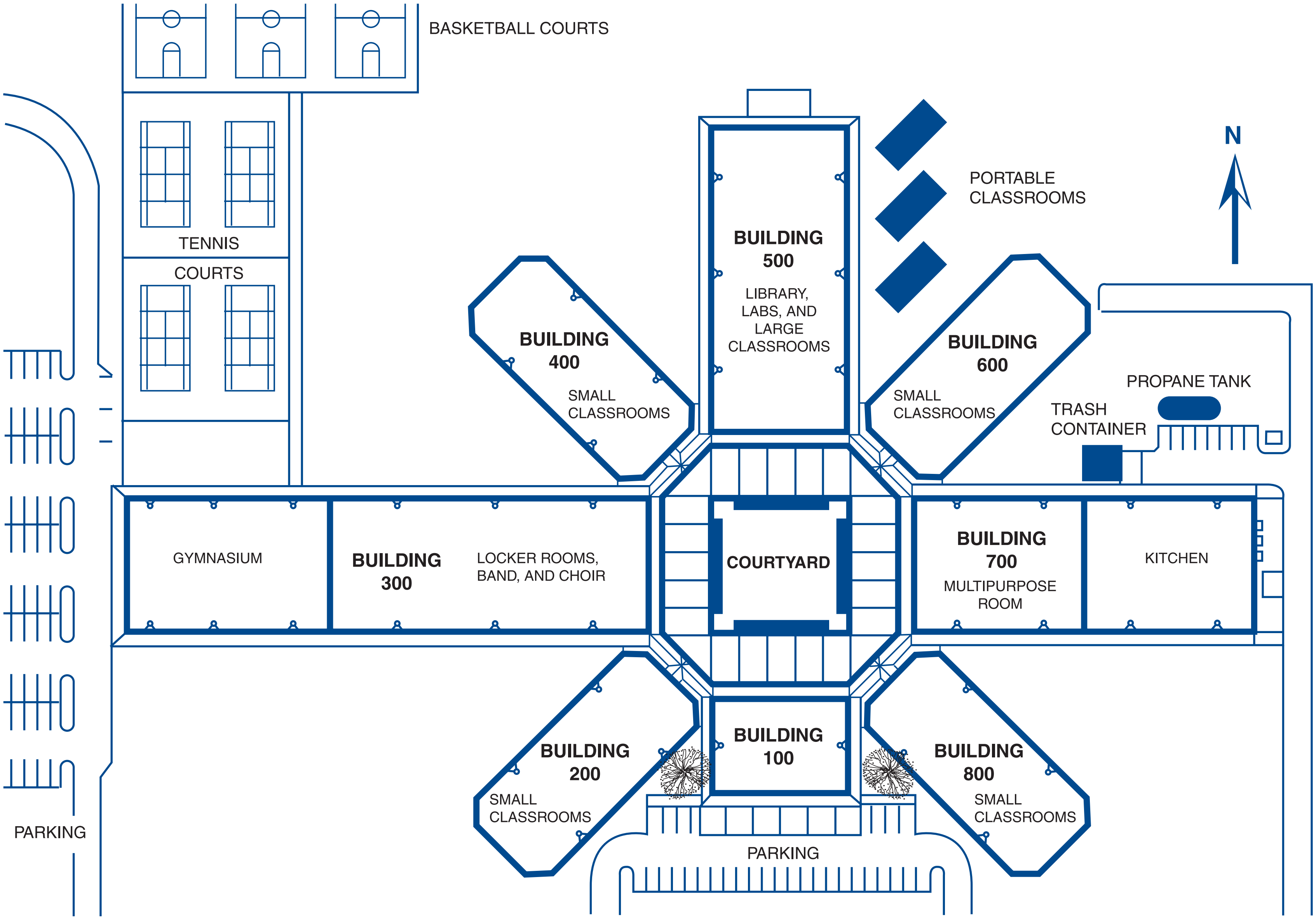



*Figure 4-6 Site plan for example facility.*

Florida. As shown by the site plan in Figure 4-6, the school consists of eight separate wings (Buildings 100–800) situated around a central courtyard. The school site includes parking areas to the west and south, several wood-framed portable classrooms near the library, a tall flagpole in the courtyard, and a trash container and aboveground propane tank near the kitchen.

The school population comprises 1,146 students, 49 faculty and administrative staff, and 3 maintenance workers and custodians. One of the students uses a wheelchair.

## Required Refuge Area Space

The following is a calculation of the required refuge area space for the population of this example school based on the guidelines in FEMA publication 361, *Design and Construction Guidance for Community Shelters*.

| | |
|---|---|
| 1,145 Children @ 5 sq ft each | = 5,725 sq ft |
| 52 Adults @ 6 sq ft each | = 312 sq ft |
| 1 Wheelchair user @ 10 sq ft each | = 10 sq ft |
| | **Total = 6,047 sq ft** |

## Architectural and Structural Characteristics

Building 100 is the main entrance to the school. It is much smaller than the other buildings and contains the administrative offices. Building 300 contains the gymnasium, locker rooms, and the band and choir areas. The library, labs, and other large classrooms are in Building 500. The kitchen and multipurpose room (a cafeteria that doubles as an auditorium) are in Building 700. Figure 4-7 shows the floor plan of Building 500. The general layouts of Buildings 100, 300, and 700 are similar to that of Building 500.

