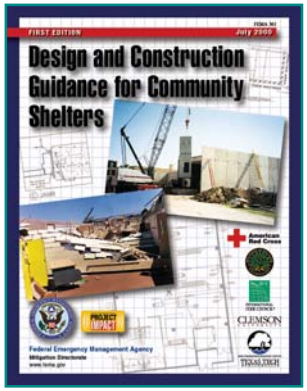
Case Studies



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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**).

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

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**

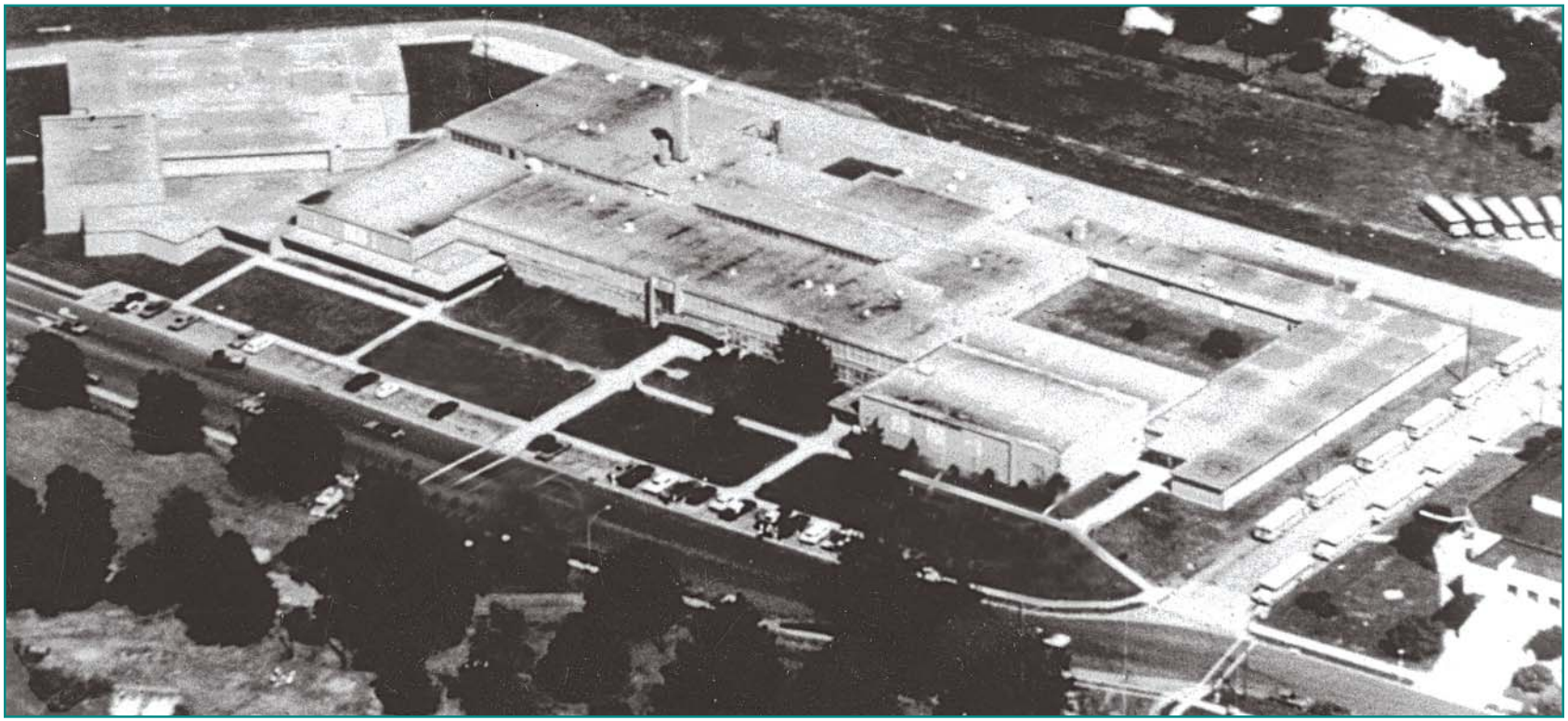

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Figure 3-1 Xenia Senior High School, Xenia, Ohio.

