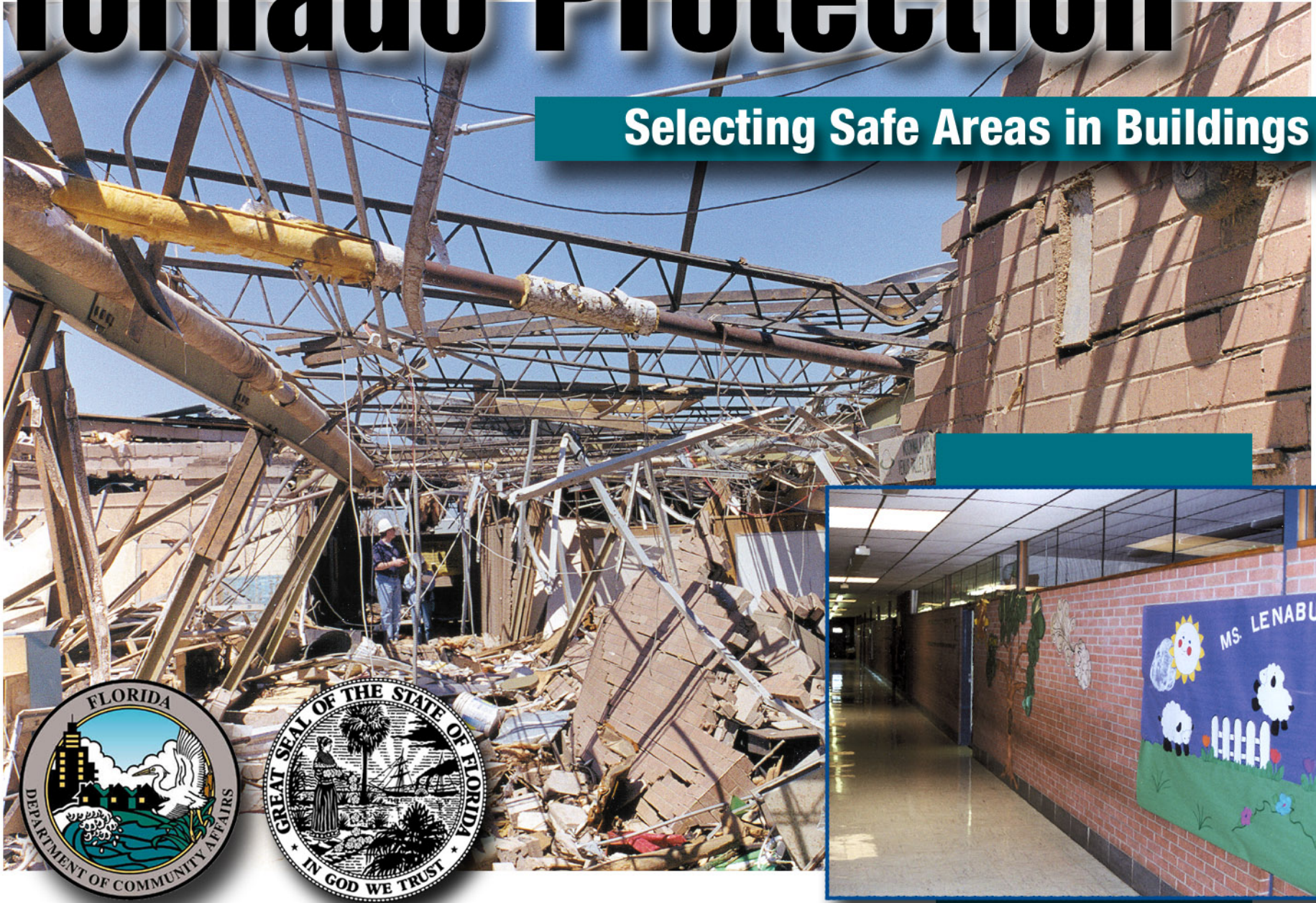


Tornado Protection

Selecting Safe Areas in Buildings



Florida Department of Community Affairs
Tallahassee, Florida

March 2002

About the Cover

The large photograph on the cover shows the remains of a central corridor in the Kelly Elementary School, in Moore, Oklahoma. The extreme damage shown 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 areas of refuge in schools and other buildings.

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Foreword

Tornadoes and extreme winds cause heavy loss of life and property damage throughout the United States. Most schools and other public buildings include areas that offer significant 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 examinations, guidance has been developed for selecting the best available shelter areas in existing buildings.

The guidance presented in this booklet is intended primarily to assist building administrators, but will also help architects and engineers design new buildings that are intended to offer protection from extreme winds.

Building administrators, architects, and engineers are encouraged to apply this guidance so that the safety of building occupants will be increased.

Introduction

The likelihood that a tornado will strike a building is a matter of probability. Tornado damage to buildings is predictable.

Administrators of buildings should know where the safest places in their buildings are—the portions that would offer protection if a tornado strikes. Most buildings offer a significant amount of protection for normal occupancy.

A trained architect or engineer can determine those portions of a building that will offer the greatest protection to occupants when a tornado strikes. This conclusion is based on site examinations of, and research concerning, tornado damage to school buildings conducted by teams of structural engineers, architects, building scientists, and specially trained members of architectural and engineering faculties and firms.

Architects and engineers should be able to use the information in this booklet to design buildings that offer higher levels of protection against high winds caused not only by tornadoes but also by hurricanes and other severe storms.

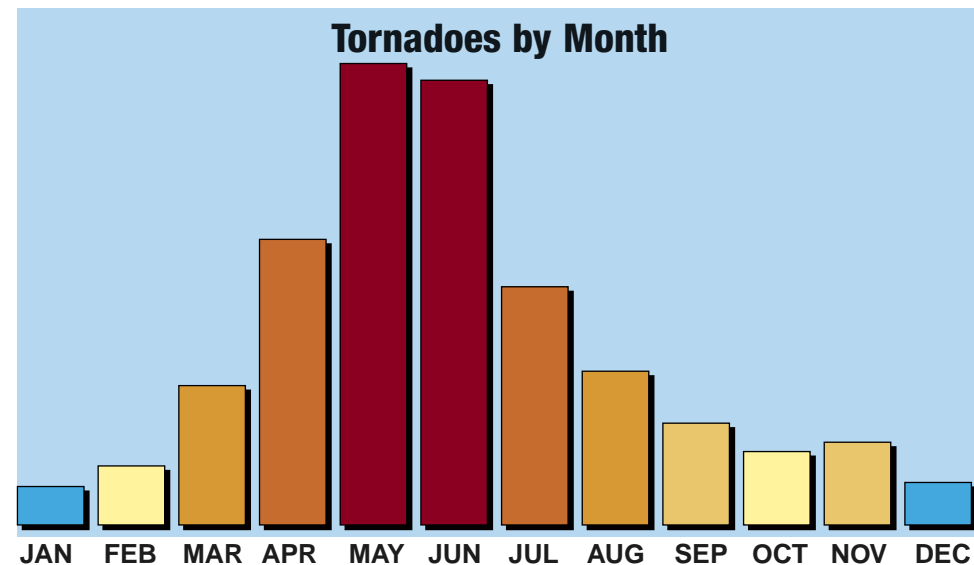
The Wind Engineering Research Center at Texas Tech University provided much of the substance of this booklet. Dr. Kishor Mehta of the Center assisted in the preparation and review of the material. Invaluable assistance was provided by the architects and engineers of the buildings presented as case studies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



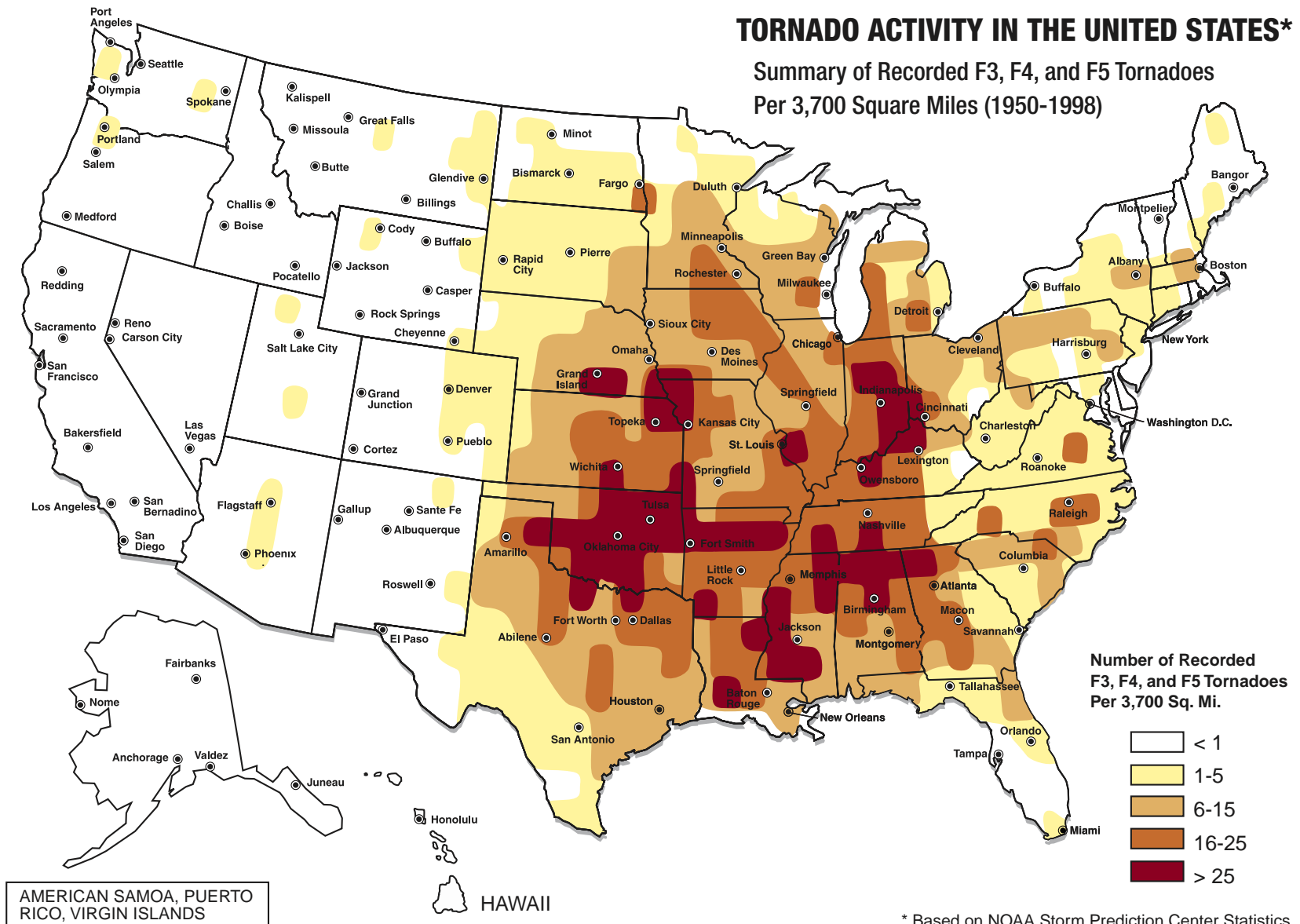


Figure 1-2 Tornado occurrence in the United States based on historical data.