Buildings 200, 400, 600, and 800 contain typical classrooms. These classrooms are smaller than the library, labs, and large classrooms in Building 500 and, unlike the rooms in Buildings 100, 300, 500, and 700, are accessed from long, central, interior corridors. Figure 4-8 shows the floor plan

***Figure 4-7***
***Floor plan of Building 500.***

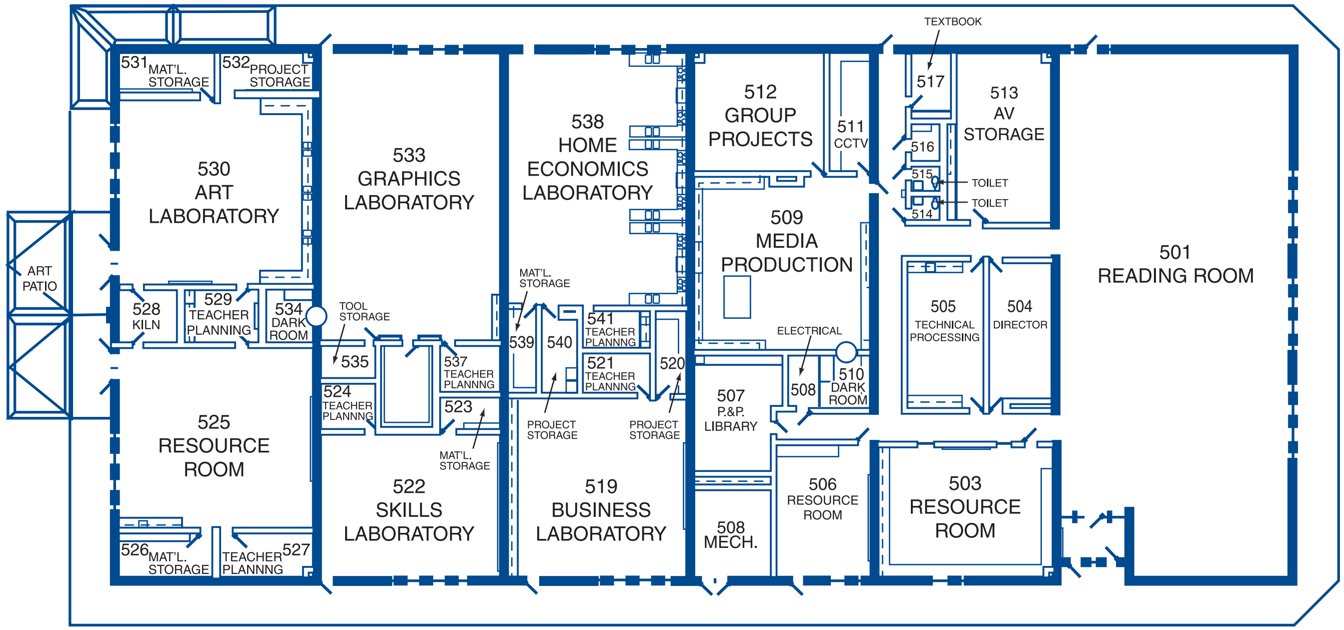



***Figure 4-8***
***Floor plan of Buildings 200, 400, 600, and 800 (see Figure 4-10 for the wall cross-section at A-A).***