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):

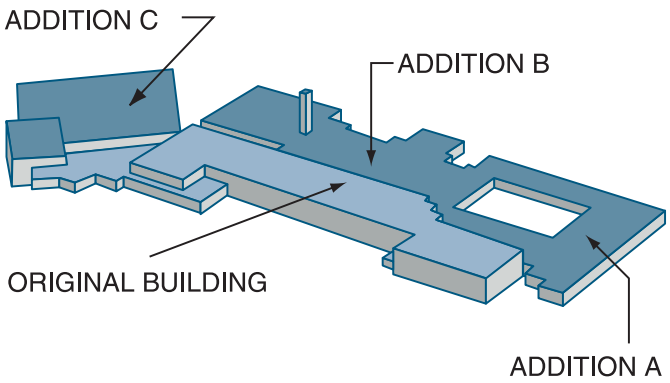
Original building and addition B: Lightweight steel frame, open-web steel joists, 2-inch gypsum roof deck.

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.

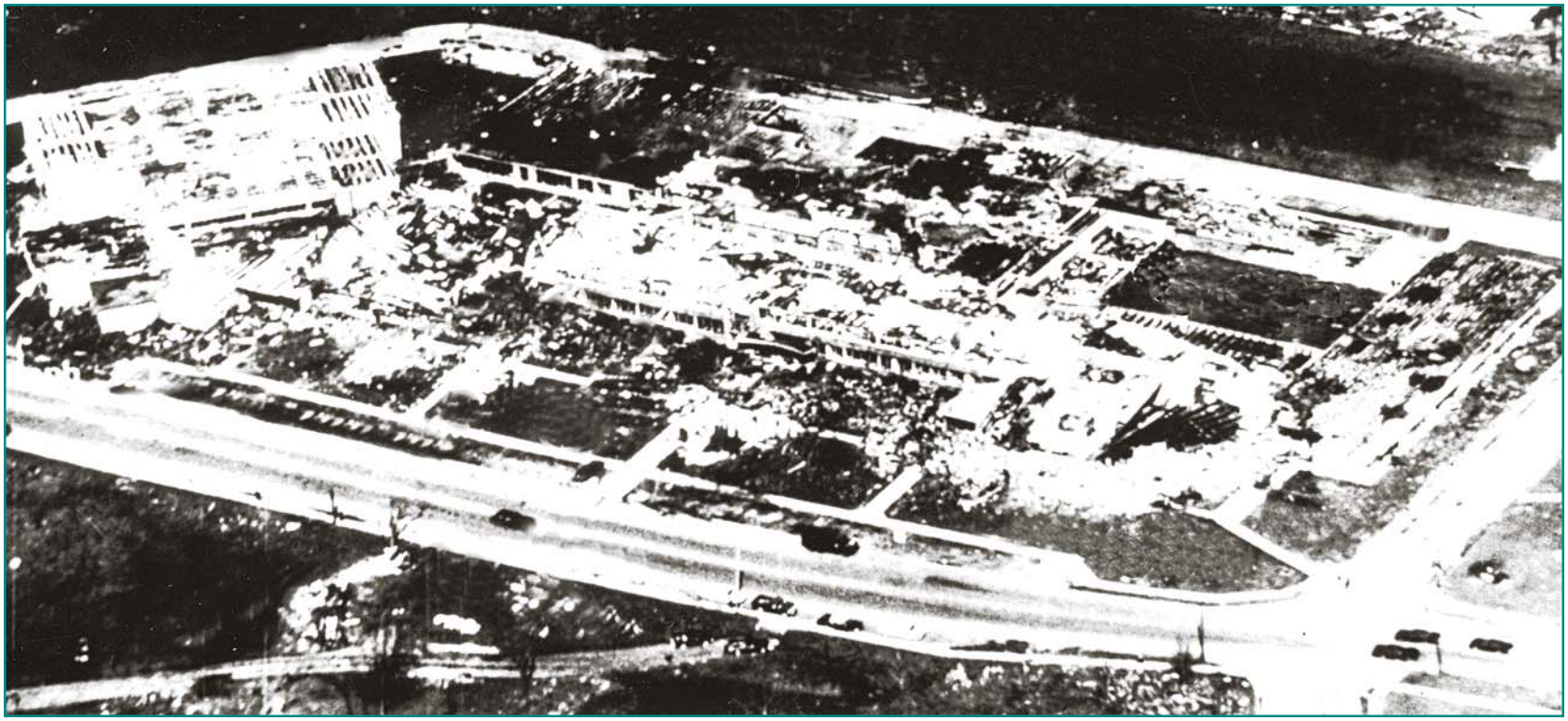


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Figure 3-2 Xenia Senior High School, Xenia, Ohio.

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.

