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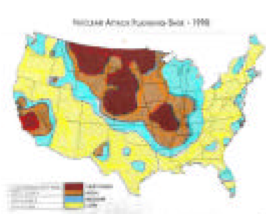
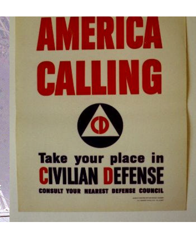
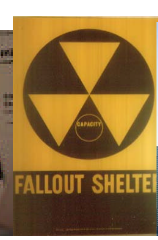






6 Performance Criteria for Debris Impact

Performance criteria for tornado and hurricane shelters will build on the design criteria in Chapter 5, the existing guidance for residential shelters, and the manuals and publications listed in Section 5.1.1. The most recent of these documents are the *National Performance Criteria for Tornado Shelters* (July 2000), ASCE 7-98, and FEMA 320. Although these documents do not address some factors and elements of the design of extreme-wind shelters, they provide the basis for the criteria presented in this chapter.

Chapter 5 of this manual and ASCE 7-98 present the information necessary for the computation of wind pressures and the loads imposed by winds on the walls, roof, windows, and doors of a shelter area. The walls, ceiling, floor, foundation, and all connections joining these elements will be designed to resist the pressures and loads calculated from the design wind speed without localized element failure and without separating from one another.

The entire shelter structure must resist failure from wind pressures and debris impacts. For the in-residence shelter designs presented in FEMA 320, ceiling spans and wall lengths were no greater than 8 feet and the design of the wall and ceiling was governed by the criteria specified for resistance to the impacts of windborne debris. For larger, community shelters, this broad statement cannot be made; the structural elements and the building envelope must be designed to resist wind-induced loads as well as impacts from debris.

6.1 Missile Loads and Successful Test Criteria

Although there is a substantial body of knowledge on penetration and perforation of small, high-speed projectiles, relatively little testing has been done on lower-speed missiles such as windborne debris impacting buildings. In the design of community shelters or other large shelters, wind loads are likely to control the structural design. However, C&C and building envelope issues may be governed by missile impact requirements. Nonetheless, after the shelter has been designed to withstand wind forces from the design wind speed, the proposed wall and roof sections must be tested for impact resistance from missiles. Roof and wall sections that have been tested for impact from the design missile are presented in Appendix E. A wall or roof section that is the same as the wall sections in Appendix E may be used without additional testing.

6.1.1 Propelled Windborne Debris – Missiles

The standard missile used for the impact tests discussed in FEMA 320 and those specified in FEMA's July 2000 edition of the *National Performance Criteria for Tornado Shelters* has remained unchanged. Although windstorms with wind speeds less than 250 mph typically result in lower missile speeds (for the same size missile), it is recommended that shelter designs be prepared for the missile size and wind speeds indicated in this section.

The standard missile used to determine impact resistance for all wind conditions is defined as follows (based on a representative missile for a 250-mph windstorm):

- 15-lb wood 2x4 (nominal) member
- typically 12 feet long

The missile is assumed to be propelled into wall and roof sections at the following missile speeds and to impact the test specimen (or shelter) 90° to the surface (see Figures 6-1 and 6-2 for examples of damage caused by this missile):

- 100-mph missile speed for horizontally travelling missiles
- 67-mph missile speed for vertically travelling missiles

The static force equivalent of this dynamic impact is difficult to calculate, and a direct conversion to a static load often results in extremely large loads. The actual impact force of the missile varies with the material used for the wall or roof section and will be a function of the stiffness of the material itself as well as the overall stiffness of the wall section in which it is used. Therefore, no formula for the determination of impact load is provided in this manual.

Various wall and roof sections tested at the WERC at TTU performed successfully. They are summarized in Chapter 6 and described in detail in Appendix E. The designer is referred to Appendix G for a selection of wall materials that have successfully passed missile impacts under the criteria outlined above.

6.1.2 Falling Debris

Falling debris also create structural damage, the magnitude of which is a function of the debris size and distance the debris falls. Falling debris generally consists of building materials and equipment that have significant mass and fall short distances from taller structures nearby. When siting the shelter, the designer should consider placing the shelter away from a taller building or structure so that if that structure collapses, it will not directly impact the shelter. When this cannot be done, the next best alternative would

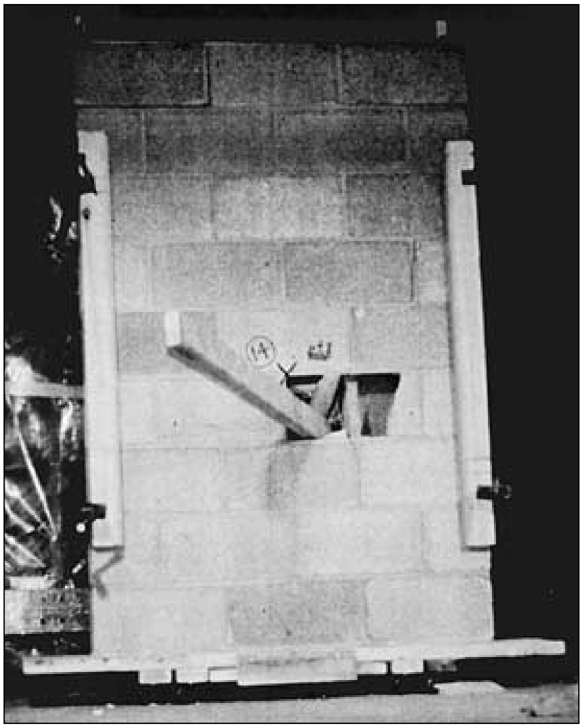


Figure 6-1
Wood 2x4 launched at 100 mph pierced unreinforced masonry wall, WERC, Texas Tech University.

Figure 6-2
Refrigerator pierced by windborne missile.

be to site the shelter in such a way that no large structure is within a zone around the shelter defined by a plane that is 1:1 (vertical to horizontal) for the first 200 feet from the edge of the shelter.

If it is not possible to site the shelter away from all the falling debris hazards at a site, the designer should consider strengthening the roof and wall systems of the shelter for the potential dynamic load that may result from these large objects impacting the shelter. Minimal guidance concerning the dynamic effect of large pieces of debris impacting shelters is available; however, the results of some limited testing, and approaches for designing for these loads, are discussed later in this chapter as performance criteria.

6.2 Windborne Debris (Missile) Impacts

The quantity, size, and force of windborne debris (missiles) generated by tornadoes and large hurricanes are unequaled by those of other windstorm debris. Missiles are a danger to buildings because the debris can damage the structural elements themselves or breach the building envelope. If the missile breaches the building envelope, wind may enter the building, resulting in an overpressurization of the building that often leads to structural failures. This high potential for missiles capable of breaching a building's exterior supports the recommended use of the internal pressure coefficient for partially enclosed buildings in the design criteria presented in Section 5.3. In addition, windborne debris may kill or injure people who cannot find shelter or refuge during a tornado or hurricane.

