7 Commentary on Debris Impact Performance Criteria for Safe Rooms

Recommended performance criteria for tornado and hurricane safe rooms are provided in Chapter 3 of this manual. A listing of the existing guidance for community and residential safe rooms (early editions of FEMA 320 and 361), the ICC-500 *Standard for the Design and Construction of Storm Shelters* (2008), and other standards, manuals, and publications referenced in this chapter are listed in Chapter 10. The most recent of these documents are the ICC-500, ASCE 7-05, and FEMA 320. Although these documents do not address all factors and elements of the design of extreme-wind safe rooms, they provide the basis for the criteria presented in this chapter.

Chapter 3 of this manual, and referenced standards ICC-500 and ASCE 7-05, provide the information necessary for the computation of wind pressures and the loads imposed by winds on the walls, roof, windows, and doors of a safe room. The walls, ceiling, floor, foundation, and all connections joining these elements should 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 commentary on these criteria was presented in Chapter 6.

For a safe room to be effective and considered as having met the criteria presented in this document, the external surfaces of the safe room (including the structural elements, the building envelope, and openings in the building envelope) should be designed to resist wind-induced loads as well as impacts from debris. For the residential and small commercial safe room designs presented in FEMA 320, the original designs called for ceiling spans and wall lengths no greater than 8 feet. The design of the wall and ceiling systems were governed by the criteria specified for resistance to the impacts of windborne debris. For the 2008 edition of FEMA 320, additional testing and design analyses were performed to expand the maximum safe room size such that they now have maximum wall and roof spans of 12 to 14 feet. However, it is important to note that debris impact still governs much of the design. For larger community safe rooms, this broad statement cannot be made. The structural elements and the building envelope should be designed to resist wind-induced loads as well as impacts from debris.

This chapter discusses what research was performed to identify the representative (large) missiles used for the tornado and hurricane hazards and the speeds at which these representative missiles should be tested. It provides direction as to how to test building components to resist the wind loads using the new test protocols outlined in Chapter 3 for both tornado and hurricane hazards using the ICC-500. This chapter also gives insight into the performance characteristics of different wall, roof, window, door, and other protective systems. The systems have been tested to meet the most restrictive design criteria (a horizontally traveling large missile represented with a 15-lb 2x4 wood board member traveling at 100 mph).

Due to the limited research and testing that has been performed with regard to debris impact testing of buildings and building components to provide life-safety protection, much of what is presented at the end of this chapter is based on the testing and use of a 15-lb 2x4 wood board member traveling horizontally at 100 mph. A significant amount of products have been tested and approved to meet lower debris impact design criteria (i.e., a 9-lb 2x4 wood member traveling horizontally at 34 mph). However, those systems are not presented here since they do not meet the protection criteria for life safety nor can they provide similar levels of protection at impact (when compared with either momentum or energy). This chapter provides information to assist with the understanding of the performance of safe rooms, safe room envelope components, and opening protective assemblies in resisting debris impact. It links that performance to testing that has been performed at research universities on this topic. It is important to note, however, that any products described here or mentioned via internet link still need to be verified to comply with the new ICC-500, Chapter 8 (Test Method for Impact and Pressure Testing) before they can be said to meet the debris impact protection criteria presented in this manual.

WARNING

ICC-500, Chapter 8 (Test Method for Impact and Pressure Testing) is a new testing protocol for building systems and components that are to provide life-safety protection. It combines and uses several existing ASTM tests and test methods (such as ASTM E1886 and E1996), and addresses issues related to product acceptance, performance for life-safety acceptance, and large missiles that are above basic code designs promulgated prior to the release of the ICC-500. As such, no product can be said to meet the ICC-500 criteria if the report on it is dated prior to the 2008 release date of ICC-500 since the criteria were not available. Product certifications and claims by manufacturers to meet the criteria of FEMA 320 (2008), FEMA 361 (2008), and the ICC-500 (2008) that pre-date the release of these three documents should be scrutinized as to how they could have product approval prior to the release of the standard (or public comment drafts of the standard).

7.1 Windborne Debris in Tornadoes and Hurricanes

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. Although there is a substantial body of knowledge on penetration and perforation of small, high-speed projectiles (such as bullets and other ammunitions, etc.), by comparison, relatively little testing has been performed on lower-speed missiles such as windborne debris impacting buildings. In the design of community safe rooms, wind loads are likely to control the structural design. However, components and cladding (C&C) and building envelope issues may be governed by missile impact requirements. Nonetheless, after the safe room has been designed to withstand wind forces from the design wind speed, the proposed wall and roof sections should be tested for impact resistance from missiles. Windborne debris may kill or injure people who cannot find adequate shelter or refuge during a tornado or hurricane.