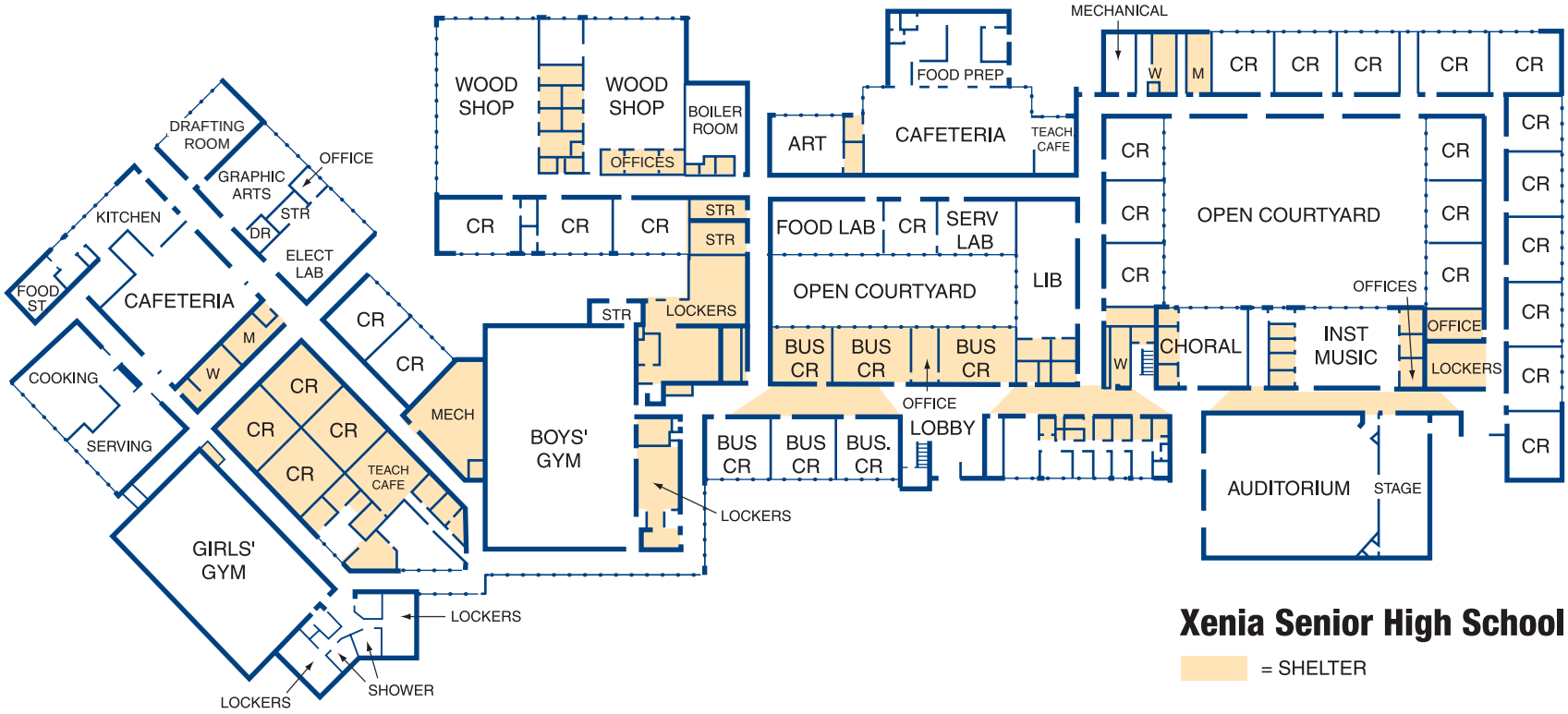

Figure 3-4 Best available refuge areas in Xenia Senior High School.

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**