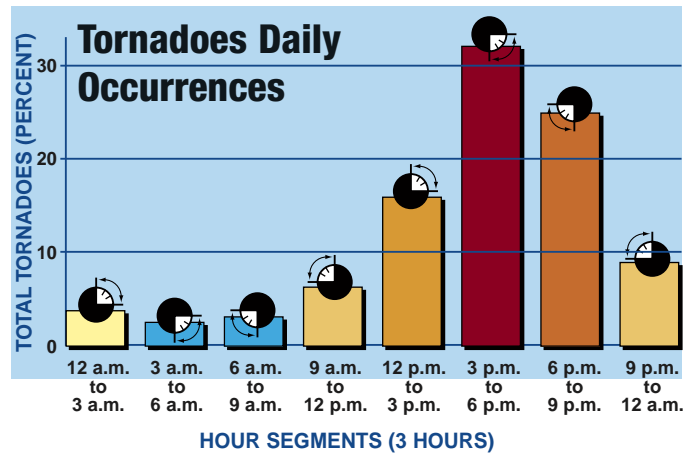


Figure 1-3 Tornado occurrence by time of day.

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.

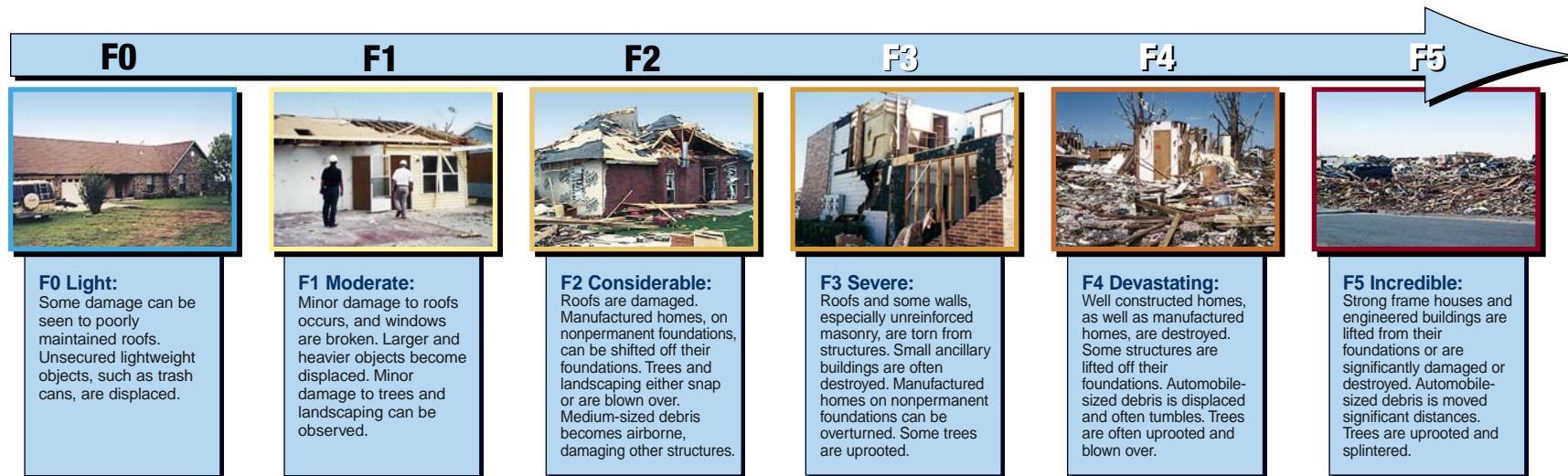


Figure 1-4 The Fujita Tornado Damage Scale.

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).

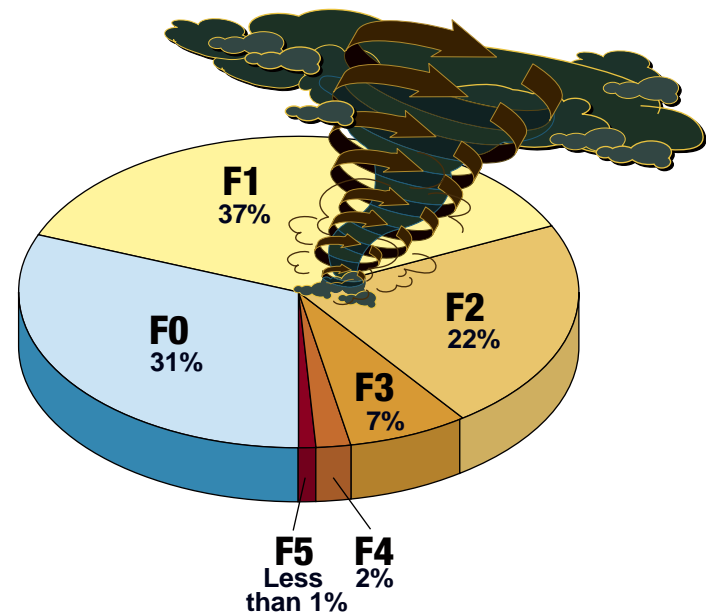


Figure 1-5 Percentage of recorded tornadoes by Fujita Tornado Damage Scale ranking.

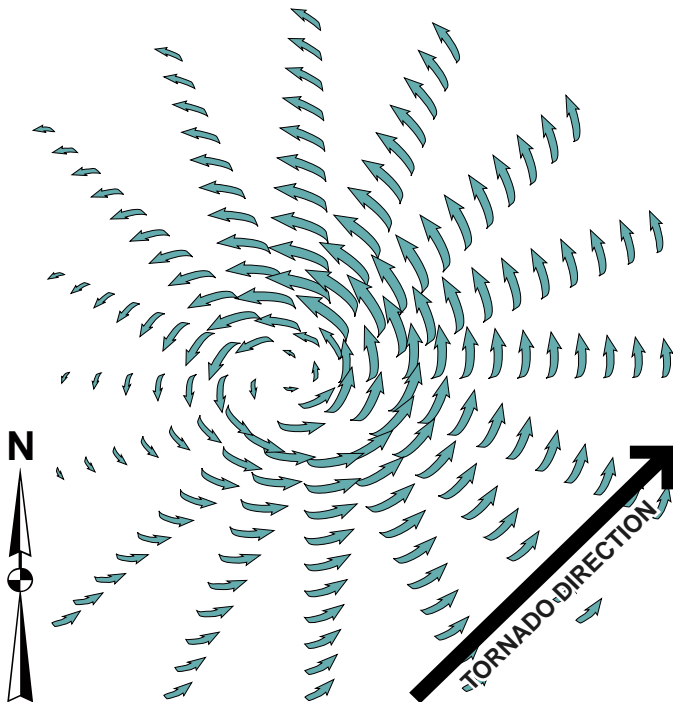


Figure 1-6 Typical tornado rotation.

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. Tornado damage to buildings can occur as a result of the following:

- 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 the building, the outward-acting pressure increases as the building geometry forces the wind to change direction. These pressure increases create uplift on the building parts, forcing the building apart. 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.

Building materials that have a better chance of surviving extreme winds are heavy (such as reinforced masonry or concrete) and are tied to all other building components with sound connections that resist the large uplift forces. Lightweight roofing materials such as gravel, wood, insulation, shingles, and even single-ply roofing membranes can 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

The design of shelter space, either within a larger building or as a standalone structure, must consider the effect of a difference between the pressures inside and outside the building. The pressure outside a building during a tornado is very low compared to the pressure inside. In most buildings, there is enough air leakage through building component connections to equalize these pressures.

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. Doors and windows should remain closed on all sides of the building during an event in order to minimize the amount of wind that can enter the building.

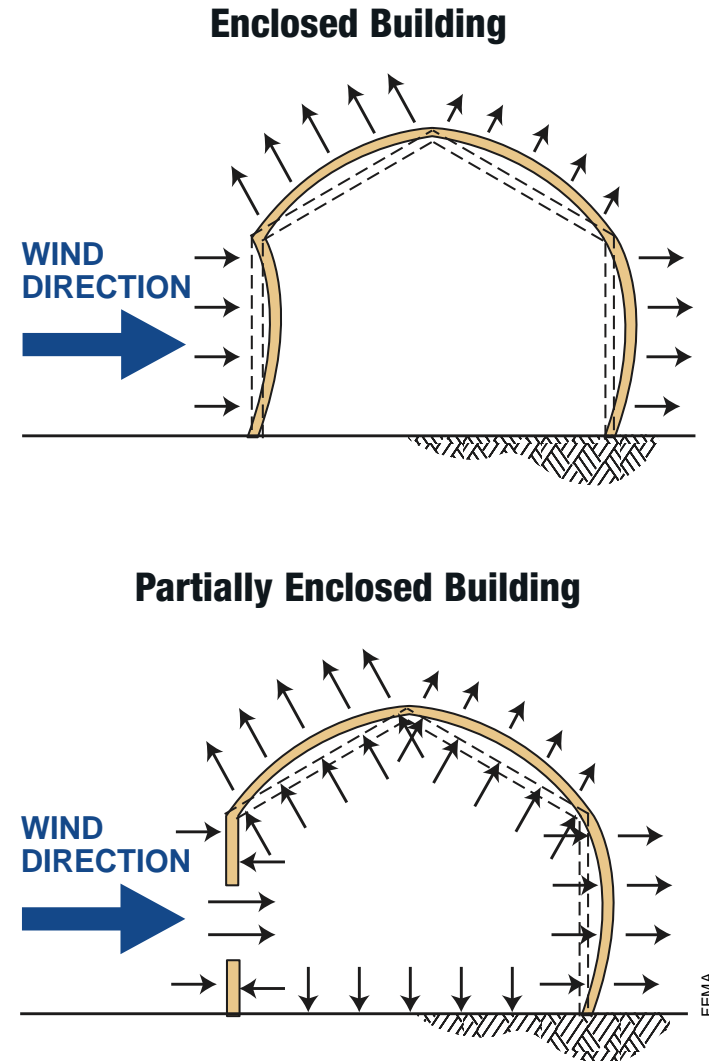


Figure 2-1 Effects of wind on a fully enclosed building and on a building with openings.