If the missile breaches the building envelope, wind may enter the building, resulting in an over-pressurization 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 Chapter 3. Most experts group missiles and debris into three classifications. Table 7-1 lists the classifications, presents examples of debris, and describes expected damage.

Table 7-1. 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

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 Chapter 3.

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.

7.1.1 Debris Potential at Safe Room Sites

Debris impacting buildings during extreme-wind events can originate from both the surrounding area and from the building itself. During the development of a safe room 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 members identified as the representative large missile, roof coverings are a very common source of windborne debris (missiles) or falling debris (ranging from roof aggregate or shingles to heavy clay tiles, slate roof coverings, and roof pavers; see Figure 7-1). Other sources of debris include roof sheathing (decking) materials, wall coverings, roof-mounted mechanical equipment, parapets, garbage cans, lawn furniture, missiles originating from trees and vegetation in the area, vehicles, 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 during extreme-wind events, 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 by the wind field when a portion of exterior sheathing remains connected and provides an aerodynamic sail area on which the wind can act.

Figure 7-1. Examples of large debris generated by tornadoes and hurricanes

Rooftop mechanical equipment that is kept in place only by gravity connections is a source of heavy deformable debris when displaced during extreme-wind events. Additional vulnerabilities to missiles and winds are created when rooftop equipment is displaced from the roof, leaving large openings in the roof surface. Cars, busses, and trucks can also be moved by strong winds (see Figure 7-2). 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 missiles (a wood board 2x4 that is either 15 or 9 pounds in weight) have been 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 safe room 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 7.6.

Figure 7-2. A school bus was lifted atop a section of Caledonia High School, Caledonia, Mississippi (January 2008)

7.1.2 Representative Missiles for Debris Impact Testing

The size, mass, and speed of missiles in tornadoes and hurricanes varies widely. Only a few direct measurements of debris velocity have been made. Such measurements require using photogrammetric techniques to analyze videos of tornadoes that contain identifiable debris. Unfortunately, very little studies (in the field or using photogrammetry) have occurred in the past 20 years to help produce a more technically documented choice for the representative missile. For this reason, the choice of the missiles that a safe room should be designed to withstand is somewhat subjective. From over 30 years of post-disaster investigations after tornadoes and hurricanes, the Wind Science and Engineering (WISE) Research Center at Texas Tech University (TTU) concluded that the missile that best represents windborne debris that is likely to perforate building components is a wood 2x4 member, weighing up to 15 pounds.

The trajectories of windborne debris of all shapes have been the subject of research in recent years (particularly at TTU, University of Florida, and Louisiana State University). This work includes trajectory trials on wind-tunnel models and validated numerical models. As part of this work, debris is categorized by its shape and flying characteristics into ‘compact,’ ‘rod,’ and ‘plate/sheet’ types. ‘Compact’ objects, usually generalized as cubes or spheres, are driven by wind drag forces, and have downward directed trajectories from their initial point of flight and often hit the ground before hitting a downwind building. On the other hand, the ‘rod’ and ‘plate’ types are subjected to significant lift forces, and can fly up before eventually attaining a downward trajectory under the influence of gravity. Therefore, these types have more potential to stay in flight and accelerate to damaging horizontal speeds before impacting a downwind building. These characteristics are consistent with the observed distances traveled, and damage observed after tornadoes and hurricanes have occurred.

The design missile chosen for much of the work done in protective structures and in storm shelters is a nominal, 2x4 wood board. It is very likely that much of the debris generated by extreme winds consists of boards and sawn lumber that came from buildings being torn apart by wind-induced pressures or other windborne debris. The 2x4 member is a representative test missile for the variety of damaging ‘plate/sheet’ and ‘rod’ type objects that have been observed during hurricanes. These include roof tiles, panels from billboards, and metal roof panels and flashing, etc., as well as timber roofing members. Furthermore, the 2x4 board has been shown to have more perforation potential than other common types of debris, including 2x6 boards (see Figure 7-3) of the same length and traveling at the same speed. Therefore, a 2x4 board has been chosen as the design missile for safe room design. The speed with which the missile travels is a function of the type of wind – straight-line, tornado, or hurricane – as well as the wind speed. The speed of the missile will be discussed more in Section 7.2.