Most experts group missiles and debris into three classifications. Table 6.1 lists the classifications, presents examples of debris, and describes expected damage.

Table 6.1
Windborne Debris (Missiles) and Debris Classifications for Tornadoes and Hurricanes

MISSILE SIZE	TYPICAL DEBRIS	ASSOCIATED DAMAGE OBSERVED
Small (Light Weight)	Aggregate roof surfacing, pieces of trees, pieces of wood framing members, bricks	Broken doors, windows, and other glazing; some light roof covering damage
Medium (Medium Weight)	Appliances, HVAC units, long wood framing members, steel decking, trash containers, furniture	Considerable damage to walls, roof coverings, and roof structures
Large (Heavy Weight)	Structural columns, beams, joists, roof trusses, large tanks, automobiles, trees	Damage to wall and roof framing members and structural systems

Although large pieces of debris are sometimes found in the aftermath of extreme wind events, heavy pieces of debris are not likely to become airborne and be carried at high speeds. Therefore, from research in the field after tornadoes and hurricanes, as well as the results of research at TTU studying windborne debris in various wind fields, the representative missile has been selected as a 15-lb wood 2x4 (12–14 feet long).

This is the same missile criterion specified in Chapter 5 of this manual. Wind events have been modeled to show that the selected 15-lb missile will have different speeds and trajectories, depending on the event. However, to be conservative, it is recommended that test criteria for missile impact resistance be as stated in this section and Section 6.1.1.

Comparisons of results from missile impact tests for missiles other than the 15-lb wood 2x4 traveling at the design missile speed are discussed in Appendix G.

6.2.1 Debris Potential at Shelter Sites

Debris impacting buildings during a severe windstorm can originate from both the surrounding area and from the building itself and is not limited to the representative missile discussed in Section 6.2. During the development of a shelter design, the design professional should review the site to assess potential missiles and other debris sources in the area.

In addition to the wood 2x4 member described in the previous section, roof coverings are a very common source of windborne debris (missiles) or falling debris (ranging from roof gravel or shingles to heavy clay tiles, slate roof coverings, and roof pavers). Other sources of debris include roof sheathing materials, wall coverings, roof-mounted mechanical equipment, parapets, garbage cans, lawn furniture, missiles originating from trees and vegetation in the area, and small accessory buildings. Missiles originating from loose pavement and road gravel have also been observed in intense windstorms. In one area impacted by Hurricane Andrew, mailboxes were filled with rocks and asphalt from surrounding roadways.

As buildings break apart in severe windstorms, the failures progress from the exterior building elements inward to the structural members (e.g., trusses, masonry units, beams, and columns). The literature on tornadoes and hurricanes contains numerous examples of large structural members that have been transported by winds for significant distances. Generally, large debris such as structural members are transported significant distances by the windfield when a portion of exterior sheathing remains connected and provides an aerodynamic sail area on which the wind can act.

Rooftop mechanical equipment that is kept in place only by gravity connections is a source of heavy deformable debris when displaced during high-wind events. Furthermore, additional vulnerabilities to missile and wind are created when rooftop equipment is displaced from the roof, leaving large openings in the roof surface. Cars and trucks are also moved by strong winds. Lightweight vehicles can be moved around in parking lots in winds with gust speeds approaching 100 mph. Although pieces of debris larger than the test missile (15-lb 2x4) are observed, the speed of these missiles is considerably less. From post-disaster investigations, the 2x4 test missile appears most representative of the high-energy missile most likely to penetrate conventional construction. However, a shelter that has been designed to provide punching shear resistance from a 15-lb wood 2x4 and the capacity to resist the large wind forces associated with an extreme wind event will likely provide protection for some level of impact from larger debris items. Additional design guidance concerning large falling debris is presented in Section 6.3.

6.2.2 Induced Loads From the Design Missile and Other Debris

Determining static design loads from a propelled missile or a piece of free-falling debris is a complex computation. This computation depends on a number of factors, including the following:

- material that makes up the missile or falling debris
- material of the wall, door, window, or roof section being impacted
- stiffness of the individual elements being impacted
- stiffness of the structural system supporting them
- angle of impact between the missile and the structure

Because of the complex nature of missile and debris impacts, this manual does not provide design criteria that can be used to calculate the static force of a missile impact on any part of the shelter. To determine adequate missile impact resistance for a shelter, the designer should use the performance criteria presented in this chapter and the results of successful wall, roof, door, and window tests that are presented in Appendixes E and F of this manual.

6.2.3 Impact Resistance of Wood Systems

Texas Tech University has conducted extensive testing of wall systems that use plywood sheathing. The most effective designs, in terms of limiting the number of layers of plywood required, incorporate masonry infill of the wall cavities or integration of 14-gauge steel panels as the final layer in the system. Appendix E shows wall sections that have been tested with the design missile without failing (i.e., provide adequate missile impact resistance). Examples are shown in Figure 6-3.

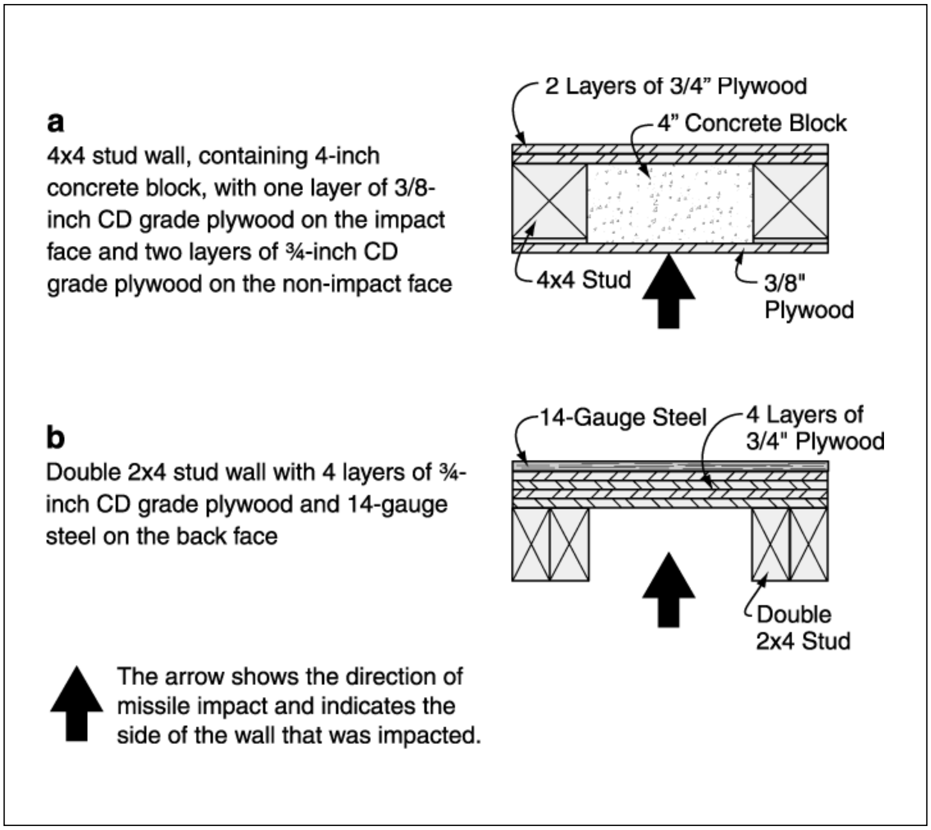


Figure 6-3
Wall sections constructed of plywood and masonry infill (a) and plywood and metal (b).