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



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Figure 2-3 Example of damage from windborne missile. Metal door pushed inward by impact of 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 become windborne debris capable of causing collateral damage to buildings. Light objects become flying missiles that can penetrate doors, walls, and roofs; heavier objects usually roll and cause crushing-type damage.

Missiles can travel vertically as well as horizontally (see Figure 2-4). For the safety of shelter occupants, protection must be provided overhead as well as on the sides of the shelter. 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 missile. Medium and small missiles penetrating through the roof of a high school.

Building Safe Spaces

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 on large shelters to develop a shelter selection guide for any building intended for use as a shelter. Many buildings contain a smaller interior area or areas that could possibly be converted or reinforced for shelter use.

The selection of shelter areas in buildings is discussed in Chapter 4.

Case Studies

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 relatively new structures at the time the tornadoes struck, 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 shelter 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

The identified shelter 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 be left standing after a tornado—before the tornado strikes
- to help architects and engineers design buildings that offer occupants excellent tornado protection at little or no additional cost

Xenia Senior High School

Xenia, Ohio

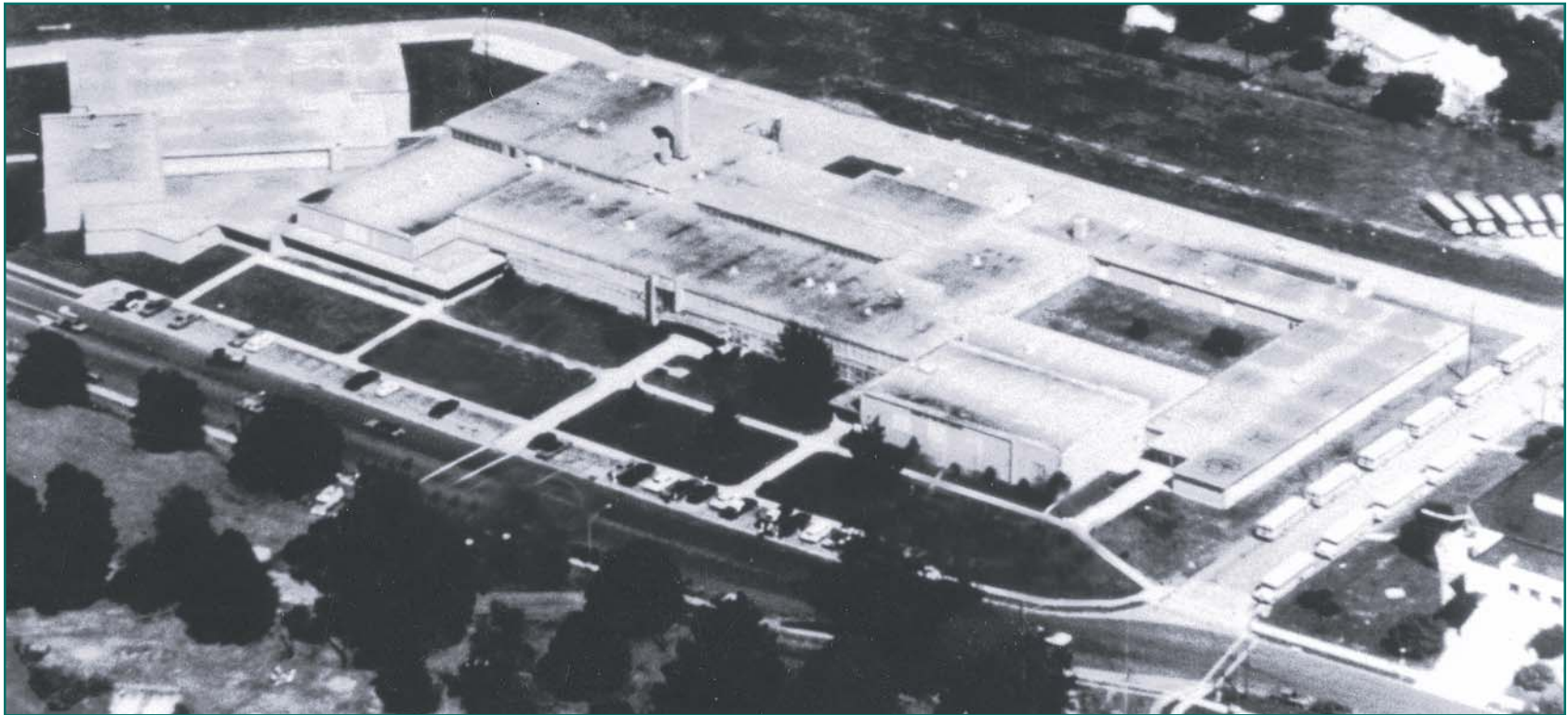
Building population: 1,450, including staff
12 students, 3 staff in building during storm

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):

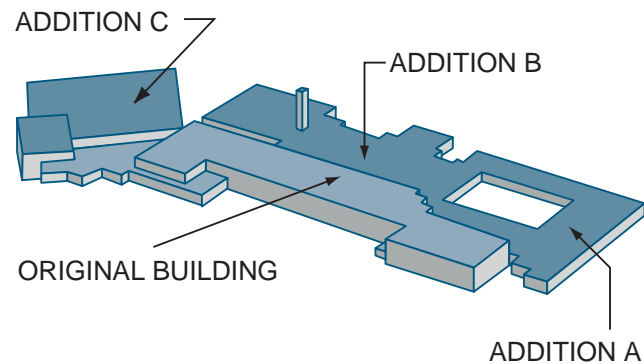
Original building and addition B: Lightweight steel frame, open-web steel joists, 2-inch gypsum roof deck.

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.



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 shelter 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 shelter 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 shelter space existed in scattered locations throughout the building (Figure 3-4).



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

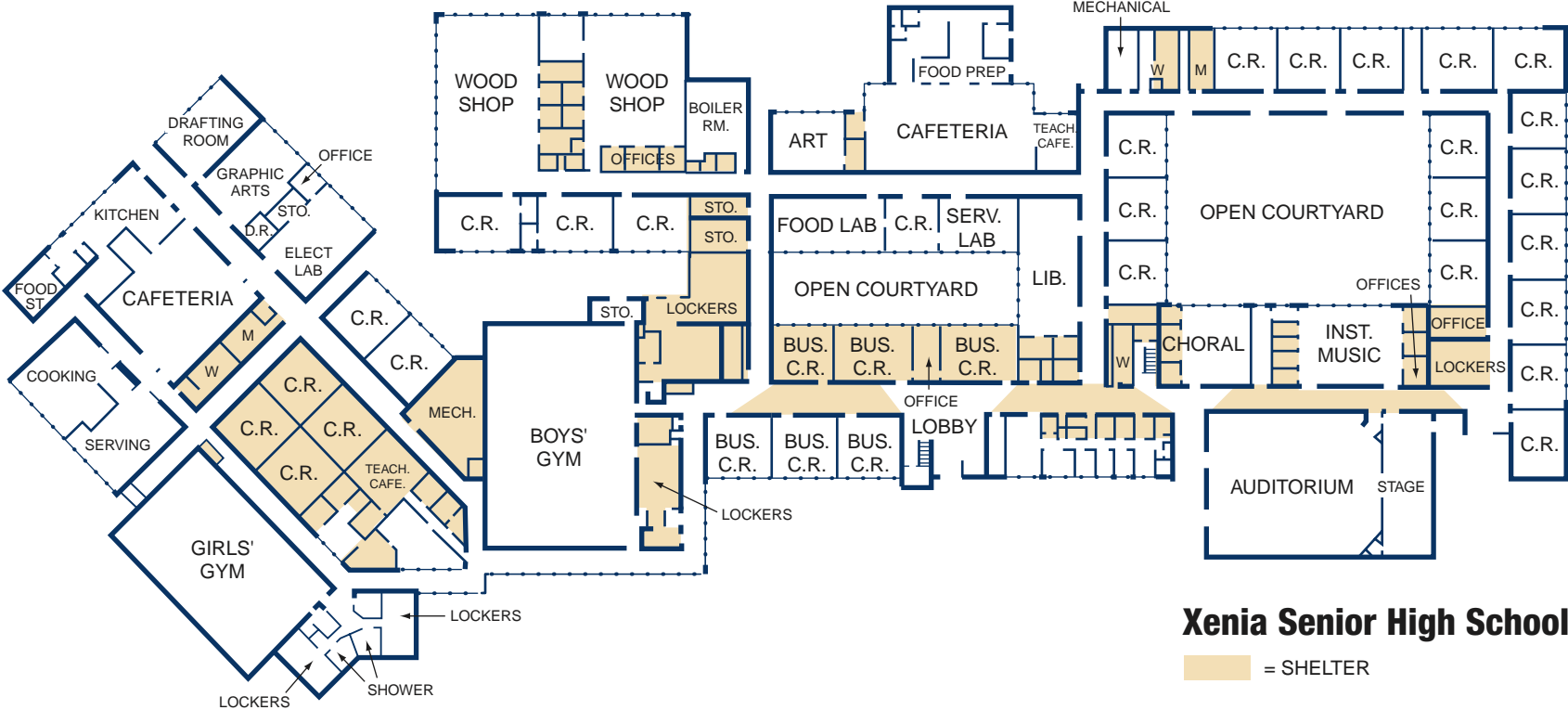


Figure 3-4 Best available shelter areas in Xenia Senior High School.

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



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 2½ 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)

Chapter 3: Case Studies

"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
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



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 shelter in a janitor's closet on the first floor and escaped injury.

Construction

The structural system consisted of 3-foot wide masonry piers of 8-inch concrete block 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 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 remained 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.