Figure 7-3. Refrigerator pierced by windborne missile (a 2x6 wood board), Moore, Oklahoma

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. Other, larger airborne missiles do occur; larger objects, such as cars, can be moved across the ground or, in extreme winds, can be tumbled, but they are less likely than smaller missiles to perforate building elements. Following the Oklahoma and Kansas tornado outbreaks of May 3, 1999, both FEMA and TTU investigated tornado damage and debris fields and concluded that the 15-lb 2x4 missile was reasonable for safe room design. Therefore, from research in the field, as well as the results of research at TTU studying windborne debris in various wind fields, the representative tornado missile has been selected as a 15-lb 2x4 (12 to 14 feet long) wood board; a larger, representative missile does not appear justified at this time. This approach is consistent with the representative missile used for the impact tests discussed in FEMA 320, the first edition of FEMA 361, and those specified in FEMA's *National Performance Criteria for Tornado Shelters* (May 1999).

For hurricanes, damage investigations have provided varying results with respect to documenting the distances that debris has traveled for the reported wind speeds of the storm events. While arguments might be made to use 15-lb 2x4 wood boards as the design missile for hurricane testing, conclusive field data in post-storm inspections supported such criteria (and were used as the basis for debris impact criteria by the Department of Energy[1] and the Florida Emergency Operations Center Design Criteria[2]), but still have not successfully resulted in a single, representative missile to be used for both tornado and hurricane hazards by the wind code community. Legacy codes and standards have had a significant impact on the desire to use a smaller missile in hurricane-prone regions. The first use of the 9-lb 2x4 as a design missile dates back to 1976 in the Darwin Area (Australia) Building Manual, which first used a design missile in

---

[1] The Department of Energy (DOE) promulgates a design standard for their facilities titled *Natural Phenomena Hazards Design and Evaluation Criteria For Department of Energy Facilities* (DOE-STD-1020-2002), dated January 2002. This DOE Standard ranks levels of protection from natural hazard events. Levels of protection from windborne debris use the following representative missiles for debris impact testing (presented from highest to lowest level of protection): a 3,000-lb automobile, a 3-inch steel pipe, and a 15-lb 2x4 wood board. See Table 7-2 for additional information).

[2] The Florida Department of Community Affairs, Division of Emergency Management design criteria for Emergency Operations Centers is presented in the 2003 document titled *Guide Publication: Emergency Operations Center Project Development and Capabilities Assessment*.

the building code in response to the devastation caused to the city by Tropical Cyclone Tracy in 1974. In the United States, despite documented research from the 1970s supporting the 15-lb missile, the devastation of Hurricane Andrew in Florida in 1992 eventually led to the use of the 9-lb 2x4 as a design missile in a domestic building code as early as 1994 in the South Florida Building Code and 1995 in ASCE 7-95. Since that time, considerable testing using a 9-lb 2x4 board (approximately 9 feet long) has been completed on building envelope materials in Florida, and other coastal states, following the ASTM test procedures using this lighter missile.

Based on the acceptance of the 9-lb 2x4 wood board as a representative missile, and the information provided earlier in this section, these considerations led to the selection of the 9-lb 2x4 as the test missile for hurricanes for a variety of wind speeds (associated with the safe room design wind speed for the site). It is important to note that the Florida windborne debris standards and past Standard Building Code (SBC) as well as the current ASCE 7-05 windborne debris requirements were all developed and promulgated to minimize damage to buildings, and not to provide for life safety or the protections of occupants within those buildings. As such, Section 7.2 discusses the test speeds from Chapter 5 that the debris is to be moving when impacting a test specimen. For several criteria, this test missile speed is notably higher than that used for building envelope protection in the model building codes.

Table 7-2 compares the debris impact criteria used in the design and construction of safe rooms, shelters, and typical buildings. These criteria were first presented in Chapter 2 in Table 2-2, which compares the different levels of protection provided by safe rooms and other buildings.