	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.

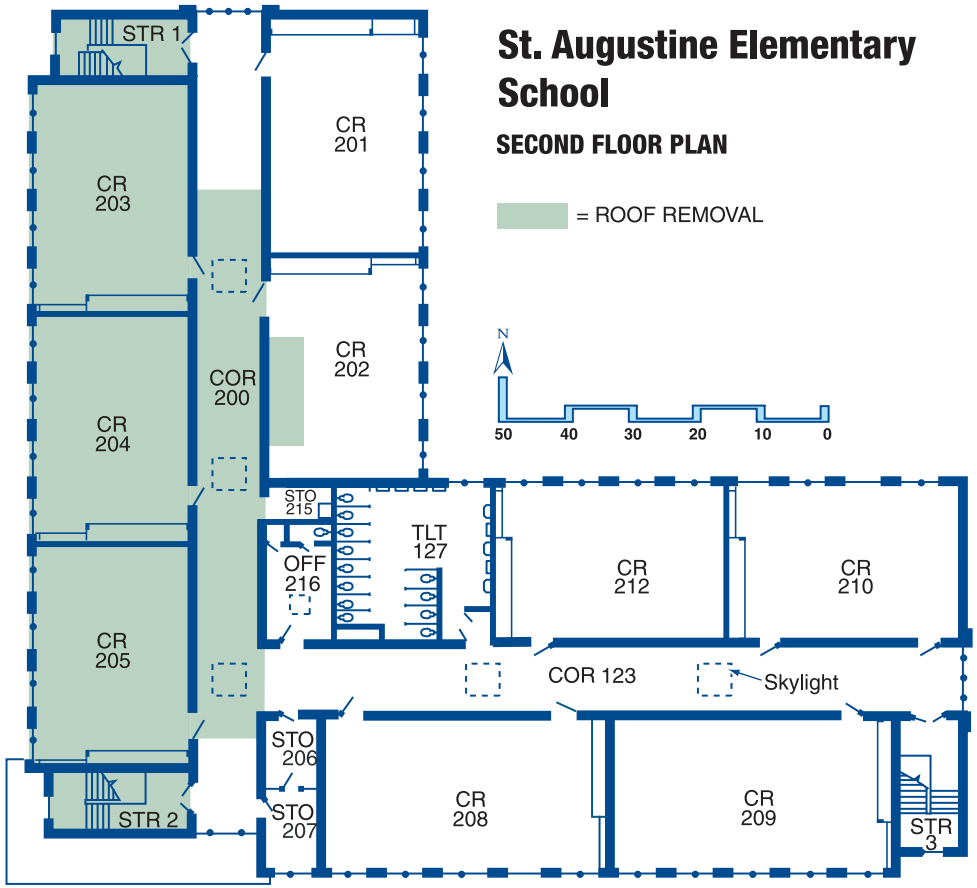

Figure 3-10
Floor plan of second floor of St. Augustine Elementary School showing locations of roof removal.