For conventional light-frame construction, the side of the wall where the sheathing or protective material is attached and the method of attachment can affect the performance of the wall in resisting damage from the impact of windborne debris. The impact of debris on material attached to the outside (i.e., harm side) of a wall pushes the material against the wall studs. Material attached to the inside of the wall (i.e., safe or shelter side) can be knocked loose from the studs if it is not adequately attached to the studs. Similarly, material on the harm side would be susceptible to being pulled off the studs by wind suction pressures if it were not adequately attached to the studs.

Consequently, sheathing materials bearing on the framing members should be securely attached to the framing members. Tests have shown that sheathing attached using an **AFG-01** approved wood adhesive and code-approved #8 screws (**not** drywall screws) penetrating at least 1-1/2 inches into the framing members and spaced not more than 6 inches apart provides sufficient capacity to withstand expected wind loads if the sheathing is attached to the exterior surfaces of the wall studs. These criteria are also sufficient to keep the sheathing attached under impact loads when the sheathing is attached to the interior surfaces of the studs. For information about oriented strand board or particleboard sheathing, see Appendix G.

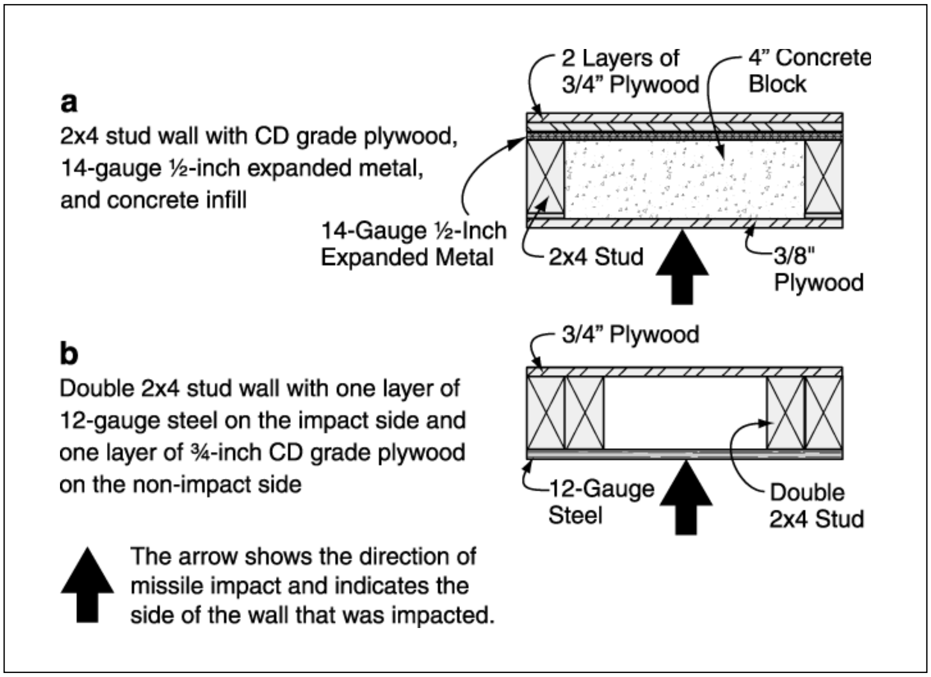
DEFINITION

AFG-01 is an American Plywood Association (APA) specification for adhesives for field gluing plywood to wood framing.

6.2.4 Impact Resistance of Sheet Metal

Various gauges of cold rolled A569 and A570 Grade 33 steel sheets have been tested in different configurations (see Figure 6-4 for an illustration of a representative wall section). The steel sheets stop the missile by deflecting and spreading the impact load to the structure. Testing has shown that if the metal is 14 gauge or lighter and is backed by any substrate that prevents deflection of the steel, the missile will perforate the steel. If the 14-gauge or lighter steel sheets are placed between plywood layers or between plywood and studs, the steel does not have the ability to deflect and is perforated by the missile. Therefore, on a wood stud wall, a 14-gauge steel sheet can resist perforation only when it is used as the last layer on the non-impact face on the interior (shelter side) of the wall, as shown in Figure 6-3.

Figure 6-4
Uses of expanded metal (a) and sheet metal (b) in wall sections.



In laboratory tests at Texas Tech University, 12-gauge or heavier steel sheets have never been perforated with the 15-lb wood 2x4 traveling at 100-mph. The 12-gauge steel has been mounted directly to studs and mounted over solid plywood. Test samples have used the standard stud spacing of 16 inches on center (o.c.). Increased spacing between supports affects the permanent deformation of the steel sheet. Permanent deformation of 3 inches or more after impact is deemed unacceptable. Tests have not been performed to determine the maximum support spacing that would control the 3-inch permanent deformation limit.

Designs provided in FEMA 320 include the use of sheet metal in shelter roof construction. If sheet metal alone is relied on for missile impact protection, it should be 12 gauge or heavier.

6.2.5 Impact Resistance of Composite Wall Systems

Composite wall systems require rigorous testing because there is no adequate method to model the complex interactions of materials during impact. Tests have shown that impacting a panel next to a support can cause perforation while impacting midway between supports results in permanent deformations but not perforation. Seams between materials are the weak links in the tested systems. The location and length of seams between different materials are critical. Currently the best way to determine the missile shielding ability of a composite wall system is to build and test a full-scale panel that consists of all the materials and structural connections to be used in constructing the panel. See Figure 6-5 for an illustration of a representative composite wall section.