Table 7-2. Comparison of Debris Impact Test Requirements for Tornadoes and Hurricanes

Guidance, Code, or Standard Criteria for the Design Missile	Horizontal Debris Impact Test Speed (mph)	Large Missile Specimen	Momentum at Impact (lb_f-s)$^+$	Energy at Impact (ft-lb_f)$^+$
Tornado Safe Room Missile Testing Requirements				
DOE-STD-1020-2002	25 mph 75 mph 150 mph (maximum) 100 mph (minimum)	3,000-lb auto 75-lb pipe 15-lb 2x4 15-lb 2x4	3,240 257 103 68	67,710 14,110 11,288 5,017
FEMA 320/FEMA 361	100 (maximum) 80 (minimum)	15-lb 2x4 15-lb 2x4	68 55	5,017 3,210
ICC-500 Storm Shelter Standard	100 (maximum) 80 (minimum)	15-lb 2x4 15-lb 2x4	68 55	5,017 3,210
IBC/IRC 2006, ASCE 7-05, Florida and North Carolina State Building Codes, ASTM E 1886/ E 1996	N/A	None	N/A	N/A

Table 7-2. Comparison of Debris Impact Test Requirements for Tornadoes and Hurricanes (continued)

Guidance, Code, or Standard Criteria for the Design Missile	Horizontal Debris Impact Test Speed (mph)	Large Missile Specimen	Momentum at Impact (lb_f-s)+	Energy at Impact (ft-lb_f)+
Hurricane Safe Room Missile Testing Requirements*				
DOE-STD-1020-2002	50	15-lb 2x4	34	1,254
FEMA 320/FEMA 361	128 (maximum) 80 (minimum)	9-lb 2x4 9-lb 2x4	53 33	4,932 1,926
ICC-500 Storm Shelter Standard	102 (maximum) 64 (minimum)	9-lb 2x4 9-lb 2x4	42 26	3,132 1,233
Florida State Emergency Shelter Program (SESP) Criteria and EOC Design Criteria	50 (EOC recommended) 55 (EHPA recommended) 34 (EHPA minimum)	15-lb 2x4 9-lb 2x4 9-lb 2x4	34 23 14	1,254 911 348
IBC/IRC 2006, ASCE 7-05, Florida and North Carolina State Building Codes, ASTM E 1886/ E 1996*	55 34	9-lb 2x4 9-lb 2x4	23 14	910 348

Notes:

+ lb_f-s = pounds (force) seconds and ft-lb_f = foot pounds (force).

* Hurricane missile testing requirements in these codes and standards only apply in the windborne debris regions (defined in the code/standard) and not throughout the hurricane-prone region.

N/A = Not applicable.

7.2 Commentary on Resistance to Missile Loads and Successful Testing Criteria

After a structure is designed to meet wind load requirements, its roof, walls, doors, windows, and opening protective systems should be checked for resistance to missile impacts. The structural integrity necessary to withstand wind forces for small residential safe rooms can be provided with materials common to both commercial and residential construction. For safe room design, the major challenge in designing small safe rooms is to protect against missile perforation as discussed in Chapter 3. A number of designs for safe rooms capable of withstanding a 250-mph design wind are presented in FEMA 320. For larger safe rooms, the design challenge shifts to providing the structural integrity necessary to resist wind loads. Walls designed with reinforced concrete or reinforced masonry to carry extreme-wind loads will normally prevent perforation by flying debris.

Relationships between wind speeds and missile speeds have been the subject of limited study over the past 30 years. For a 250-mph wind speed, the highest design wind speed considered necessary for safe room design, the horizontal speed of a 15-lb missile is calculated to be 100 mph based on a simulation program developed at TTU. The vertical speed of a falling wood 2x4 is considered to be two-thirds the horizontal missile speed. Although the probability is small that the missile will travel without rotation, pitch, or yaw and strike perpendicular to the surface, these worst case conditions are assumed in design and testing for missile perforation resistance.

While it is recognized that this is not the only type of debris that is carried by extreme winds, it is considered a reasonable representative missile to be used for design and testing purposes. In considering perforation of a structure or wall section, worst case conditions are assumed. Testing at TTU determined that blunt (square-faced) boards are more likely than pointed ones to perforate shelter surfaces. Furthermore, in numerous post-storm damage documentation studies, it was observed that 2x4 boards are the missiles most often found to have perforated building surfaces. While beams, bar joists, concrete blocks, and heavier objects are sometimes found, they are most often found on the ground close to the point of origin.

DEFINITION

Perforation is the term used to describe the failure of a safe room component from windborne debris. When a missile impacts a safe room component and passes through it and into the protected space of the safe room, this is called **perforation**. This is different than **penetration**. Penetration is when a component is impacted by debris and the debris enters the component but not to the extent that it enters the protected space. A missile may penetrate a door, wall section, etc., and remain lodged within the component, but the component does not allow the missile to completely perforate the component and enter into the safe room protected space.