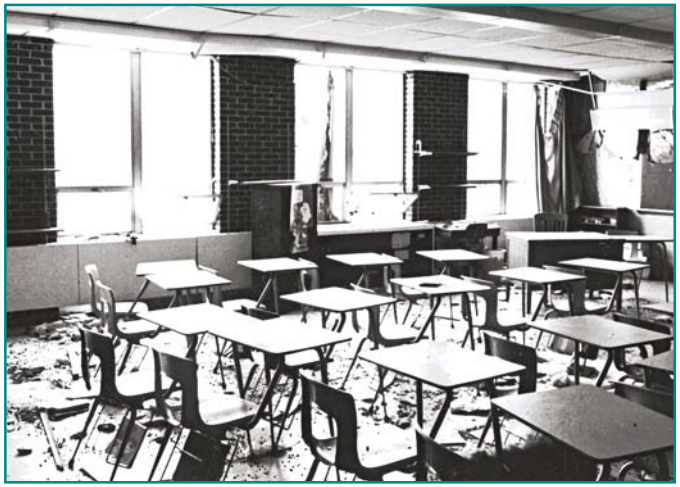

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Figure 3-11
Broken windows and debris in classroom of St. Augustine Elementary School building.

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).

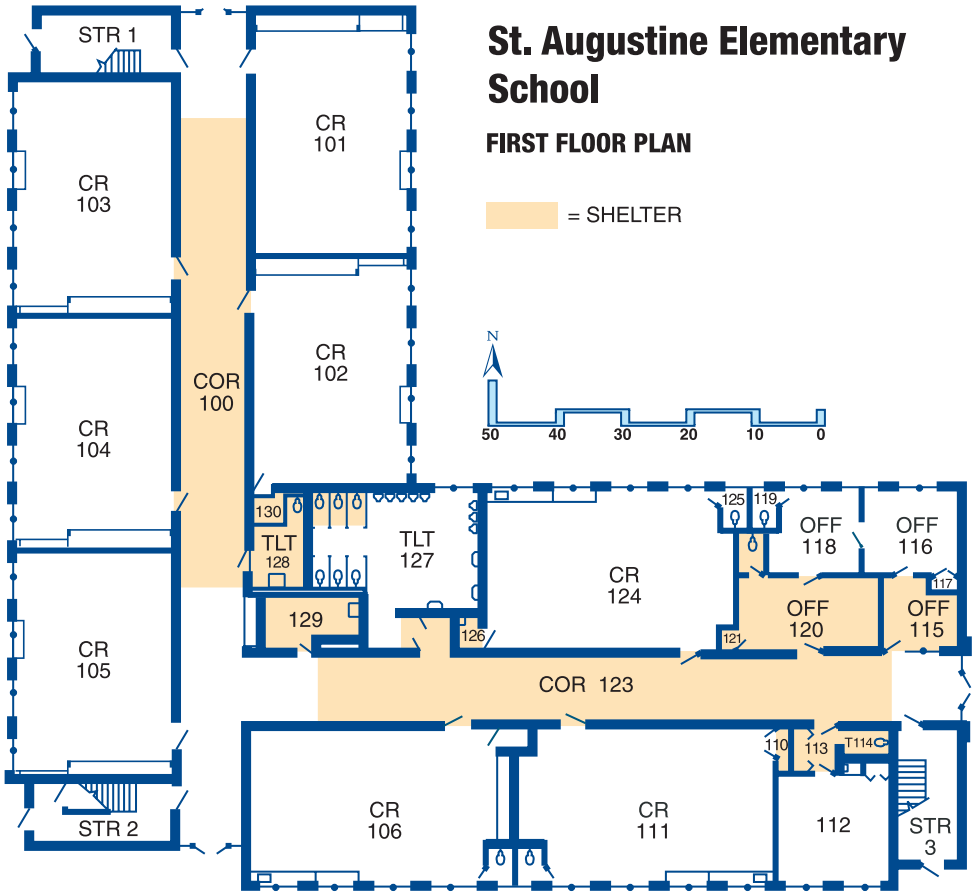

Figure 3-12
Best available refuge areas in the St. Augustine Elementary School building.

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.

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).