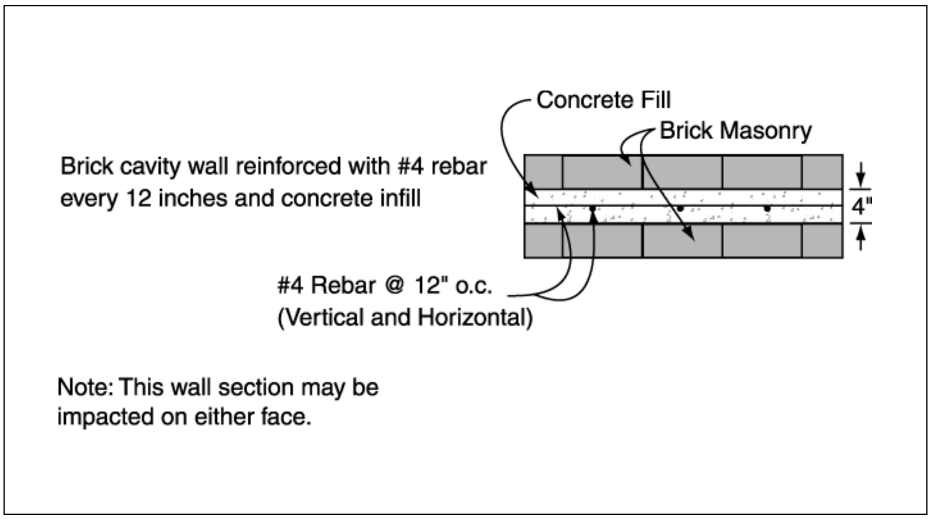
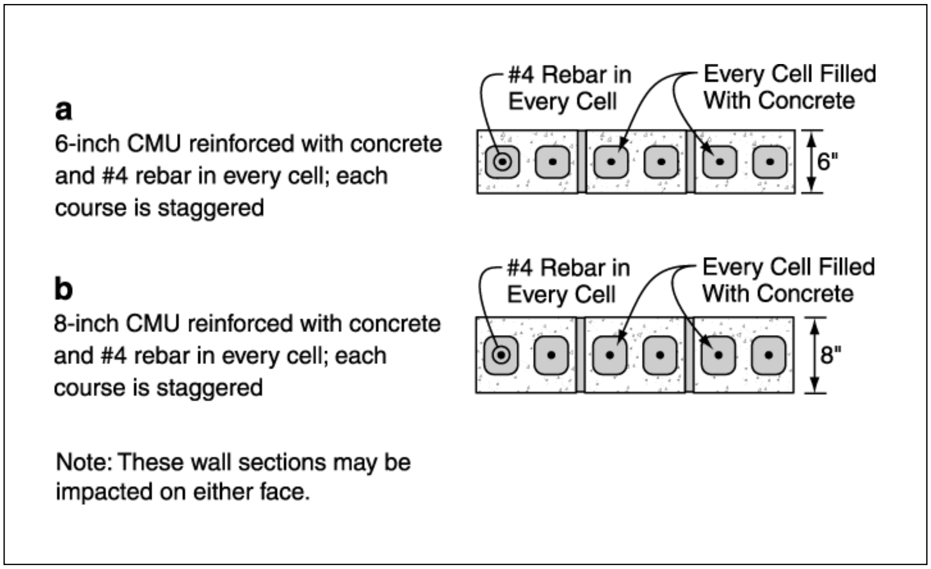


Figure 6-5
Composite wall section.

6.2.6 Impact Resistance of Concrete Masonry Units

Texas Tech research has demonstrated that both 6- and 8-inch-thick concrete masonry unit (CMU) walls that are fully grouted with concrete and reinforced with #4 reinforcing steel (rebar) in every cell (see Figure 6-6) can withstand the impact of a 15-lb 2x4 wood member striking perpendicular to the wall with speeds in excess of 100 mph.

Figure 6-6
Concrete masonry unit (CMU) wall sections.



6.2.7 Impact Resistance of Reinforced Concrete

Research related to the design of nuclear power facilities has produced a relatively large body of information and design guides for predicting the response of reinforced concrete walls and roofs to the impact of windborne debris. The failure modes have been identified as penetration, threshold spalling, spalling, barrier perforation, and complete missile perforation (Twisdale and Dunn 1981). From a sheltering standpoint, penetration of the missile into, but not through, the wall surface is of no consequence unless it creates spalling where concrete is ejected from the inside surface of the wall or roof. Spalling occurs when the shock wave produced by the impact creates tensile stresses in the concrete on the interior surface that are large enough to cause a segment of concrete to burst away from the wall surface. Threshold spalling refers to conditions in which spalling is just being initiated and is usually characterized by small fragments of concrete being ejected. When threshold spalling occurs, a person directly behind the impact point might be injured but is not likely to be killed.

However, as the size of the spalling increases, so does the velocity with which it is ejected from the wall or roof surface. When spalling occurs, injury is likely for people directly behind the impact point and death is a possibility. In barrier perforation, a hole occurs in the wall, but the missile still bounces off the wall or becomes stuck in the hole. A plug of concrete about the size of the missile is knocked into the room and can injure or kill occupants. Complete missile perforation can cause injury or death to people hit by the primary missile or wall fragments. Design for missile impact protection with reinforced concrete barriers should focus on establishing the minimum wall thickness to prevent threshold spalling under the design missile impact. Twisdale and Dunn (1981) provide an overview of some of the design equations developed for nuclear power plant safety analysis.

It should be noted that the missiles used to develop the analytical models for the nuclear industry, which are most nearly suitable for wood structural member missiles, are steel pipes and rods. Consequently, the models are expected to provide conservative estimates of performance when a “softer” missile, such as a wood structural member, impacts the walls. A summary of test results from a number of investigations (Twisdale and Dunn 1981) suggests that 6-inch-thick reinforced concrete barriers are needed to stop a 15-lb wood 2x4 missile impacting at 100 mph without threshold spalling. Texas Tech University research indicates that a 6-inch reinforced concrete wall (see Figure 6-7, illustrations a and b) provides sufficient protection from the 15-lb wood 2x4 missile impacting at 100 mph. Furthermore, reinforced concrete walls constructed with insulating concrete forms with a concrete section 4 inches thick (see Figure 6-7, illustration c) also provide sufficient protection. The Texas Tech University research also shows that a 4-inch-thick reinforced concrete roof provides sufficient protection from a 15-lb wood 2x4 missile impacting at 67 mph (the free-falling missile impact speed recommended in this document).