The horizontal wind speeds of all types of windborne missiles progressively increase with distance traveled and the duration of flight, since the horizontal wind forces continue to act in the direction of the wind until the missile speed reaches the wind speed. However, this equality never occurs as the missile will invariably strike the ground or another building well before this situation is reached. Thus, the horizontal speed at which a given missile strikes a building wall depends on several factors: the gust wind speed (most missile flights occur in less than 3 seconds), the weight and shape of the object, the initial angle at release, and the distance it has traveled before impact. A discussion on the basis for which horizontal and vertical speeds of the debris propelled during impact testing identified in Chapter 3 is presented in Section 7.2.1.

NOTE

Few window or glazing systems tested for resistance to missile impact have met the missile impact criteria recommended in this manual.

The roof, wall sections, and coverings that protect any openings in a safe room should be able to resist missile impacts. Doors, and sometimes windows, are required for some safe rooms for egress and by the building code. However, doors and other openings are vulnerable to damage and failure from missile impact. Large doors with quick-release hardware (required in public buildings) and windows present challenges to the designer. Design guidance for doors and windows is given in Section 7.4.

7.2.1 Debris Impact Test Speeds for Representative Missiles

Chapter 3 provided debris impact test speeds for each missile for each hazard. The speeds at which the representative missiles are propelled for the tests are representative of the safe room design wind speed at the safe room site. For tornadoes, the debris impact test speeds for the horizontal missile range from a maximum of 100 mph to a minimum of 80 mph, varying from 0.4 to 0.6 times the safe room design wind speed. For hurricanes, the debris impact test speeds range from 128 mph to 80 mph, simply 0.5 times the safe room design wind speed. This section discusses how these speeds were selected.

During the development of the ICC-500, some new research was completed. These experimental and numerical studies of windborne debris of the ‘rod’-type (Holmes, Letchford, and Lin 2005)[3] concluded how long it takes for the debris to speed up while being propelled through the wind field. The results were that a 2x4 board accelerates to about:

- 0.5 times the local gust 3-second gust wind speed at a distance of 33 feet downwind from the source,
- 0.6 times the gust speed at a distance of 66 feet, and
- 0.8 times the gust speed at about 197 feet.

When considering the speed of the missile, an assumption has to be made at what height the missile is released into the wind field. A simplistic approach suggests taking the missile release point to be 33 feet above grade, the same elevation used to define and select the safe room design wind speed. However, many will argue that the maximum height of a safe room (typically located on the ground level of a facility) will be less than 33 feet. Therefore, the closer to the ground a missile is during flight, the slower the missile speed is because the surface roughness has reduced the safe room design wind speed; this is accounted for in the wind load design process through the use of K_z when calculating wind loads on building surfaces at heights other than 33 feet.

Instead of considering the increases and decreases in elevation of the debris in the wind field depending on whether or not the debris is released above or below 33 feet, the missile speed can be assumed to be constant if a conservative and simplistic approach is taken. To establish a minimum bound on the missile wind speed, it is assumed the representative debris is introduced into the wind field at the same height in which it strikes another building or object (heights of

---

[3] The remainder of this section has taken text from the J.D. Holmes, C.W. Letchford, and N. Lin paper (“Investigations of plate type windborne debris, Parts I and II.” *Journal of Wind Engineering and Industrial Aerodynamics)* and consolidated it for shortness of presentation and inclusion in this manual.

0-15 feet). This is a minimum bound since this is the lowest elevation at which debris may be introduced into the wind field. Next, the designer should consider the reduced speed of the wind, using K_z; for low-rise buildings in urban areas, the gust wind speed is approximately equal to 0.75 times the reference gust speed at 33 feet (height above grade) in open terrain used for design (i.e., K_z in ASCE-7 of $0.57 \cong 0.75^2$). Assuming that the horizontal distances between buildings in the vicinity of a safe room are typically in the range of 30 to 60 feet, it is reasonable to assume horizontal missile speeds of 0.5 to 0.6 times the maximum, *local* gust speed. This is equivalent to a speed of 0.375 (0.5 x 0.75) with 30 feet of travel, 0.45 (0.6 x 0.75) with 65 feet of travel, and 0.6 (0.8 x 0.75) with 200 feet of travel times the basic design gust speed for Exposure B. Table 7-3 presents these data along with the same calculation made for Exposure C.