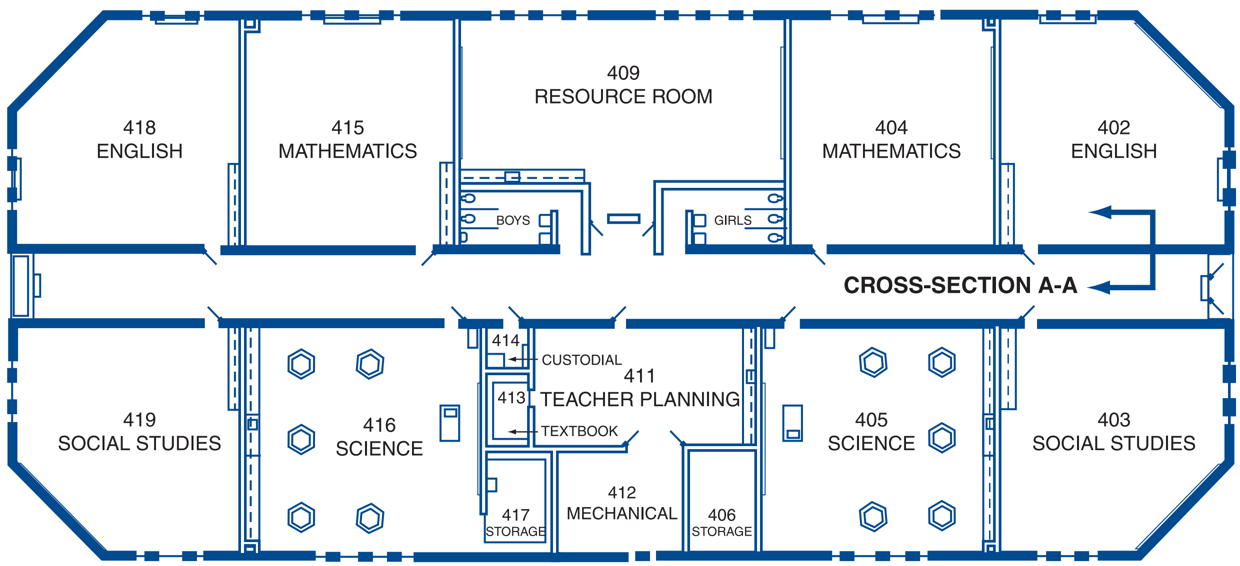



*Figure 4-9*

***Interior central corridor – typical of the corridors in Buildings 200, 400, 600, and 800.***

of Buildings 200, 400, 600, and 800. One of the central corridors in these buildings is shown in Figure 4-9.

In each of the eight buildings, exterior and interior loadbearing concrete block masonry walls support the roof above. These walls are reinforced with vertical steel spaced at 2 feet 8 inches on center. Figure 4-10 shows a cross-section of one of the loadbearing corridor walls in Buildings 200, 400, 600, and 800 (the location of this cross-section is shown in Figure 4-8). The exterior walls include a brick veneer that is relatively resistant to the impact of small wind-borne debris. The interior partition (non-loadbearing) walls are unreinforced masonry, extend only 6 inches above the suspended ceilings, and are not laterally secured to the roof.