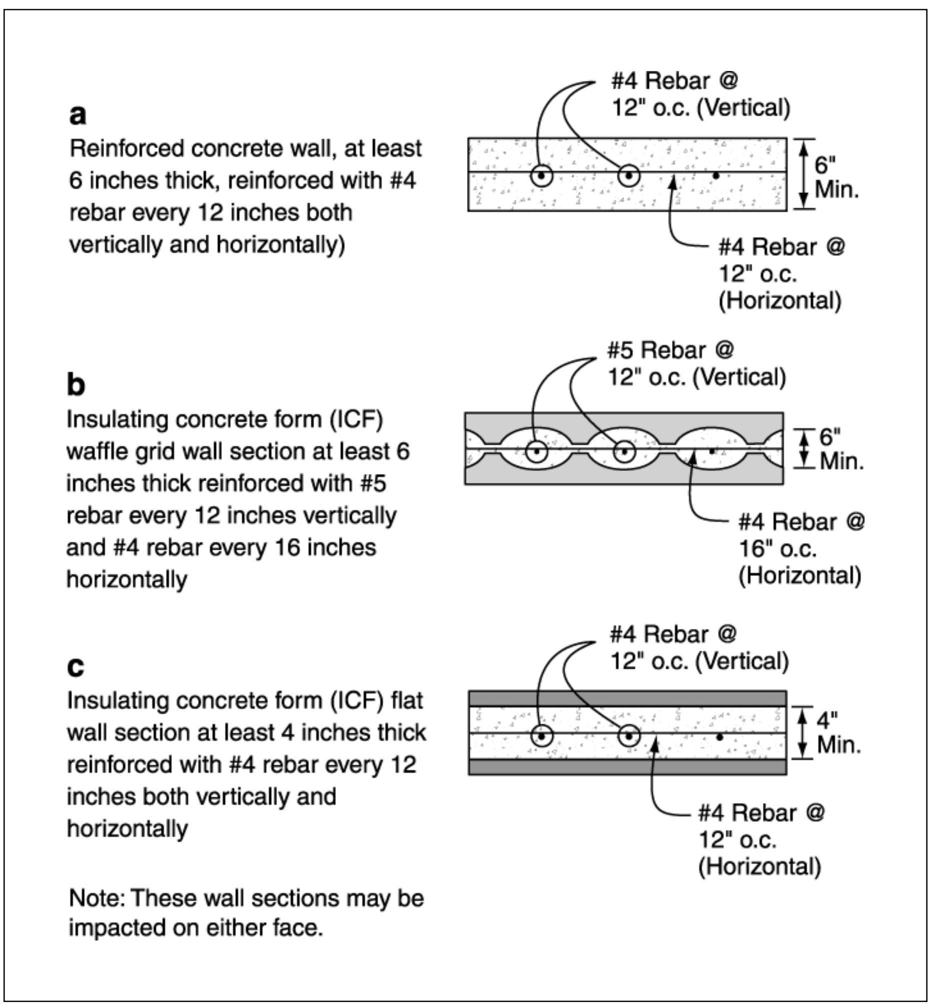


Figure 6-7
Reinforced concrete wall section (a), reinforced concrete “waffle” wall constructed with insulating concrete forms (b), and reinforced concrete “flat” wall constructed with insulating concrete forms (c).

6.3 Large Falling Debris

The design requirements for the wind speed selected from Figure 2-2 and the representative missile impact criteria outlined in Section 6.2 provide most shelter designs with roof and wall sections capable of withstanding some impacts from slow-moving, large (or heavy) falling debris. The residual capacity that can be provided in shelter designs was the subject of limited large debris impact testing at Clemson University. The purpose of this testing was to provide guidance on the residual capacity of roof systems when the shelter is located where falling debris may be a hazard. In this testing, two types of shelter roofs were subjected to impacts from deformable, semi-deformable, and non-deformable debris released from heights up to 100 feet and allowed to impact the roofs by free-fall.

Non-deformable debris included barrels filled with concrete weighing between 200 and 1,000 lb. Semi-deformable debris included barrels filled with sand weighing between 200 and 600 lb, while deformable debris included heating/ventilation/and air-conditioning (HVAC) components and larger objects weighing from 50 to 2,000 lb. Impact speeds for the falling debris were calculated from the drop height of the debris. The speed of the objects at impact ranged from approximately 17 to 60 mph. Impacts were conducted in the centers of the roof spans and close to the slab supports to observe bending, shear, and overall roof system reactions.

Cast-in-place and pre-cast concrete roof sections were constructed from the design plans in Case Studies I and II in Appendixes C and D, respectively. The heavily reinforced, cast-in-place concrete roof performed quite well during the impact testing. Threshold spalling, light cracking, to no visible damage was observed from impacts by deformable missiles, including the large 2,000-lb deformable object that impacted the slab at approximately 60 mph. Impacts from the 1,000-lb concrete barrel did cause spalling of concrete from the bottom surface of the roof near the center of the slab that would pose a significant hazard to the occupants directly below the point of impact. However, significant spalling required relatively high missile drops (high impact speeds).

Spalling of the slab extended into the slab from the bottom surface to the middle of the slab during impacts from the 1,000-lb concrete barrel impacting at approximately 39 mph. During this heavy spalling, the largest fragments of concrete were retained in the roof by the steel reinforcing. Metal decking (22 gauge) was successfully used as cast-in-place formwork on one of the test samples to retain concrete spalls created by the falling debris. The metal decking, however, must be connected to reinforcing within the slab or secured to the concrete to contain the spalling concrete.

The 1,000-lb concrete barrel completely perforated the flange of the double-tee beam in one drop from 50 feet (impacting at 39 mph) and caused significant damage to the stem in a second drop from the same height. Little damage occurred when the deformable debris materials (HVAC units, the 300-lb sand barrels, and a 1,500-lb deformable object) were dropped on the double-tee beams. Only light cracking and threshold spalling were observed from impacts from these deformable objects.

Based on the observed behavior of these roof specimens, it is believed that roof designs that incorporate a uniform thickness (i.e., flat slab) provide a more uniform level of protection from large debris impacts, anywhere on the roof, than a waffle slab, ribbed slab, or other designs that incorporate a thin slab supported by secondary beams. This approach is the best means of protecting shelter occupants from large impacts on shelter roof systems if siting the shelter away from potential falling debris sources is not a viable solution. Future research may yield information that will result in a more refined approach to designing shelters to resist the forces created by large falling debris.

6.4 Doors and Door Frames

Door failures are typically related to door construction and door hardware. Previous research and testing has determined that steel doors with 14-gauge or heavier skins prevent perforation by the design missile traveling horizontally at 100 mph. Furthermore, such doors in widths up to 3 feet are capable of withstanding wind loads associated with wind speeds up to 250 mph when they are latched with three hinges and three deadbolts. Because community shelters may have doors larger than those previously tested for use in in-home safe rooms, testing was performed for doors up to 44 inches wide. Double-door systems with center mullions and different types of closure hardware were also tested. The information presented here and in Appendix F is a compilation of the test information available to date.

Critical wind loads on doors and door frames are calculated according to the guidance presented in Chapter 5 of this manual and ASCE 7-98 for C&C loading. Calculations indicate that the maximum wind load expected on a door system (due to external suction wind forces combined with internal pressures for a 250-mph design wind) is 250 psf or 1.75 psi. Doors have been tested at these pressures through laboratory pressure tests. The doors were tested with positive pressure. The doors and frames were mounted as swing-in or swing-out doors to simulate either positive or negative pressures acting on the door. The doors were tested from both sides with positive pressure because the door and frame could not be sealed properly to pull a vacuum on the door to simulate negative pressures. Sliding door systems have been tested in the same manner.

NOTE

The design pressure for a 250-mph wind on doors in wall corner regions of a community shelter is 1.75 psi for components and cladding (C&C) elements with an area of 21 ft^2. Locating the door outside the corner region reduces the design pressure for the door to approximately 217 psf or 1.5 psi (corner regions are defined as the first 3 feet from the corner, 10 percent of the least wall dimension, or 4 percent of the wall height). These pressures are different from the 1.37-psi maximum door pressure used for the small, flat-roofed shelters in FEMA 320 that were assumed to be designed for "enclosed building" conditions (as defined in ASCE 7-98).