Table 7-3. Missile Speed as a Function of Exposure and Distance Traveled (expressed as a percentage of the safe room design wind speed)

Exposure Considerations			V Missile / V Safe Room Design		
	K_z	% 33 ft speed	with 33 ft travel	with 65 ft travel	with 200 ft travel
Exp C (33ft)	1.00	1.00	0.50	0.60	0.80
Exp C (15ft)	0.85	0.92	0.46	0.55	0.74
Exp B (15ft)	0.57	0.75	0.38	0.45	0.60

V = velocity (mph)

Selection of the appropriate velocity ratio of the missile to the safe room design wind speed also considered the horizontal distance that the missile could travel in the wind. Again, this assumes the missile impacts a building or structure at the same height it was introduced into the wind field (because assuming a higher point of release would increase the distance traveled, thus increasing missile wind speed). Table 7-4 shows the horizontal distances traveled by 4.5-lb and 15-lb missiles as predicted by Holmes et al. for various wind speeds.

Table 7-4. Missile Speed and Distance Traveled Relationships

	Distance Traveled	
	4.5 lb	15 lb
90 mph	26.4 ft	49.5 ft
134 mph	99 ft	214.5 ft
avg =	62.7 ft	132 ft

Based on the above table, it is reasonable to assume that, for safe room design wind speeds of 160 mph and greater, debris generated within 15 feet of the ground can be transported over 65 feet. For both Exposure B and Exposure C situations, many examples can be provided in which buildings and structures would be separated by 65 feet or more. When debris is provided with

65 feet or more, it can be shown to accelerate to at least 0.45 times the safe room design wind speed for Exposure B and 0.55 times the safe room design wind speed for Exposure C.

Hurricane winds are considered straight-line winds without an upward component of velocity (which is a discriminating difference when comparing tornado and hurricane wind fields). Hurricane winds increase to their maximum speed more slowly than in tornadoes. There is no sudden atmospheric pressure change in hurricanes. Windborne debris is arguably released faster in tornadoes than in hurricanes and, therefore, can be said to travel farther. For the hurricane safe room, this has led to the choice of the ratio of 0.50 times the basic design wind speed as the horizontal missile speed for the 9-lb 2x4 in this guidance for the design of hurricane safe rooms.

Note that the probability of a missile like a 2x4 being released at the critical distance and angle of attack upstream and then actually striking a vulnerable part of a safe room during any given storm is quite small and to use the 'worst case' missile would be considered conservative. For the tornado safe room, this has led to the choice of acknowledging the gradation of missile speed with a design speed that was presented in the first edition of FEMA 361 in Table 3-3, but not allowed in the performance criteria. For this edition, the speed of the tornado missile varies from 0.40 to 0.65 times the safe room design wind speed.

NOTE

For additional information on windborne debris research and testing, the following internet sites provide links to FEMA, State of Florida Division of Emergency Management, and Texas Tech University, web pages containing reports on this subject area:

- http://www.fema.gov/plan/prevent/saferoom/index.shtm
- http://floridadisaster.org/Response/engineers/Wind_Missile_Impact.htm
- http://www.wind.ttu.edu/Research/DebrisImpact/TestingLab.php

7.2.2 Induced Loads From the Design Missile and Other Debris

The static force equivalent of the dynamic impact of a missile into a component of the safe room envelope 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, but the following discussion is provided for background and understanding of the impact loads.

Determining static design loads from a propelled missile or a piece of free-falling debris is a complex computation that 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 safe room. To determine adequate missile impact resistance for a safe room, the designer should use the performance criteria presented in this chapter and the results of successful wall, door, window, and roof tests that are presented in Appendices E and F of this manual.

Windborne debris and falling objects are two of the risks that safe rooms are designed to mitigate against and can be described in terms of their mass, shape, impact velocity, angle of impact, and motion at impact (i.e., linear motion or tumbling). The mass and impact velocity can be used to calculate a simple upper bound on the impact momentum (I_m) and impact energy (I_e) by assuming linear motion of the debris striking perpendicular to the surface. In this instance, the impact momentum is calculated using Formula 7-1, where W is the weight of the debris, g is the acceleration of gravity, and V is the impact velocity. For similar conditions, the impact energy can be calculated from Formula 7-2. I_m and I_e are the impact momentum and impact energy, respectively, for simple linear impacts perpendicular to the surface.