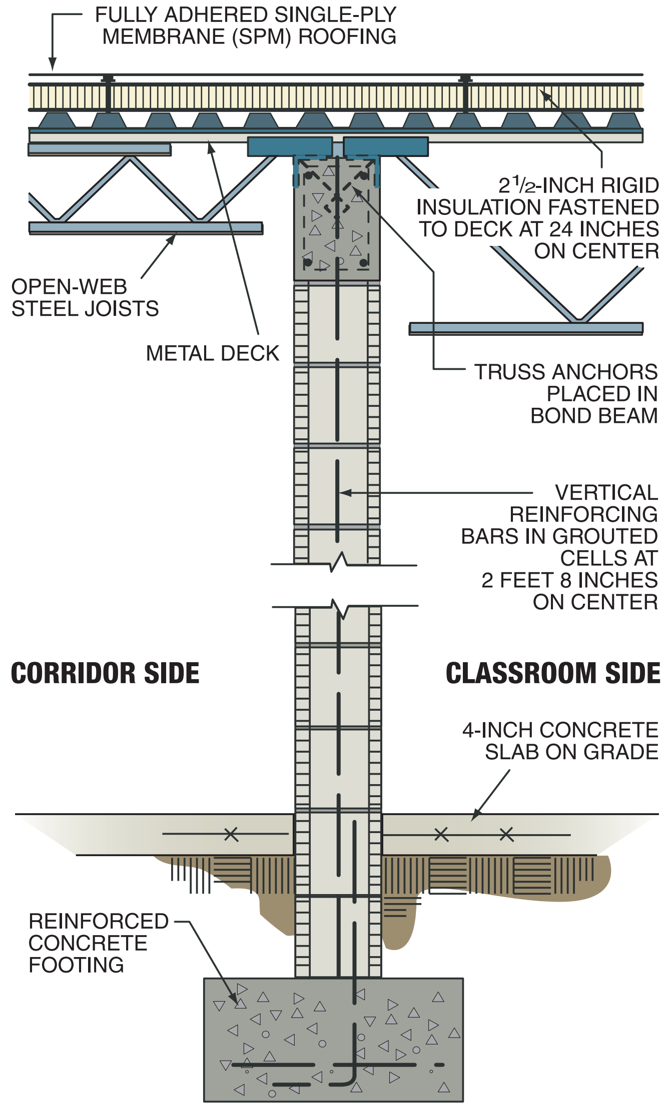



*Figure 4-10*

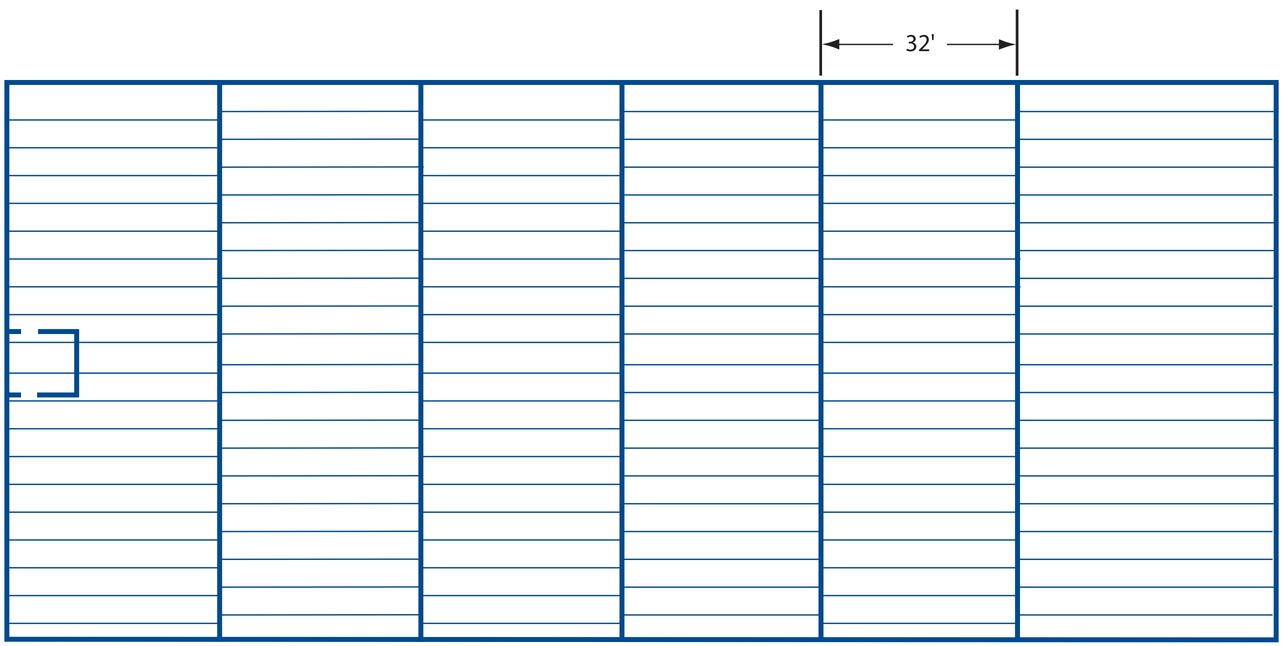
***Cross-section A-A through corridor/classroom wall – Buildings 200, 400, 600, and 800 (see Figure 4-8 for location of A-A).***

Note that a visual inspection of structure walls will **not** reveal whether or how they are reinforced. Construction drawings will show whether the wall design includes reinforcement and will provide details regarding the intended size and placement of reinforcing steel. However, only an inspection of the interior of a wall will reveal the actual construction. Such inspections can be made with nondestructive tests (e.g., magnetic, ultrasonic, or x-ray).

The roofs of the eight buildings are relatively lightweight and are constructed with open-web steel roof joists, metal decking, rigid insulation, and single-ply membrane roofing. In Buildings 300, 500, and 700, the roof framing typically spans 32 feet between the supporting loadbearing walls (Figure 4-11). The roof framing in Building 100 is similar.

In Buildings 200, 400, 600, and 800, the roof framing spans 34 feet 4 inches from the exterior loadbearing walls to the center loadbearing corridor walls.