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

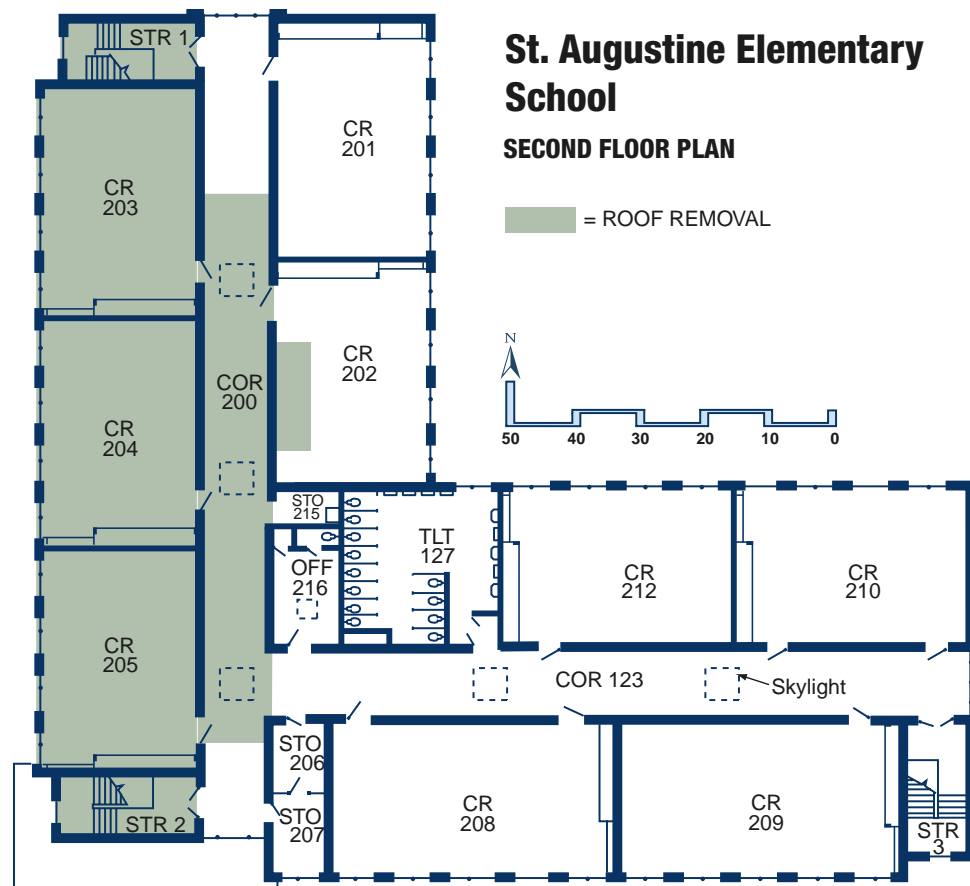


Figure 3-10 Floor plan of second floor of St. Augustine Elementary School showing locations of roof removal.



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** remained 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).

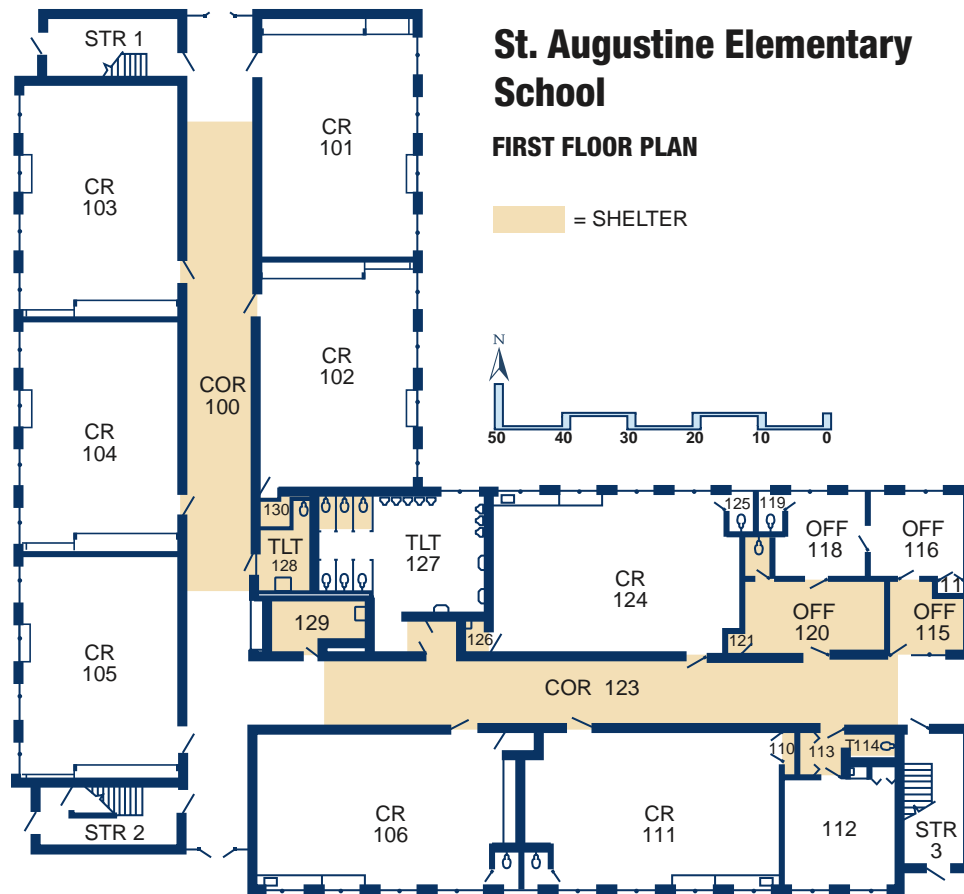


Figure 3-12 Best available shelter areas in the St. Augustine Elementary School building.

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 of 12-inch concrete block 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 corrugated steel roof deck was connected to joists with puddle welds.



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. The lower floor (in two-story or higher buildings) generally provides good protection for occupants when there are two or more walls between the shelter area and the outside.



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



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.

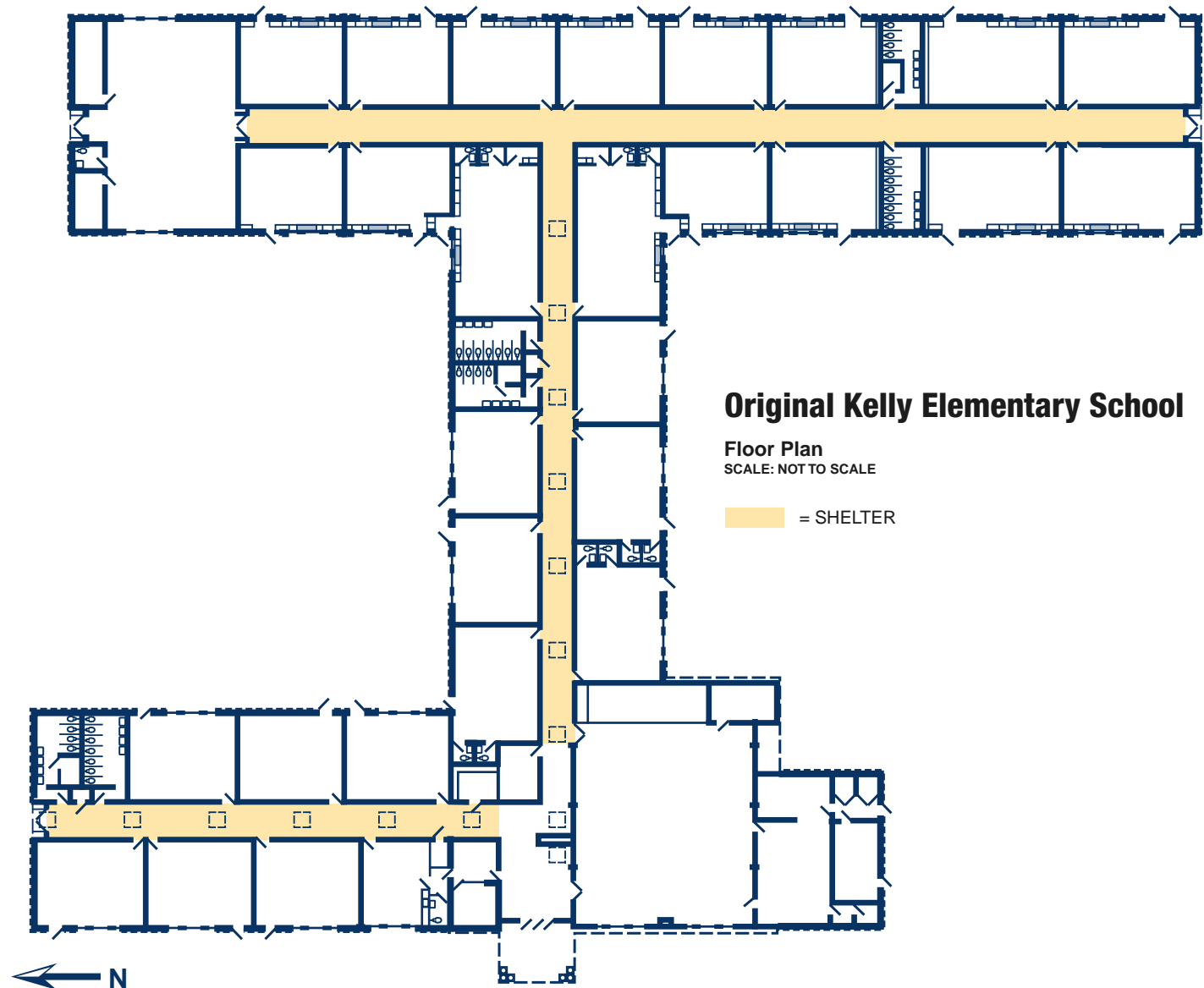


Figure 3-16 Designated shelter areas in the original Kelly Elementary School.

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).



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



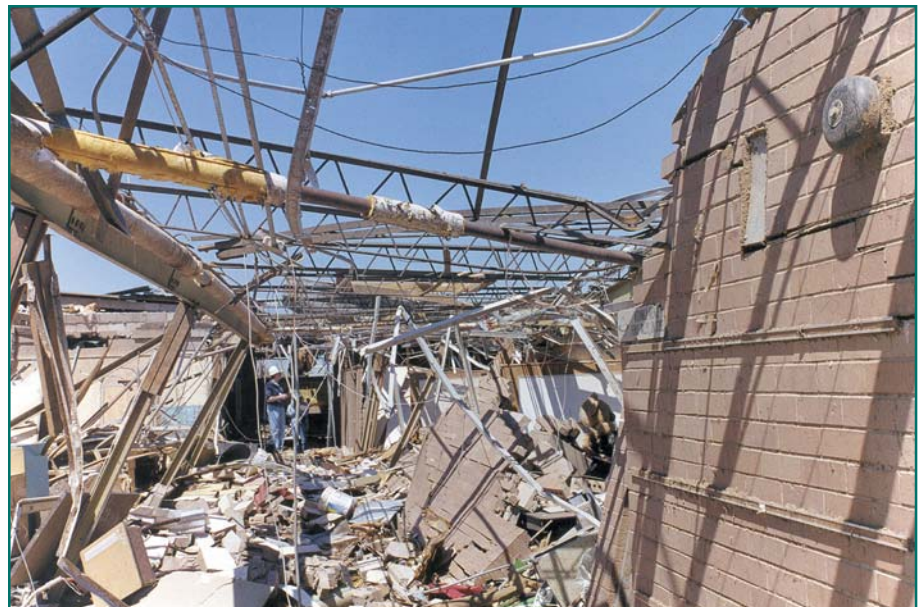
Figure 3-18 Corridor area. Separation of reinforced bond beam (indicated by circles) from supporting wall.