These equations provide reasonable estimates of impact momentum and impact energy for compact debris, where the length-to-diameter ratio is less than about 2, striking perpendicular to the surface. They also provide reasonable estimates for slender rigid body missiles striking on end, perpendicular to the surface when there is very little rotation of the missile. For off-angle impacts of compact debris (impacts at some angle to the surface), the normal component of the impact momentum and impact energy can be estimated with Formulas 7-1 and 7-2 if the velocity V is replaced by an effective velocity V´, where $V' = V \cos(\Theta)$ and the angle Θ is measured relative to the axis normal to the surface.

formula

Formula 7-1 Impact Momentum

$$I_m = (W/g)(V)$$

where: I_m = impact momentum
W = weight of debris
g = acceleration of gravity
V = impact velocity

formula

Formula 7-2 Impact Energy

$$I_e = (1/2)(W/g)(V^2)$$

where:
I_e = impact energy
W = weight of debris
g = acceleration of gravity
V = impact velocity

For slender, rigid-body missiles such as wood structural members, pipes, or rods, where the length-to-diameter ratio is greater than about 4, the angle of impact and the motion characteristics at impact become very important. Research has shown that the normal component of the impact drops off more rapidly than a simple cosine function for linear impact of long objects because the missile begins to rotate at impact (Pietras 1997). Figure 7-4, based on data from Pietras 1997, shows the reduction in normal force as a function of angle as compared to a cosine function reduction. For tumbling missiles, the equivalent impact velocity has been estimated using a complex equation (Twisdale and Dunn 1981, Twisdale 1985).

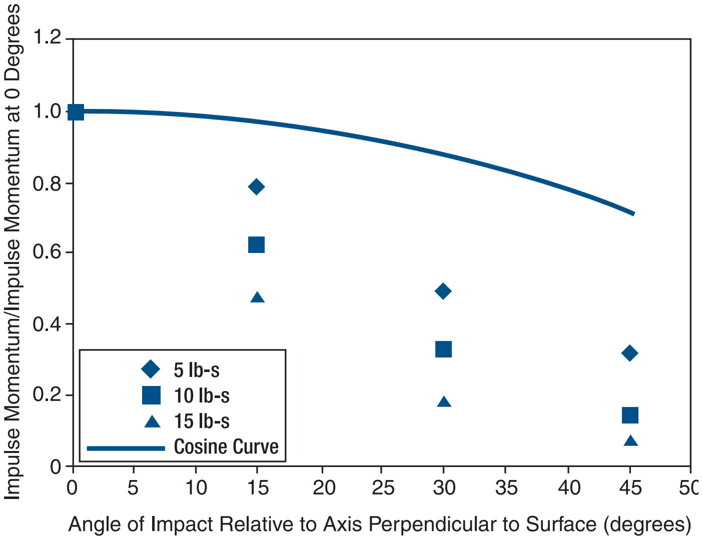


Figure 7-4. Variations of impact impulse as a function of impact angle

The impact of windborne debris can apply extremely large forces to the structure and its components over a very short period of time. The magnitude of the force is related to the mass of the object and the time of the deceleration as the missile impacts a surface of the safe room. The magnitudes of the forces also depend on the mechanics involved in the collision. For example, inelastic crushing of the wall or the missile will absorb some of the impact energy and reduce the force level applied to the structure. Similarly, large elastic or inelastic deformation of the structure in response to the impact can increase the duration of the deceleration period and therefore reduce the magnitude of the impact forces. For a perfectly elastic impact, the impulse force exerted on the structure is equal to twice the impact momentum since the missile rebounds with a speed of equal magnitude to the impact velocity but in the opposite direction. For a perfectly plastic impact, the missile would not rebound and the impulse force would be equal to the impact momentum.

Figure 7-5 illustrates the impulse loading applied by a 4.1-lb Southern Yellow Pine 2x4 (nominal) missile striking a rigid impact plate at a velocity of 21 mph (42.3 feet per second [fps]). Note that the entire impulse force is applied over a period of 1.5 milliseconds and the peak force approaches 10,000 pounds. Similar tests with a 9-lb wood 2x4 at 34 mph (50 fps) generated peak forces of around 25,000 pounds. The dotted (raw) line represents the measured impulse force and includes some high-frequency response of the impact plate. The signal has been "filtered" to remove the high-frequency response of the impact plate and illustrate the expected impulse forces time history.