***Figure 4-11***
***Roof framing plan for Building 500.***



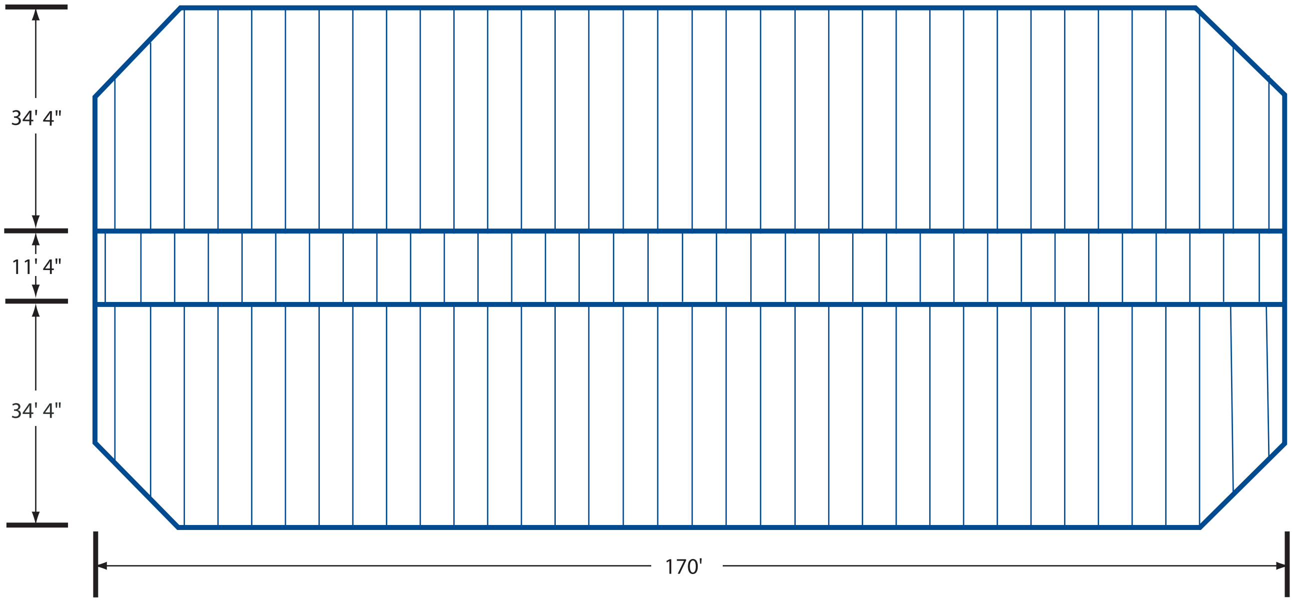



***Figure 4-12***
***Roof framing plan for Buildings 200, 400, 600, and 800.***

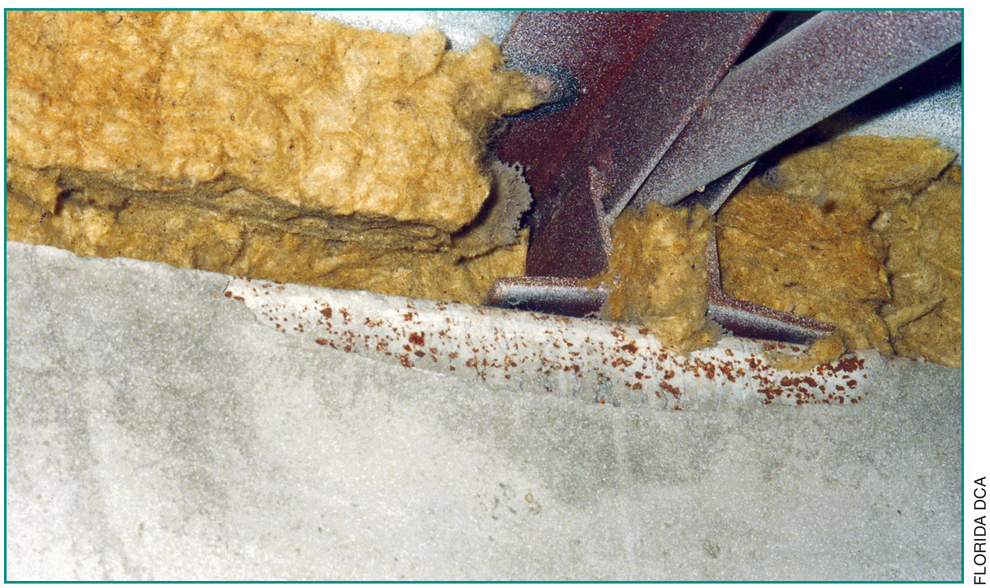



***Figure 4-13 Typical roof truss connection to exterior wall in the example school.***

Separate roof joists span the 11-foot 4-inch-wide corridors (Figure 4-12). In all eight buildings, the roof joists are fastened to the tops of the masonry load-bearing walls with welded base plates and anchor bolts (Figure 4-13).

The exterior windows in all eight buildings have aluminum frames and tempered glass. The exterior doors—including the exterior corridor doors in Buildings 200, 400, 600, and 800 (Figure 4-14)—are insulated metal-framed units with large windows. The doors from the corridors to the classrooms in these four buildings are wood with small windows (Figure 4-15).

## Identifying the Best Available Refuge Areas

In the identification of the best available refuge areas, several locations were ruled out because of their limited strength, inherent weaknesses, or lack of usable space.


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***Figure 4-14***
***Exterior corridor doors in the example school.***

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***Figure 4-15***
***Door connecting classroom to corridor – Buildings 200, 400, 600, and 800.***

Buildings 300, 500, and 700 were ruled out for two reasons:

1. **Vulnerability to debris impact and wind penetration.** These buildings contain many large exterior windows that are extremely vulnerable to penetration by windborne debris. As noted in Chapter 2, once the building envelope is breached, wind enters the building and the pressures on the building increase. In addition, debris can enter the building through the window openings and may injure or kill building occupants.

2. **Long roof spans.** As noted earlier, the roof spans in these buildings are 32 feet long. Long-span roofs are more susceptible to uplift, which can lead to the collapse of the supporting walls.

Building 100 was also ruled out. In addition to sharing the vulnerabilities of Buildings 300, 500, and 700, Building 100 is relatively small, as are the rooms it contains. The available space in this building is further restricted by the large amount of furniture and office equipment normally found in an administrative building.

The interior corridors in Buildings 200, 400, 600, and 800 (Figure 4-16) offer the best available refuge areas in this example. The corridors have relatively short roof spans and relatively small percentages of exterior window glass. In addition, because the classroom doors open onto the corridors, the occupants of these buildings would have ready access to these refuge areas.