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.



FEMA

Chapter 3: Case Studies

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 3-22 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 3-21 Failed roof structure showing broken welds between metal roof deck and tops of joists (upper circle) and lack of vertical reinforcement (bottom circle).



Figure 3-22 Damaged door pushed in by impact of heavy windborne debris.

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 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 shelter areas for the school's occupants. As in the original building, the central corridors of the three wings are the designated shelter areas (Figures 3-23 and 3-24).

The creation of shelter 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

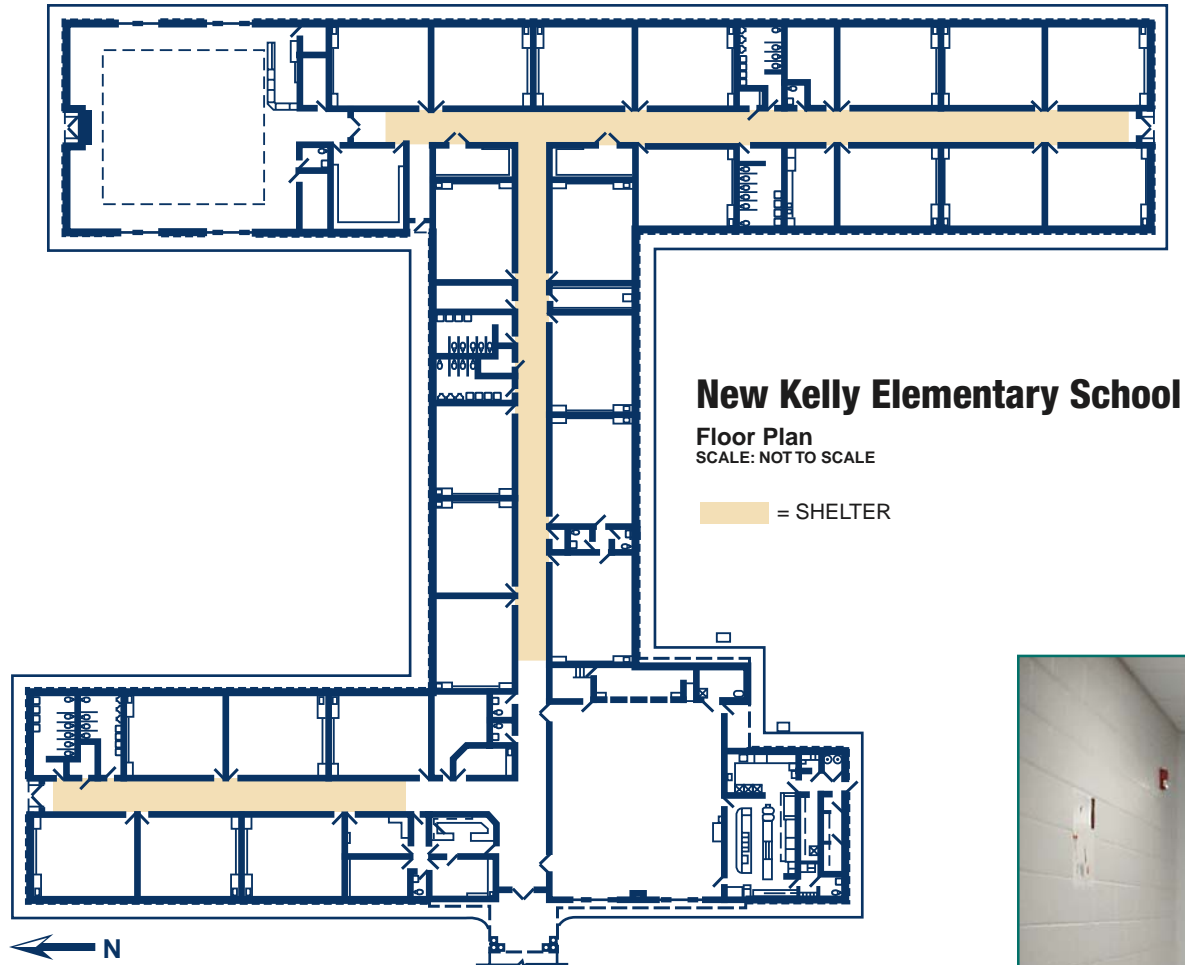


Figure 3-23 Designated shelter areas in the reconstructed Kelly Elementary School.



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

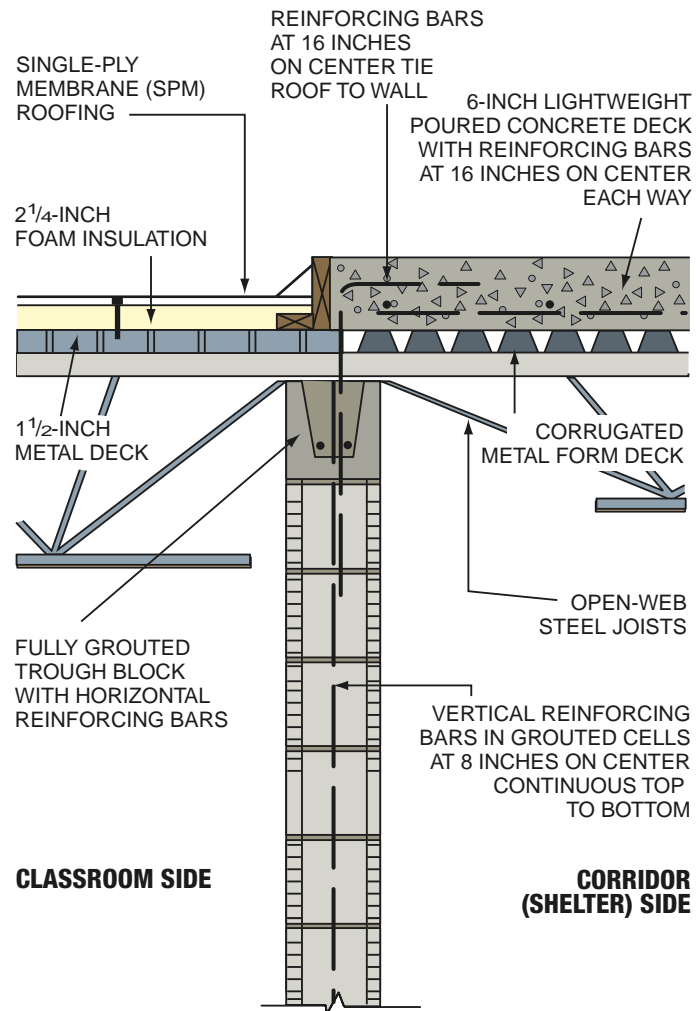


Figure 3-25 Typical cross-section of top of safe area wall in the reconstructed Kelly Elementary School.

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 shelter areas can be incorporated into new construction.

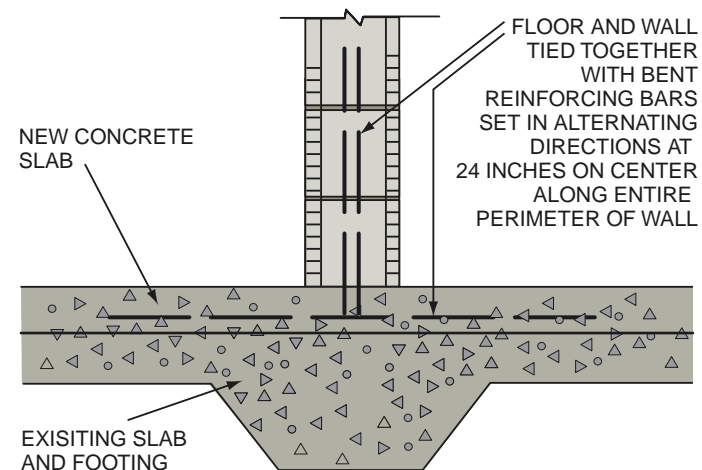


Figure 3-26 Typical cross-section of bottom of safe area wall in the reconstructed Kelly Elementary School.

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 the most resistant to severe winds, referred to in this booklet as the **most resistant areas available**. When used as shelters during severe-wind events, these areas do not guarantee safety; they are, however, the safest areas available for the protection of 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 areas of many buildings can survive these lesser events without catastrophic damage or collapse. Placing building occupants in the **most resistant areas available** within a building greatly reduces the risk of death or injury.

Selecting the **most resistant areas** involves three main steps:

- **assessing the surrounding site** to identify potential windborne missiles or collapsible structures
- **determining how much shelter space is required** to house building occupants and determining where the shelter area(s) must be located to minimize the time required for people to reach shelter
- **reviewing construction drawings and inspecting the building** to identify the strongest portion(s) of the building

Assessing the site and determining the required shelter space are relatively straightforward tasks that can be completed by many people. The drawing review and building inspections are more technical in nature. Structural engineers may need to be consulted for those tasks.

Assess the Site

Inspect the entire site and its surroundings to identify potential windborne missiles. The types and locations of potential missiles should be noted on a site plan that shows the building and its surroundings. (An example of a site plan is shown in the Assessment Example presented later in this chapter.)

When identifying missile sources, keep in mind that stronger tornadoes create larger missiles. An F0 tornado can create missiles out of roof gravel, but it takes a much stronger storm to create missiles out of automobiles. Look for trash containers, air conditioning units, athletic field equipment, portable classrooms, storage sheds, parking areas, and anything else that can be picked up and carried by the wind. Check all roofs on the building and note any gravel ballast, vents, and roof-mounted equipment. Identify tall communication towers, chimneys, and trees that could topple under high winds. Keep in mind that, during stronger tornadoes, tall structures can not only topple but also be lifted and thrown by high winds.

While tornadoes can create strong winds from all directions, most move from the southwest to the northeast and have a diameter of 300 to 500 feet. Therefore, particular attention should be paid to identifying missile sources south and west of the building and within a 300- to 500-foot radius from the building. Often, potential missiles can be removed or secured to alleviate the risk of their becoming windborne. At a minimum, identifying potential missile sources will help identify the best shelter areas.

Determine Required Amount of Shelter Space

Shelter 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.

Example Shelter Space Calculation

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 shelter space involves identifying all groups of occupants and their shelter 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 shelter space could be provided by a total of 375 feet of 8-foot-wide corridor or by a combination of smaller areas.