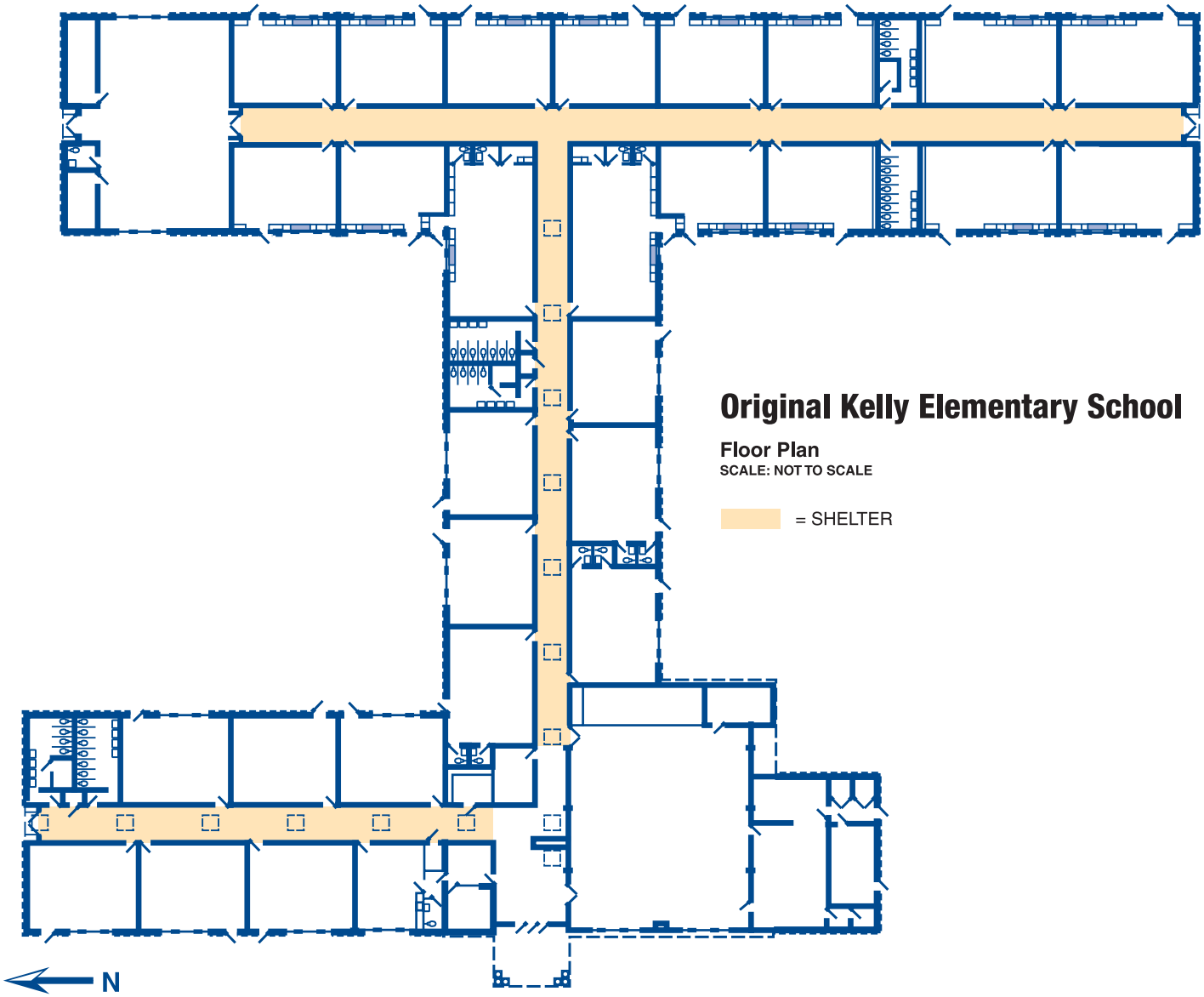

Figure 3-16 Designated refuge areas in the original Kelly Elementary School.

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.