Each corridor is 10 feet 8 inches wide (11 feet 4 inches minus the 8-inch wall thickness) and 170 feet long, and provides approximately 1,800 square feet of **gross refuge area space**. Assuming that a 2-foot-wide clear area must be

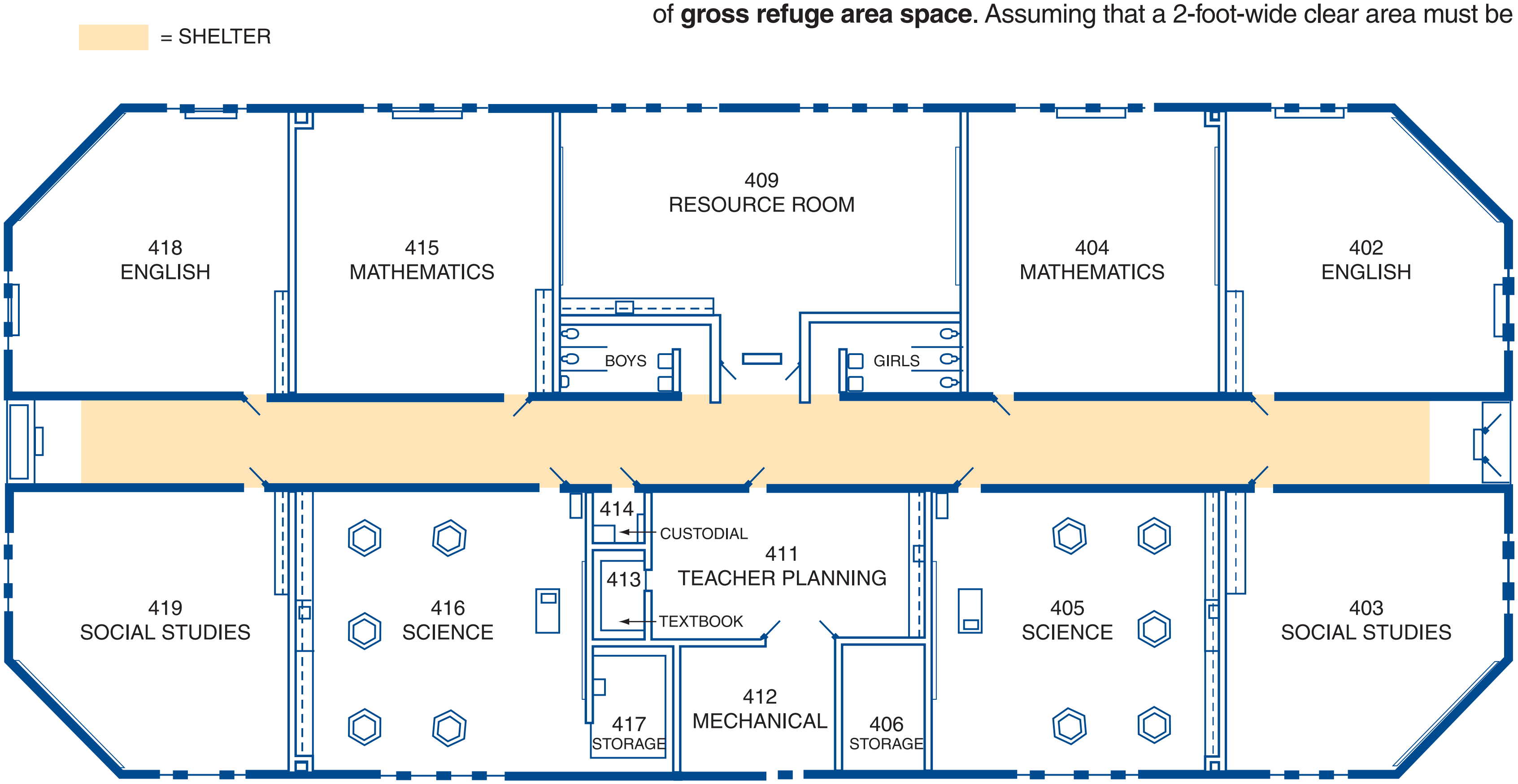



***Figure 4-16 Best available refuge areas in the example school – corridors in Buildings 200, 400, 600, and 800.***

maintained to allow students and staff to access the refuge area, each corridor can provide approximately 1,500 square feet of **usable refuge area space**. The four corridors provide 6,000 square feet of usable refuge area. While slightly less than the recommended total of 6,047 square feet, the available usable refuge area space satisfies the intent of FEMA publication 361.

Although these corridors are the best available refuge areas in this example, they could be made more resistant by the construction of a wind-resistant alcove that would protect the exterior glass doors and help prevent the entry of wind and debris into the refuge area (Figure 4-17). An alternative would be to install solid, wind-resistant exterior doors that, although normally left open, could be closed when a tornado warning is issued. A less desirable option would be to add a double set of laminated glass exterior doors.

Building administrators and school officials must weigh the protective benefits of such modifications against potential security problems, in the case of solid-wall alcoves, and the need for adequate warning time, for the operation of protective doors. An upgrade alternative for the interior corridor doors would be to replace them with stronger doors equipped with stronger hardware and small laminated glass windows.

In many buildings, the size of the best available refuge area will be less than the required size determined according to the guidelines in FEMA publication 361. In such buildings, the occupants will need to be housed in either smaller areas or more vulnerable areas. Although there are physical limits to the number of people a space can accommodate, housing more people in less space is preferable to locating them in more vulnerable areas.