Shelter space requirements vary according to the age of the shelter 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.

The shelter space must also be readily accessible to all building occupants. FEMA 361 recommends that shelter areas be situated so that all occupants can reach them within 5 minutes. In larger buildings, it may be necessary to provide several shelter areas so that travel times are minimized. Building oc-

cupants with special needs, such as wheelchair users, may require additional time to reach the shelter.

Review Construction Drawings and Inspect 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.

Determining the most resistant areas available 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 resistant areas that are less prone to failure during a tornado.

Protective Elements

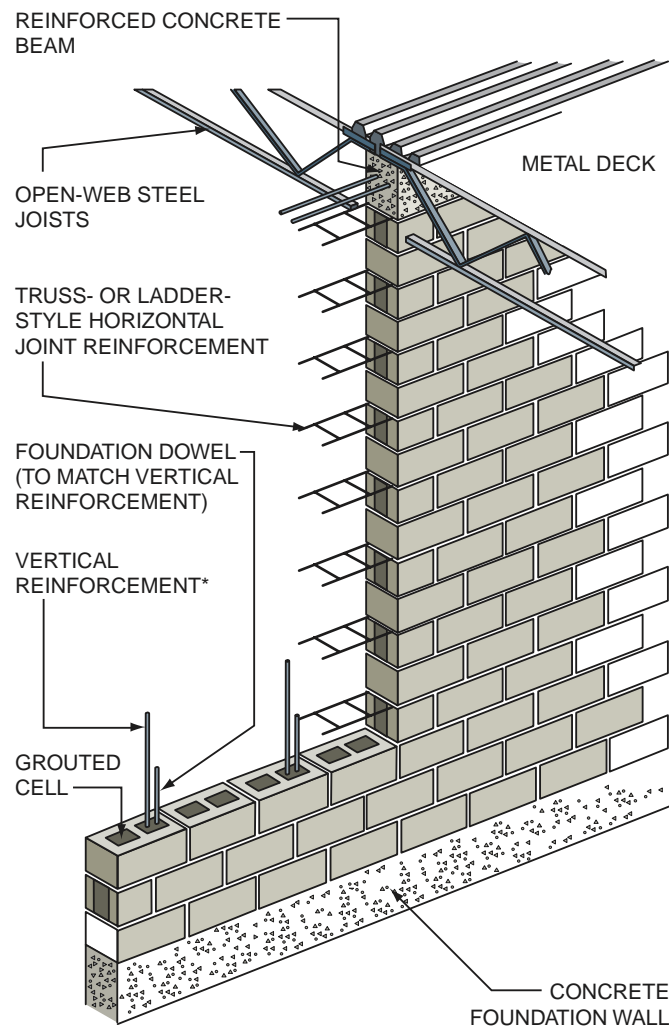
The **lowest floor** of a building is usually the safest. Upper floors receive the full strength of the winds. Occasionally, tornado funnels hover near the ground but hit only upper floors. **Belowground space** is almost always the safest location for shelter. If a building has only one floor and no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

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 internal partitions that contain windows.

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.

For hurricane shelters, the Red Cross limits roof spans to 40 feet. Because tornadoes can produce much higher winds, the 40-foot criterion should be considered an absolute maximum unless an engineering analysis determines that the roof system is adequate. Preferably, tornado shelters 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 reinforced masonry construction.

2. **Short spans** on the roof (see sidebar) or floor structure usually remain intact. This is because short spans limit the amount of uplift caused by winds. Although short spans are best, small rooms, even those with walls that do not support the roof, are usually safe. If the roof rises and then collapses, the interior walls may become supporting walls and thereby protect the occupants.
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 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 reinforced masonry wall construction.

Hazardous Elements

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

1. **Long-span roofs** are almost always found on rooms with high ceilings. 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 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, 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.
3. **Heavier roofs**, especially precast concrete planks, 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.
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. Windows at the ends of corridors are particularly dangerous because high winds can blow them down the corridor. See the sidebar for information about window protection.
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.
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.

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 shelter area with large windows should be avoided. The presence of small view-windows, like those in many doors, should not preclude an otherwise satisfactory area from being used as a shelter. In those spaces, occupants should not take refuge within the potential path of debris from those windows.

Example of Shelter Area Assessment

The following example illustrates the methodology for assessing shelter needs and identifying the most resistant areas available.

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 Florida. As shown by the site plan in Figure 4-2, the school buildings consist 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 1,147 students, 49 faculty and administrative staff, and 3 maintenance workers and custodians. One of the students uses a wheelchair.

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 multi-purpose room (a cafeteria that doubles as an auditorium) are in Building 700. Figure 4-3 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, they are accessed from long, central, interior corridors. Figure 4-4 shows the floor plan of Buildings 200, 400, 600, and 800. One of the central corridors in these buildings is shown in Figure 4-5.

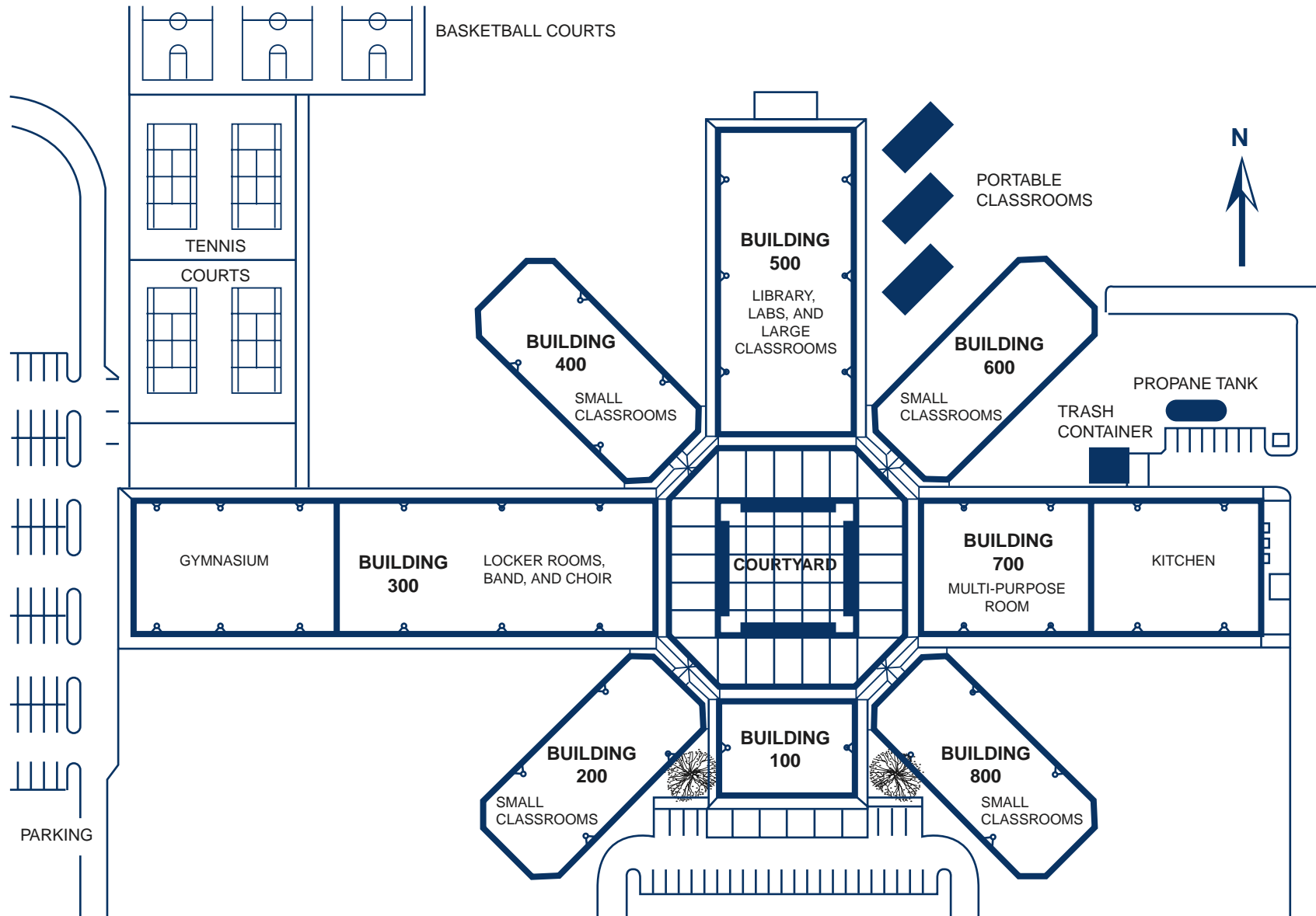


Figure 4-2 Site plan for example facility.

Figure 4-3 Floor plan of Building 500.

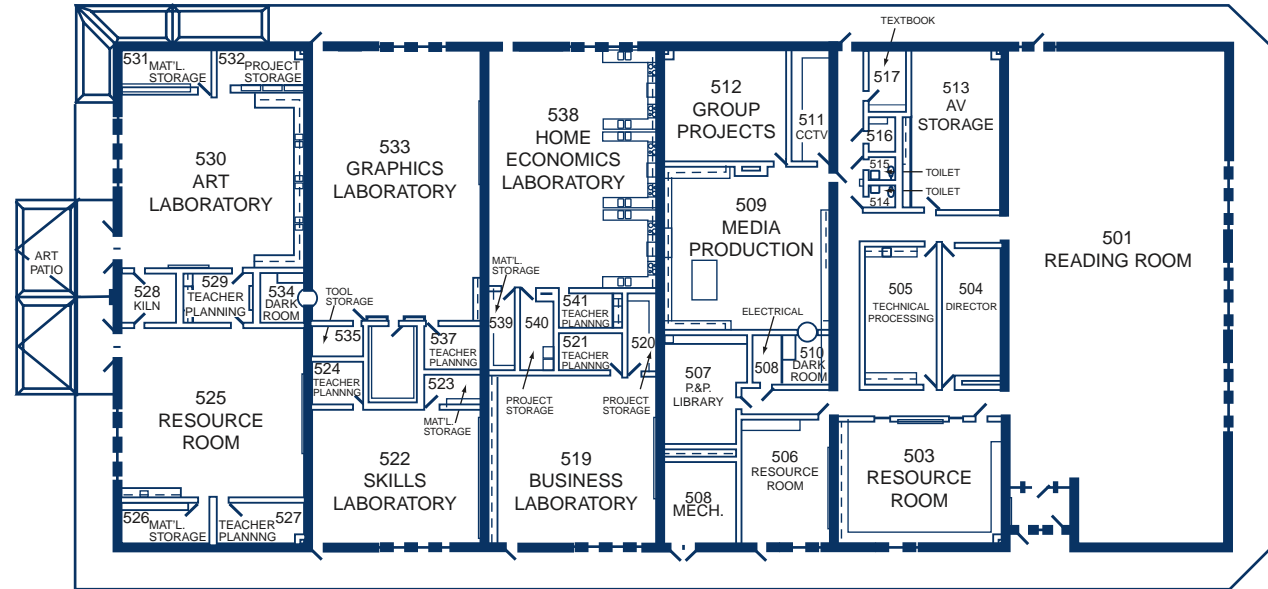


Figure 4-4 Floor plan of Buildings 200, 400, 600, and 800 (see Figure 4-6 for the wall cross-section at A-A).