NOTE

The weak link of door systems when resisting wind pressures and debris impact is the door hardware. Testing was performed on a limited number of door and door hardware systems that represented off-the-shelf products to indicate their expected performance in shelters. Although these systems passed the missile impact tests, they did not pass the maximum wind pressure tests. The maximum wind pressures on any shelter occur at building corners in Wind Zone IV. Therefore, any shelter door system in Wind Zone IV should be protected by an alcove or debris barrier until further testing can be performed or until other door and hardware systems are successfully tested for the design wind pressures. See Appendix F for more detailed guidance.

6.4.1 Door Construction

Door construction (primarily the exterior skin) has been found to be a limiting element in the ability of a door to withstand missile impacts, regardless of the direction of door swing (inward or outward). Both steel and wood doors have been tested for missile impact resistance. Previous research and testing has determined that steel doors with 14-gauge or heavier skins prevent perforation by the design missile. Furthermore, such doors in widths up to 3 feet are capable of withstanding forces associated with wind speeds up to 250 mph when they are latched with three hinges and three deadbolts. At this time, no wood door, with or without metal sheathing, has successfully passed either the pressure or missile impact tests using the design criteria for 250-mph winds.

6.4.1.1 Single-Door Systems Less Than 36 Inches Wide

The following is a list of single-door systems less than 36 inches wide that have successfully withstood the missile impact criteria of this manual:

- Steel doors with exterior skins of 14 gauge or thicker. These doors can be used without modification of the exterior skin. The internal construction of the doors should consist of continuous 14-gauge steel channels as the hinge and lock rails and 16-gauge channels at the top and bottom. The minimum hardware reinforcement should be 12 gauge. The skin should be welded the full height of the door. The weld spacing on the lock and hinge rails should be a maximum of 5 inches o.c. The skin should be welded to the 16-gauge channel at the top and bottom of the door with a maximum weld spacing of 2-1/2 inches o.c. The door may include fill consisting of polystyrene infill or a honeycomb core. Greater strength can be gained through the use of doors that have internal 20-gauge steel ribs.
- Lighter-skinned steel doors may be used with modification. The modification is the addition of a 14-gauge steel sheet to either side of the door. The installation of the steel should be with 1/4-inch x 1-1/4-inch self-tapping screws with hexagon washer heads attached at 6 inches o.c. along the perimeter of the sheathing and 12 inches o.c. in the field. The internal door construction should meet the specifications listed above.
- Site-built sliding doors constructed of two layers of 3/4-inch plywood and an 11-gauge steel plate attached to the exterior face of the door with 1/4-inch x 1-1/4-inch self-tapping screws with hexagon washer heads attached at 6 inches o.c. along the perimeter of the sheathing and 12 inches o.c. in the field. These doors must be supported by "pockets" capable of transferring loads on the door to the shelter wall.

6.4.1.2 Single-Door Systems Greater Than 36 Inches Wide

A pressure test was performed on a single door 3 feet 8 inches wide (44 inches) and 7 feet tall. The door was constructed as described in the first bullet of

Section 6.4.1.1. The door was installed in a 14-gauge frame constructed within an 8-inch reinforced CMU wall and connected to the CMU with steel T-anchors spaced at 16 inches o.c.; the void between the frame and the masonry wall was grouted solid. The door was connected to the frame with five 4-1/2-inch heavyweight hinges. The latching hardware on the door tested was the single-lever-operated hardware (described in Section 6.4.3).

This door system did not withstand the pressure test and failed before reaching the design pressure of 1.75 psi. The door failed when the pressure reached 1.19 psi. The door deflected during the pressure test and buckled around the latching hardware. After this first test, the door could not be closed and secured. Further testing to identify door construction for 44-inch doors is required before design guidance may be given for these large, single doors.

NOTE

Heavy-gauge steel doors have been tested for resistance to wind pressures. Testing has shown that the weak link in available door products is the door hardware. At the time this manual was published, only one door/door hardware system resisted the pressures from a 250-mph wind at leeward wall surfaces (away from building corners); see Appendix F. Wind pressures can be reduced at building corners with an alcove that protects the door system from edge effects. See Section 6.4.3 for testing of door hardware systems

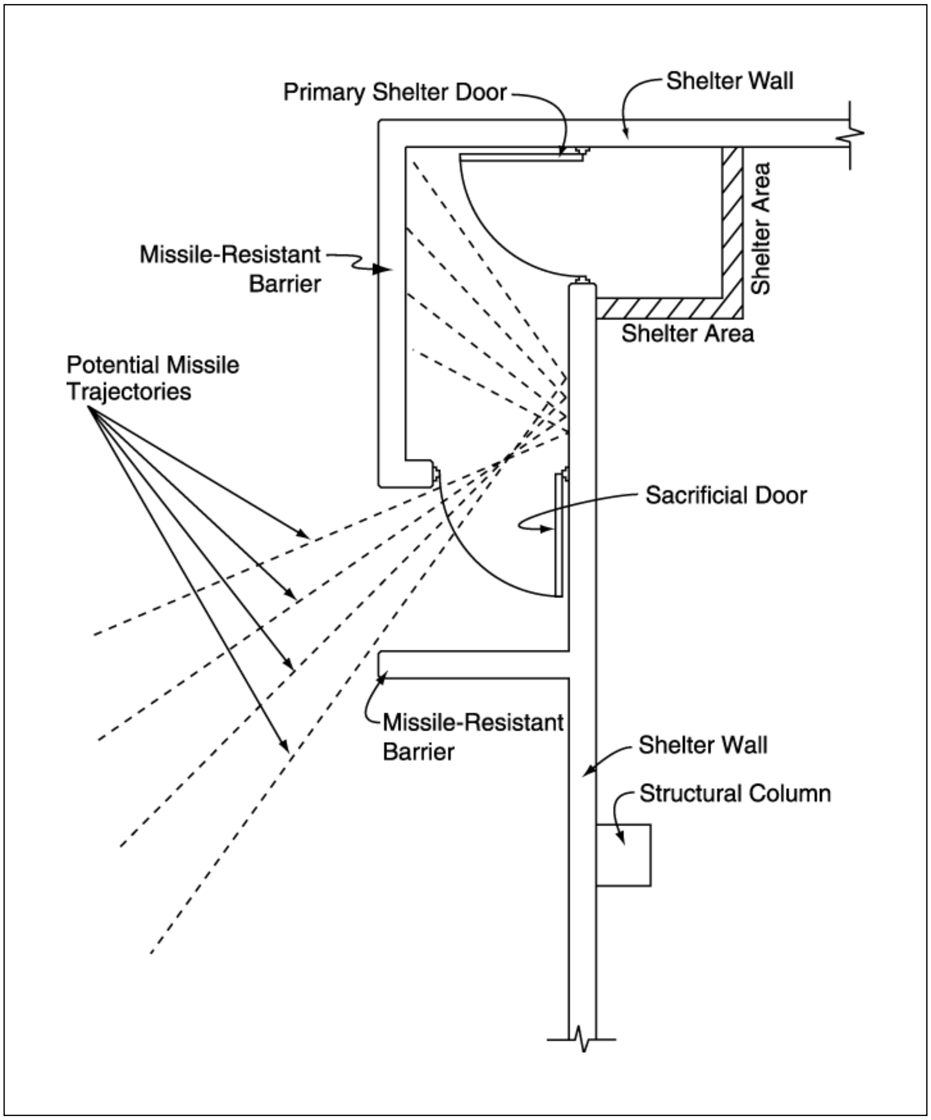
6.4.1.3 Double-Door Systems (With Center Mullion)