## Verifying the Best Available Refuge Areas

After refuge areas have been selected according to the methodology described in this chapter, the evaluation checklists in FEMA publication 361 should be used to verify that the selected areas are the best available in the building. FEMA 361 also includes information that can help building adminis-

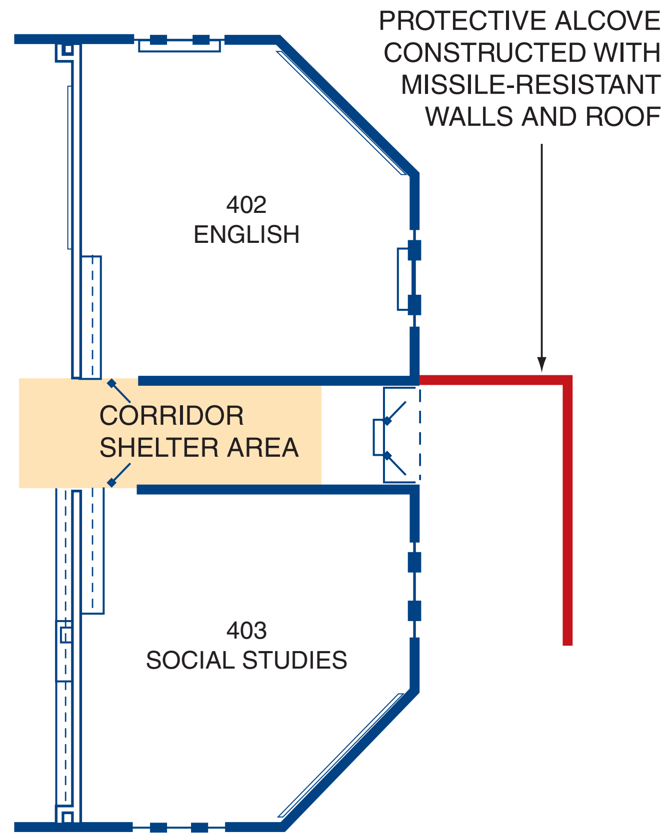



***Figure 4-17***
***Glass exterior doors can be protected from wind and debris with a wind-resistant alcove.***

trators improve the effectiveness of the selected refuge areas (e.g., guidelines concerning signage and operations plans).

# Selecting the Best Available Refuge Areas in Other Types of Buildings

## Mid-Rise and High-Rise Buildings

In buildings with more than five stories, the building frames receive custom structural engineering analysis and design attention. Experiences of the past 50 years indicate that these buildings do not collapse under wind loads, but the outside walls and roof structure can receive major damage. The best available refuge areas in these buildings are in the lower floors (basement if available) and in the central part of the building. Stairwells (particularly those with reinforced concrete walls) typically provide the best available refuge. If the stairwells have inadequate capacity for the occupant load, restrooms typically provide the next best available refuge areas.

## Large Stores and Movie Theaters

In large stores and movie theaters, the best available refuge areas will typically be restrooms, closets, or narrow storage areas. For example, in 2002, in Van Wert, Ohio, 50 people in a movie theater took refuge in restrooms when warned about an approaching tornado. The building collapsed, but no one suffered significant injury. In grocery stores, if restrooms, closets, or narrow storage areas are not accessible, building occupants should crouch in narrow frozen food aisles between freezer cases and cover their heads. This tactic will reduce the likelihood of injuries from a falling roof. The aisles used should be as far as possible from exterior glass and masonry walls. Also, aisles with very tall storage racks should be avoided.

Again, the selection of refuge areas should always be verified with the checklists provided in FEMA publication 361.

# Conclusions

In regions of the United States subject to tornadoes, the identification of best available refuge areas within schools and other public buildings is essential for the safety of building occupants. Shelters specifically designed and constructed to resist wind-induced forces and the impact of windborne debris provide the best protection. However, findings from investigations of past tornadoes show that many buildings contain rooms or areas that may afford some degree of protection from all but the most extreme tornadoes (i.e., tornadoes ranked F4 or F5 on the Fujita Tornado Damage Scale—see Chapter 1). In buildings not designed and constructed to serve as shelters, the goal should be to select the **best available refuge areas**—the areas that will provide the greatest degree of protection.

A building administrator, working with a qualified architect or structural engineer, can select the **best available refuge areas** within a building. As discussed in Chapter 4, the selection must account for the required amount of shelter space, the layout and structure of the building, and potential missiles at and near the building site. In general, the **best available refuge areas** will meet the following criteria:

**Interior rooms.** Rooms that do not depend on the exterior walls of the building are less likely to be penetrated by windborne debris.

**Location below ground or at ground level.** Upper floors are more vulnerable to wind damage.

**A minimal amount of glass area.** Typical windows and glass doors are extremely vulnerable to high wind pressures and the impact of windborne debris.

**Reinforced concrete or reinforced masonry walls.** Reinforced walls are much more resistant to wind pressures and debris impact, but can fail if the roof deck is blown away.