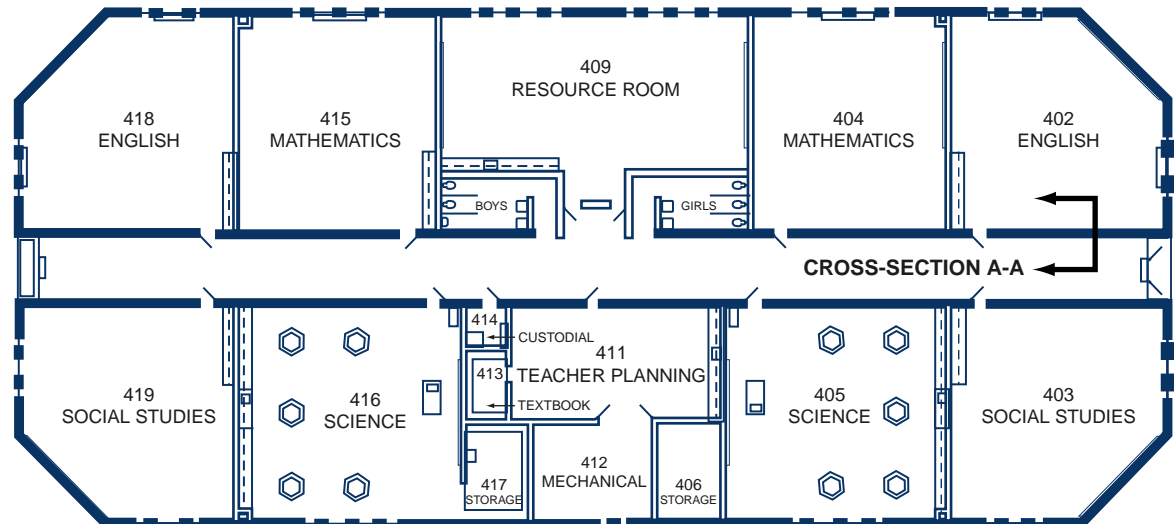




Figure 4-5 Interior central corridor – typical of Buildings 200, 400, 600, and 800.

In each of the eight buildings, exterior and interior loadbearing concrete block walls support the roof above. These walls are reinforced with vertical steel spaced at 2 feet 8 inches on center. Figure 4-6 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 4-4). The exterior walls include a brick veneer that is relatively resistant to the impact of small windborne 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.

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

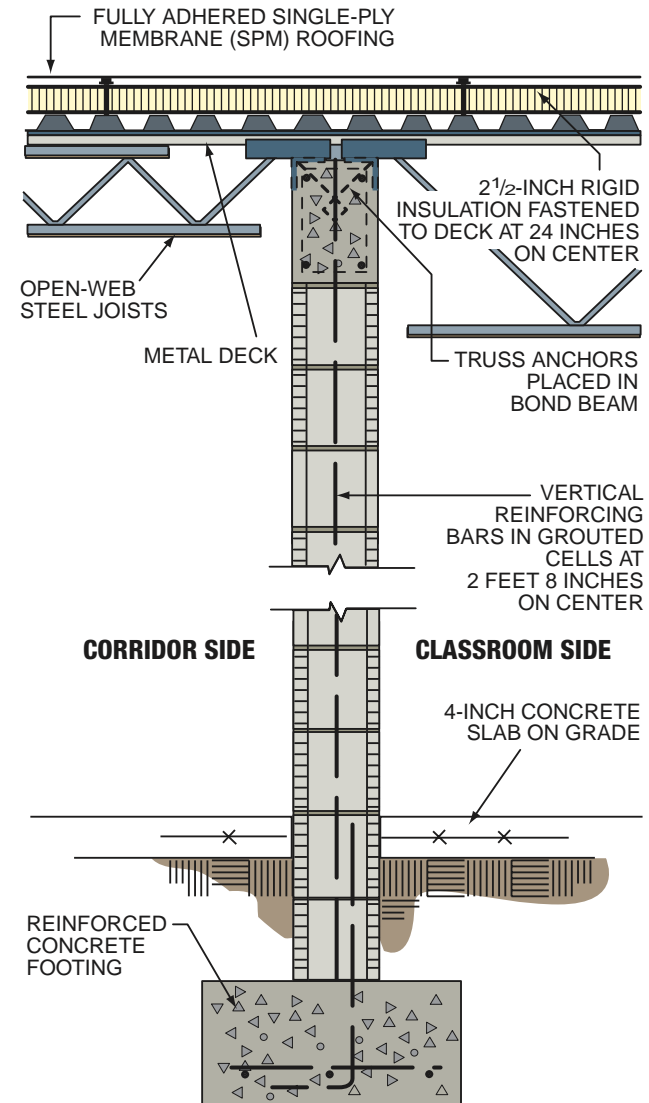


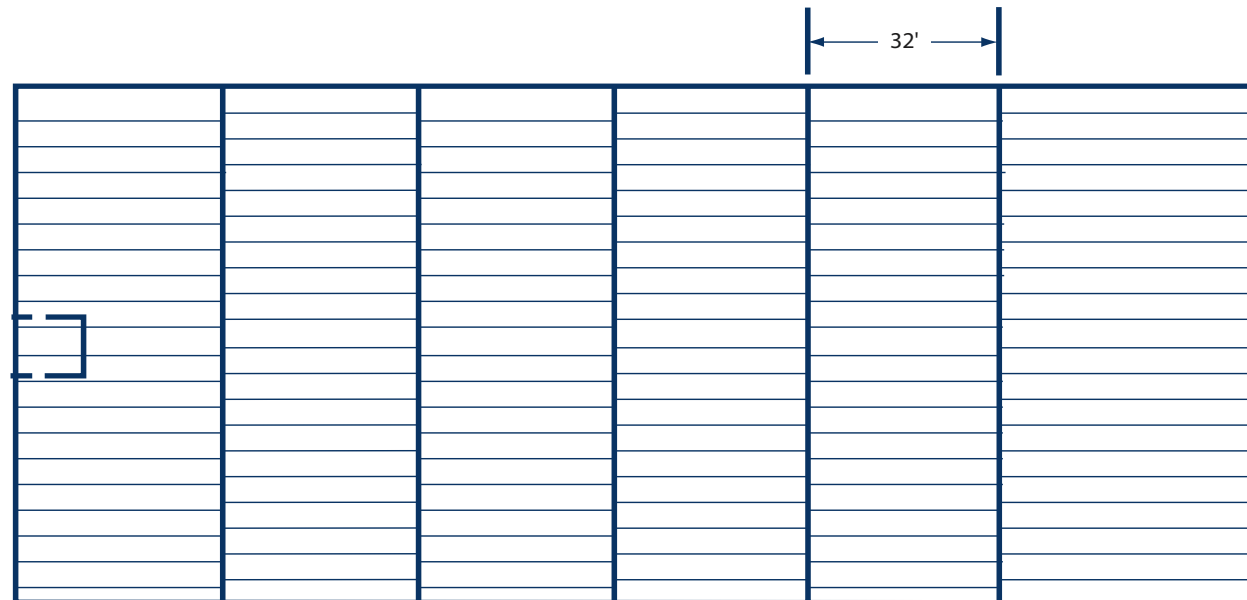
Figure 4-6 Cross-section A-A through corridor/classroom wall – Buildings 200, 400, 600, and 800 (see Figure 4-4 for location of A-A).

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, corrugated 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 4-7). 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. Separate roof joists span the 11-foot 4-inch-wide corridors (Figure 4-8). In all eight buildings, the roof joists are fastened to the tops of the masonry loadbearing walls with welded base plates and anchor bolts (Figure 4-9).

Figure 4-7 Roof framing plan for Building 500.



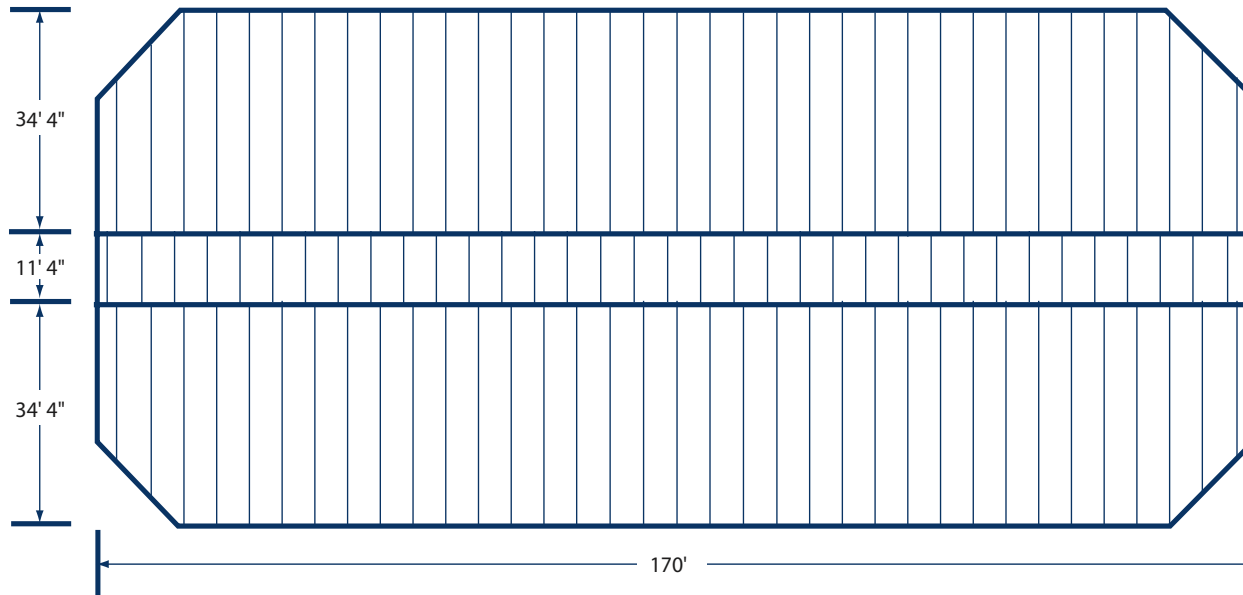


Figure 4-8 Roof framing plan for Buildings 200, 400, 600, and 800.