A double-door system (with a fixed center mullion) was tested for resistance to damage from wind pressures and missile impact. One door was equipped with a panic bar mechanism; the other was equipped with a single-action lever mechanism. This configuration was tested twice. The door configuration for these tests used two doors arranged in a swing-out configuration (a typical requirement for code-compliant egress). Each door was 3 feet wide and 7 feet tall and was constructed as described in the first bullet of Section 6.4.1.1. The doors were mounted in a 14-gauge steel frame with a 4-3/4-inch-deep frame with a 14-gauge center steel mullion. The mullion was bolted to the top of the frame and to a 12-gauge steel base plate at the sill with a 3/8-inch bolt at each location. The bolts extended from the front to the back of the mullion so as not to interfere with the doors when they were closed. The steel base plate was connected to the foundation below the sill with a 5/8-inch-diameter anchor bolt. The center mullion was reinforced with a T-shape 1/4 inch thick and 4 1/2 inches deep. The T-shape was welded to the back side of the mullion with 3-inch fillet welds at 9 inches o.c. Finally, the frame was attached to an 8-inch, fully reinforced, CMU wall with steel T-anchors spaced 16 inches o.c., and the void between the frame and the masonry wall was grouted solid. No grout was placed in the center mullion.

The double-door system was tested with pressures associated with the 250-mph design wind and for the 15-lb design missile. This door configuration was tested to a pressure of 1.37 psi, but was not tested to failure. However, deflection of the double-door system during the pressure testing damaged one of the lock mechanisms (this is discussed further in Section 6.4.3). During the missile impact tests, one door withstood the impacts and remained closed, but the hardware on that door (the panic bar hardware) was no longer operational. The second door (with the single-action lever hardware) was damaged such that the door was pushed through the frame, causing a rotation in the center mullion. For life-safety considerations, these results meet the missile impact criteria since the missile did not enter the shelter area. However, when functionality is a requirement (such as in the Dade County Florida impact test criteria), this result does not meet the impact requirements.

Therefore, double-door systems require further testing before a system capable of resisting the missile impact tests can be specified. Designers who wish to use double-door systems should use an alcove system that prevents direct missile impacts on the double-doors (see Figure 6-8) or should test double-door systems and hardware with heavier construction than those described in this section before installing the doors in a shelter in Wind Zone IV.

Figure 6-8
The door of the shelter in Case Study I (Appendix C) is protected by a missile-resistant barrier. Note: the shelter roof extends past the shelter wall and connects to the top of the missile-resistant barrier to prevent the intrusion of missiles traveling vertically.



6.4.2 Door Frames

Sixteen-gauge steel door frames in either a welded or knockdown style are known to be adequate to carry design wind and impact loads on a single door. Care must be taken in the installation of the frame so that it works properly and does not hinder the rest of the shelter construction. Frames used in stud construction must be attached to the MWFRS. This attachment is achieved with #8 x 3-inch screws, placed 6 inches o.c., installed through the jamb of the frame into the studs that make the rough opening of the door. Frames used in masonry construction are connected to the structure with T-anchors. It is critical that the T-anchors be bent at the internal edge of the masonry so that the tail of the anchor does not interfere with the placement of reinforcing steel and pea-gravel concrete.

Frames for large single doors should be constructed of at least 14-gauge steel. Frames for double-door systems should be constructed of at least 14-gauge steel frames and use a 14-gauge, steel center mullion as described in Section 6.4.1.3. The double-door system used in the testing secured the mullion to a 12-gauge steel base plate. The base plate was secured to the concrete below the doorsill with a single 5/8-inch diameter bolt. However, displacement and twisting of the center mullion (and base plate) occurred during the missile impact tests. If two bolts are used instead of one, this frame assembly should withstand the impact from the design missile and remain functional without loss of shape.

6.4.3 Door Hardware

Door hardware was found to be another limiting element in the ability of doors to withstand wind and missile impact loads. Although some standard door hardware was capable of withstanding wind pressures associated with Zones II and III (see Figure 2-2), none of the conventional hardware tested during the preparation of FEMA 320 (for wind zone IV on Figure 2-2) was capable of carrying design wind loads or withstanding missile impacts when the impact occurred near the lock set or door handle mechanism. Hence, testing found that steel doors with supplemental latching mechanisms near the top and the bottom are required to carry design wind loads and to prevent an inward-swinging door from being knocked open with a well-placed missile. Three latching mechanisms are required so that, if a debris impact close to one destroys it, two latches will be left to carry the wind loads.

WARNING

Maintenance problems have been encountered with some 3-point latching systems currently in use. If the door system uses a latch that engages a floor-mounted catch mechanism, proper maintenance is required if the latch is to function properly. Lack of maintenance may lead to premature failure of the door hardware during a high-wind event.

6.4.3.1 Single-Latch Mechanisms

Previous testing of latching and locking mechanisms consisted of testing an individual latch/lock cylinder or a mortised latch with a throw bolt locking function. In each case, tests proved that these locks, when used alone (without supplemental locks) did not pass the wind pressure and missile impact tests.

NOTE

All doors tested by FEMA prior to January 2000 were equipped with latching mechanisms composed of three, individually activated deadbolt closures. Between January and May 2000, multiple latching mechanisms activated by a single lever or by a panic bar release mechanism were tested.

Further testing proved that doors with these latching mechanisms and two additional mortised, cylindrical dead bolts (with solid 1/2-inch-thick steel throw bolts with a 1-inch throw into the door jamb) above and below the original latch would meet the requirement of the wind pressure and missile impact tests. It is important to note, however, that hollow deadbolts containing rod inserts failed the tests.

However, the use of a door with three individually operated latching mechanisms may conflict with code requirements for egress for areas with large occupancies. Sections 6.4.3.2 and 6.4.3.3 discuss door hardware operated with panic hardware and single-action lever hardware. Additional guidance on door and egress requirements is provided in Section 6.4.4.

6.4.3.2 Latching Mechanisms Operated With Panic Hardware

An extensive search was performed to locate three-point latching systems operated from a single panic bar capable of resisting the wind pressures and missile impacts specified in this chapter. A single system was selected and tested. This system consists of a panic-bar-activated headbolt, footbolt, and mortised deadbolt. The headbolt and footbolt are 5/8-inch stainless steel bolts with a 1-inch projection (throw) at the top and bottom and are encased in stainless steel channels. Each channel is attached to the door with a mounting bracket. The headbolt and footbolt assembly can be mounted inside the door or on the exterior of the door; only the externally mounted assembly was tested. The mortised lock complies with ANSI/BHMA 115.1 standard mortise lock and frame preparation (1-1/4-inch x 8-inch edge mortise opening with mounting tabs). All three locking points were operated by a single action on the panic bar.