**Strong connections between walls and roof and walls and foundation.** Walls and roofs will be better able to resist wind forces when they are securely tied together and anchored to the building foundation.

**Short roof spans.** Roofs with spans of less than 25 feet are less likely to be lifted up and torn off by high winds.

As illustrated in the case studies and selection procedure presented in this booklet, long central corridors often qualify as the **best available refuge areas** in a school building. In addition to having desirable structural characteristics (e.g., short roof spans, minimal glass area, and interior locations), corridors usually are long enough to provide the required amount of refuge area space and can be quickly reached by building occupants. Other potential refuge areas include small interior storage rooms, restrooms, and offices.

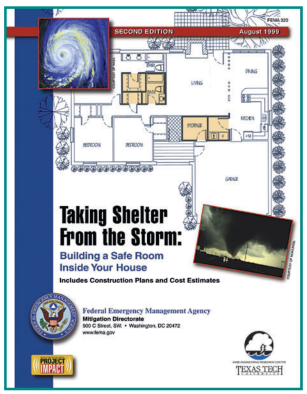
Building administrators should also consider increasing the resistance of existing rooms or areas within a building whenever repairs or reconstruction are necessary. In high-risk areas, it may be prudent to perform remedial work (such as that noted on page 54) without waiting for other repairs or reconstruction to become necessary. As discussed in Chapter 3, the modifications made to the Kelly Elementary School during reconstruction after tornado damage are an excellent example of what can be done to improve the wind resistance of a school and provide shelter areas.

In conclusion, it is particularly important for building administrators and building occupants to be aware that the best available refuge areas do **not** ensure the safety or survival of their occupants. They are simply the areas of a building in which survival is most likely. To provide a high reliability of safety, a shelter area must be intentionally designed and constructed as a shelter. Refer to FEMA publication 361, *Design and Construction Guidance for Community Shelters*, for shelter performance criteria, sample construction plans, and other detailed information.

# Information Sources

**Additional information about tornado shelters is available from the Federal Emergency Management Agency (FEMA).**

## FEMA Publications

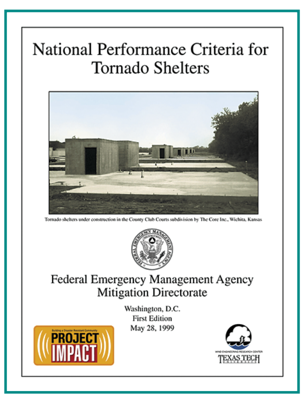



FEMA 320

FEMA

***Taking Shelter From the Storm – Building a Safe Room in Your House***
FEMA Publication 320, August 1999

This illustrated, full-color booklet is intended for homeowners and contractors. It explains the hazards posed by severe winds associated with tornadoes and hurricanes, includes maps and charts for assessing tornado risk, presents shelter design criteria, and includes estimated costs and detailed construction drawings for several types of in-residence shelters.




FEMA NPC

FEMA

***National Performance Criteria for Tornado Shelters***
August 1999

The performance criteria presented in this booklet are intended for design professionals, shelter manufacturers, building officials, and emergency management officials. The issues addressed include resistance of shelter walls, ceilings, and doors to wind loads and missile impacts; shelter size, ventilation, lighting, and accessibility; and multihazard (e.g., flooding and earthquake) effects. The criteria form the basis for the construction of tornado shelters that will provide a consistently high level of protection.

### *Building Performance Assessment Team Report, Midwest Tornadoes of May 3, 1999*

FEMA Publication 342, October 1999

This illustrated, full-color report presents the observations and conclusions of the Building Performance Assessment Team (BPAT) deployed by FEMA after the May 3, 1999, tornadoes in Oklahoma and Kansas. The report describes the tornado damage; assesses the performance of residential and nonresidential structures, including tornado shelters; and presents recommendations for property protection, building code enforcement, and residential and group sheltering.

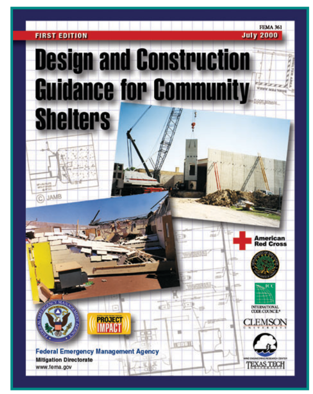

FEMA

***FEMA 342***

### *Design and Construction Guidance for Community Shelters*

FEMA Publication 361, July 2000

This illustrated manual is intended for engineers, architects, building officials, and prospective shelter owners. It explains tornado and hurricane hazards, presents shelter design criteria based on performance requirements and human factors, and outlines emergency management considerations for community shelters. Also provided are site assessment checklists that can be used in the selection of shelter areas in existing buildings; case studies that include wind load analyses, costs, and construction drawings; and the results of laboratory tests of shelter construction materials.




FEMA

***FEMA 361***

For more information about FEMA publications, wind hazards, and wind shelters, visit the FEMA website at **www.fema.gov**.

FEMA

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