Figure 4-9 Typical roof truss connection to exterior wall in the example school.

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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 4-10)—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 4-11).

Figure 4-10 Exterior corridor doors in the example school.



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Required Shelter Space

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

1,146 Children @ 5 sq ft each	= 5,730 sq ft
52 Adults @ 6 sq ft each	= 312 sq ft
1 Wheelchair user @ 10 sq ft each	= 10 sq ft
Total = 6,052 sq ft	



Figure 4-11 Door connecting classroom to corridor – Buildings 200, 400, 600, and 800.

Identifying the Most Resistant Areas

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

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 4-12) offer the most resistant 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 the designated shelter areas.

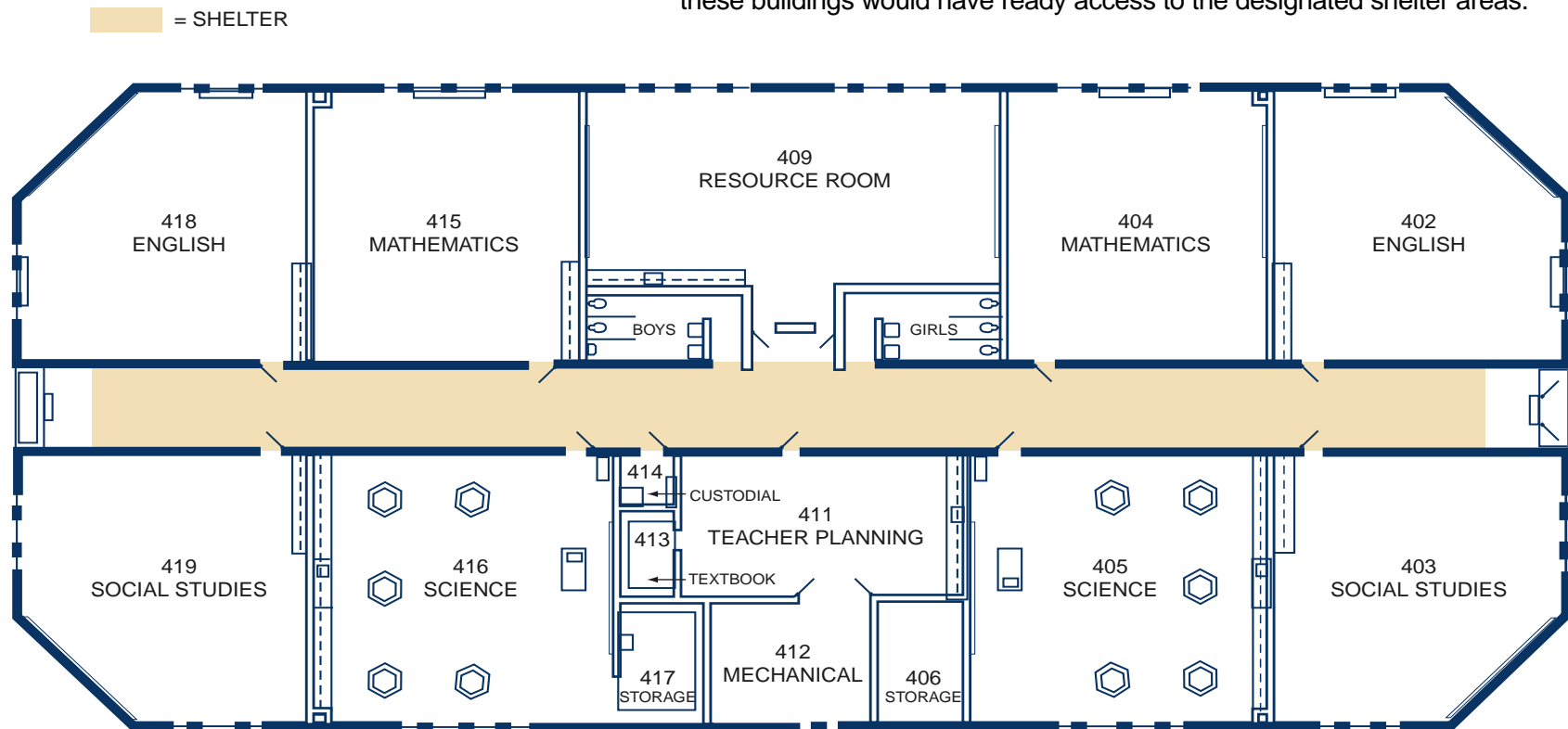


Figure 4-12 Best available shelter areas in the example school – corridors in Buildings 200, 400, 600, and 800.

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 shelter space**. Assuming that a 2-foot-wide clear area must be maintained to allow students and staff to access the shelter, each corridor can provide approximately 1,500 square feet of **usable shelter space**. The four corridors provide 6,000 square feet of usable area for sheltering. While slightly less than the recommended total area of 6,052 square feet, the available usable shelter space satisfies the intent of FEMA publication 361.

Although these corridors are the most resistant 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 shelter area (Figure 4-13). An alternative would be to install solid, wind-resistant doors that, although normally left open, could be closed when a tornado warning is issued. 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.

In many facilities, the size of the most resistant area available will be less than the required size determined according to the guidelines in FEMA publication 361. In such facilities, building occupants will need to be housed in either smaller areas or more vulnerable areas. While 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.

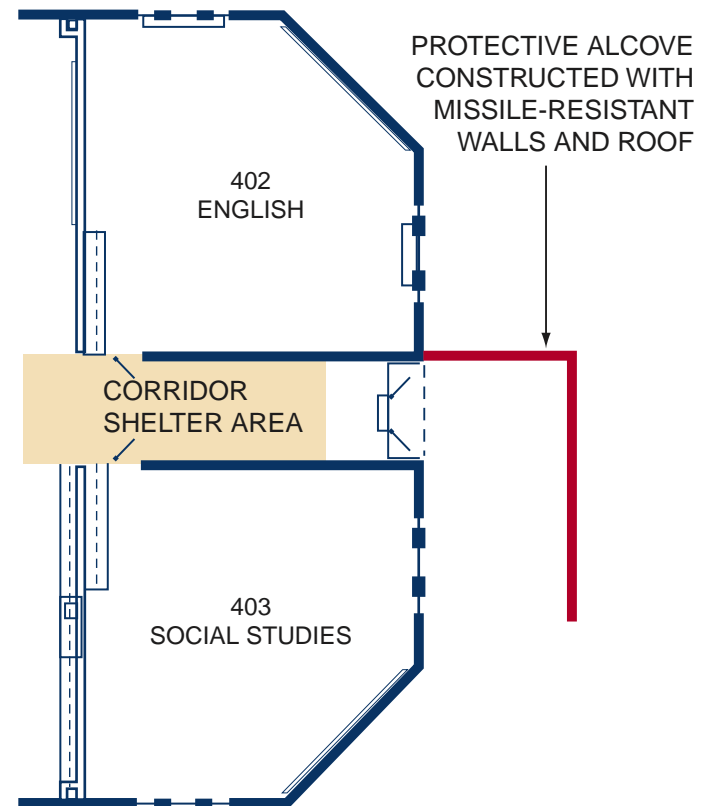


Figure 4-13 Corridor areas with glass exterior doors can be protected from wind and debris through the construction of a wind-resistant alcove.

Conclusions

In regions of the United States subject to tornadoes and other extreme winds, the identification of shelter areas within schools and other public buildings is essential for the safety of building occupants. Shelter areas 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 will 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 **most resistant areas available**—the areas that will provide the greatest degree of protection.

A building administrator, working with an architect or engineer, can select the **most resistant areas available** within a building. As discussed in Chapter 4, the selection must account for potential missiles at the building site, the required amount of shelter space, and the layout and structure of the building. In general, the **most resistant 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. 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.

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 **most resistant areas available** 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 shelter space and can be quickly reached by building occupants. Other potential shelter areas include small interior storage rooms and offices.

Building administrators should also consider increasing the resistance of existing rooms or areas within a building whenever repairs or reconstruction are 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.

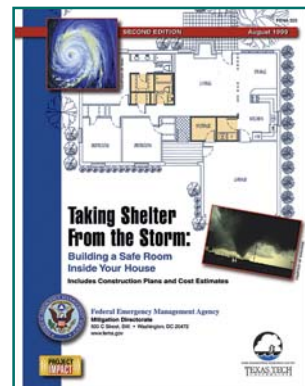
Information Sources

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

FEMA Publications

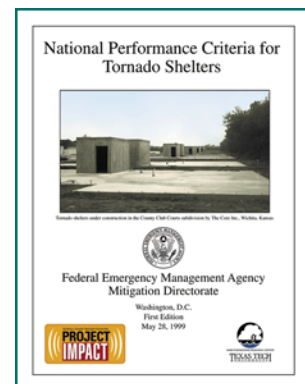
Taking Shelter From the Storm – Building a Safe Room in Your House
FEMA Publication 320, August 1999

This illustrated, full-color booklet is intended for homeowners and construction 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 320

FEMA



FEMA NPC

FEMA

National Performance Criteria for Tornado Shelters
August 1999

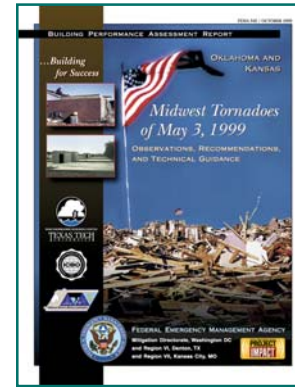
The performance criteria presented in this booklet are intended for design professionals, shelter manufacturers, building officials, and emergency management officials. The issues addressed include resistance of shelter walls, ceilings, and doors to wind loads and missile impacts; shelter size, ventilation,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

Information Sources

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 wind shelters; and presents recommendations for property protection, building code enforcement, and residential and group sheltering.



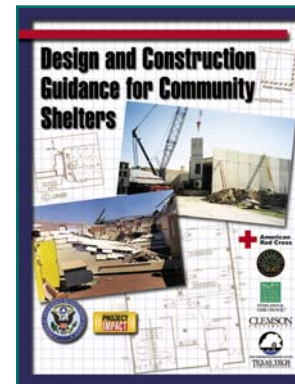
FEMA

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.



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



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