This hardware was used for the double-door tests discussed in Section 6.4.1.3. Each of the doors was fitted with the panic bar hardware and three-point latches. This system was tested to 1.37 psi without failure. The system also passed the missile impact test, and the door remained closed; however, the hardware was not operational after the test.

6.4.3.3 Latching Mechanisms Operated With Single-Action Lever Hardware

A three-point latching system operated with a single-action lever was also tested for its ability to resist the wind pressures and missile impacts specified in this chapter. This system meets ANSI/BHMA A156.13 Operational Grade 1 and fits a modified ANSI 115.1 door and frame preparation. The mortise case is heavy-duty wrought steel with a lever-activated latch and a 1-inch solid bolt with a 1-inch throw. Operation of the latch activates two 1-inch x 3/8-inch solid hookbolts. One hookbolt is located 1 foot 4 inches above the deadbolt and the other is located 1 foot 4 inches below the deadbolt.

This hardware system was used in the large single-door tests and the double-door tests discussed in Sections 6.4.1.2 and 6.4.1.3, respectively. During the pressure test on the 44-inch single door, the deflection of the door resulted in the hookbolts (engaged in the frame) pulling out of the door itself. During the double-door tests, this hardware was damaged during the pressure test when the top hookbolt failed at its connection to the door (securing screws failed in shear). During the missile impact tests, the hardware resisted the missile impacts until a missile shot caused the center mullion to rotate, releasing the throw from the mullion. Further testing is required to determine whether the hardware or door can be modified to stabilize the hookbolts and prevent failure.

6.4.4 Doors and Egress Requirements

All doors must have sufficient points of connection to their frame to resist design wind pressure and impact loads. Each door should be attached to its frame with six points of connection (three connections on the hinge side and three connections on the latch side). Model building codes and life safety codes often include strict requirements for securing doors in public areas (areas with assembly classifications). This guidance often requires panic bar hardware, single-release mechanisms, or other hardware requirements. For example, the IBC and the NFPA life safety code require panic bar hardware on doors for assembly occupancies of 100 persons or more. The design professional will need to establish what door hardware is required and what hardware is permitted.

Furthermore, most codes will not permit primary or supplemental locking mechanisms that require more than one action to achieve egress, such as dead bolts, to be placed on the door of any area with an assembly occupancy classification, even if the intended use would only be during an extreme-wind event. This restriction is also common for school occupancy classifications.

These door hardware requirements affect not only shelter areas, but also rooms and areas adjacent the shelter. For example in a recent project in North Carolina, a school design was modified to create a shelter area in the main hallway. Structurally, this was not a problem; the walls and roof systems were designed to meet the wind pressure and missile impact criteria presented in this manual. The doors at the ends of the hallway also were easily designed to meet these criteria. However, the doors leading from the classrooms to the hallway were designed as rapid-closing solid doors without panic hardware in order to meet the wind pressure and missile impact criteria. This configuration was not a problem when the students were in the hallway that functioned as a shelter, but it was a violation of the code for the normal use of the classrooms. The designer was able to meet the door and door hardware requirements of the code for the classrooms by installing an additional door in each classroom that did not lead to the shelter area, thereby providing egress that met the requirements of the code.

Another option for protecting doors from missile impacts and meeting the criteria of this manual is to provide missile-resistant barriers. The shelter designs presented in Appendixes C and D of this manual use alcoves to protect doors from missile impacts. A protective missile-resistant barrier and roof system should be designed to meet the design wind speed and missile impact criteria for the shelter and maintain the egress width provided by the door itself. If this is done, the missile impact criteria for the door and code egress requirements for the door are satisfied. Although the wind pressures at the door should be reduced by the presence of the alcove, significant research to quantify the reduction has not been performed. Therefore, the door should be designed to resist wind pressures from the design wind. See Figure 6-8 for an example of an alcove used to protect a door assembly from missile impact.

Finally, the size and number of shelter doors should be determined in accordance with applicable fire safety and building codes. If the community or governing body where the shelter is to be located has not adopted current fire safety or model building codes, the requirements of the most recent edition of a model fire safety and model building code should be used.

6.5 Windows

Natural lighting is not required in small residential shelters; therefore, little testing has been performed to determine the ability of windows to withstand the debris impacts and wind pressures currently prescribed. However, for non-residential construction, some occupancy classifications require natural lighting. Furthermore, design professionals attempting to create aesthetically pleasing buildings are often requested to include windows and glazing in building designs. Glazing units can be easily designed to resist high-wind pressures and are routinely installed in high-rise buildings. However, the controlling factor in extreme-wind events, such as tornadoes and hurricanes, is protection of the glazing from missile perforation (the passing of the missile through the window section and into a building or shelter area).

NOTE

No window or glazing system tested for resistance to missile impact has met the missile impact criteria recommended in this manual.

Polycarbonate sheets in thicknesses of 3/8 inch or greater have proven capable of preventing missile perforation. However, this material is highly elastic and extremely difficult to attach to a supporting window frame. When these systems were impacted with the representative missile, the deflections observed were large, but were not measured.

For this manual, window test sections included Glass Clad Polycarbonate (2-ply 3/16-inch PC with 2-ply 1/8-inch heat-strengthened glass) and four-layer and five-layer laminated glass (3/8-inch annealed glass and 0.090 PVB laminate). Test sheets were 4 feet x 4 feet and were dry-mounted on neoprene in a heavy steel frame with bolted stops. All glazing units were impact-tested with the representative missile, a 15-lb wood 2x4 traveling at 100 mph.

Summarizing the test results, the impact of the test missile produced glass shards, which were propelled great distances and at speeds considered dangerous to shelter occupants. Although shielding systems can contain glass spall, their reliability is believed to degrade over time. Further testing of the previously impacted specimen caused the glass unit to pull away from the frame.

Testing indicates that glass windows in any configuration are undesirable for use in tornado shelters. The thickness and weight of the glass systems required to resist penetration and control glass spall, coupled with the associated expense of these systems, make them impractical for inclusion in shelter designs.

It is therefore recommended that glazing units subject to debris impacts not be included in shelters until products are proven to meet the design criteria. Should the shelter design require windows, the designer should have a test performed consistent with the impact criteria. The test should be performed on the window system with the type and size of glass specified in the design and mounted in the actual frame as specified in the design. A "PASS" on the test must agree with the following: 1) the missile must not perforate the glazing, 2) the glazing must remain attached to the glazing frame, and 3) glass fragments or shards must remain within the glazing unit. It is important to note that glass block is also not acceptable. Glass block, set in beds of unreinforced lime-rich mortar, offers little missile protection.