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

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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

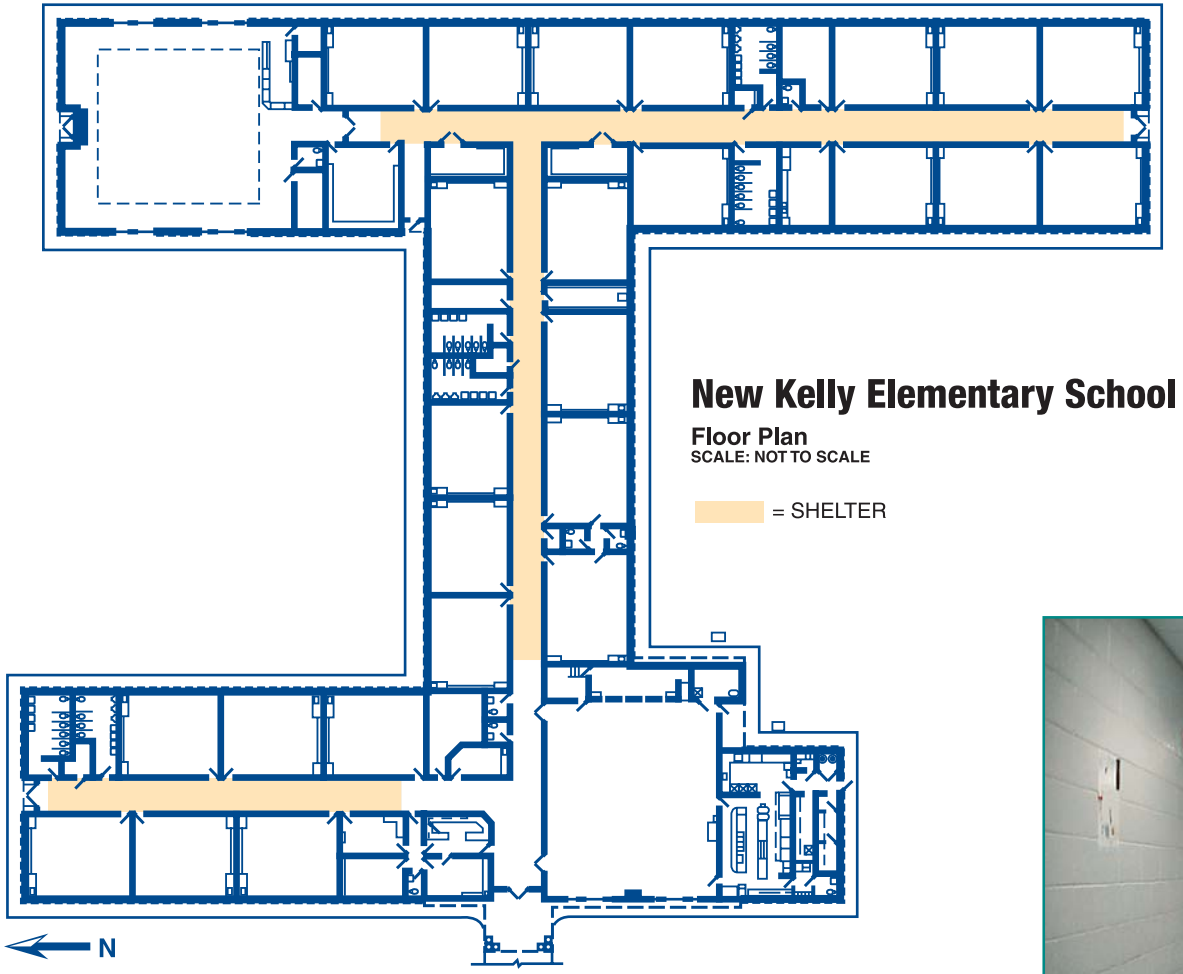

Figure 3-23
Designated refuge areas in the reconstructed Kelly Elementary School.

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.

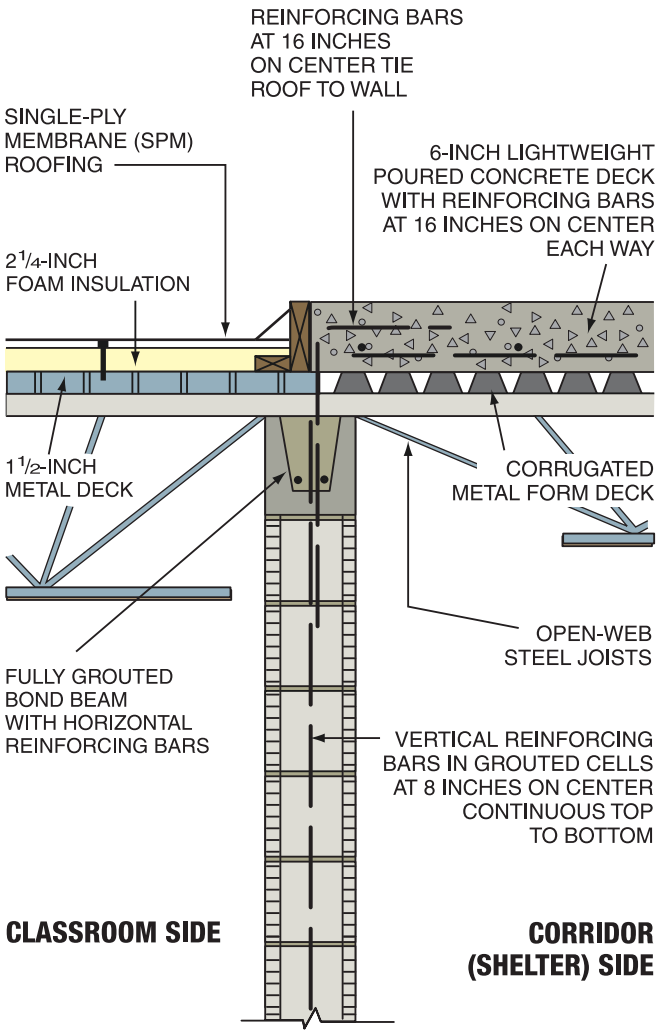

Figure 3-25
Typical cross-section of top of safe area wall in the reconstructed Kelly Elementary School.

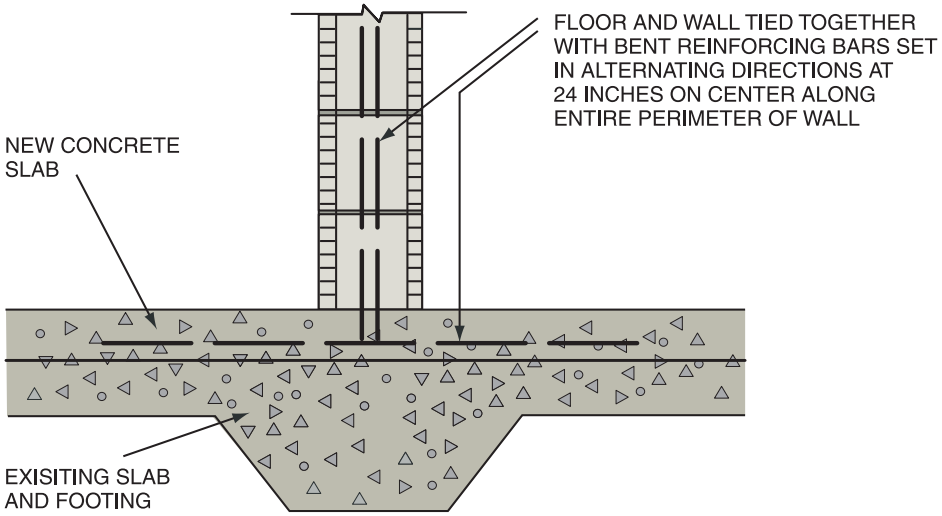

Figure 3-26
Typical cross-section of bottom of safe area wall in the reconstructed Kelly Elementary School.