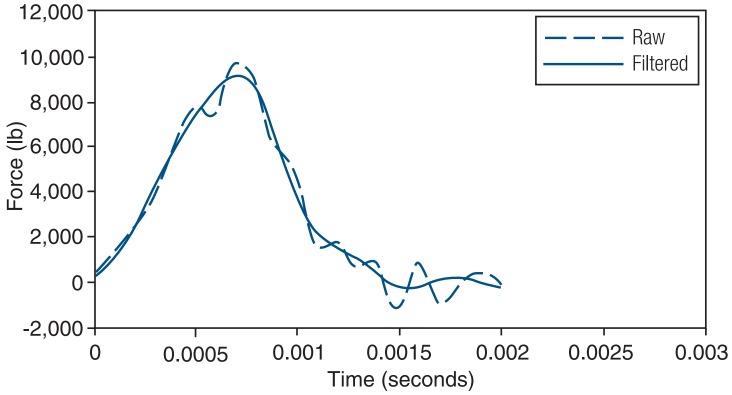


Figure 7-5. Raw and filtered forcing functions measured using impact plate for impact from a 4.1-lb 2x4 moving at 42.3 fps (Sciaudone 1996)

Impact test results for Southern Yellow Pine 2x4 members of various masses striking the impact plate at different velocities illustrate the complex nature of the impact phenomenon (Sciaudone 1996). Figure 7-6 compares the impulse force measured with the impact plate against the initial momentum of the missile. At low velocities, the impulse is characteristic of an inelastic impact where the impulse is equal to the initial momentum. This is likely due to the localized crushing of the wood fibers at the end of the missile. As the missile speed increases (initial momentum increases), the impulse increases toward a more elastic impact response because the impulse force increases to a value, which is substantially greater than initial momentum.

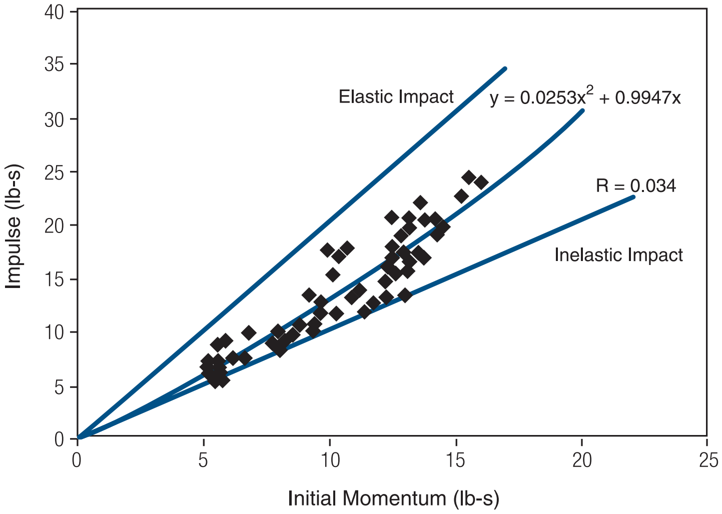


Figure 7-6. Impulse as a function of initial missile momentum for 2x4

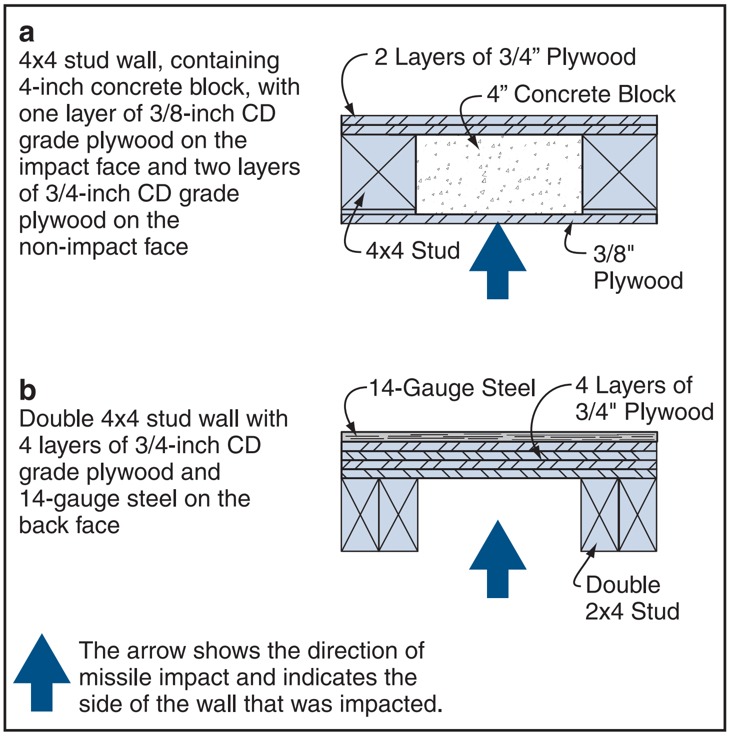
Design considerations should include local failures associated with missile perforation or penetration, as well as global structural failure. Sections 7.3 and 7.4 provide discussions that center on local failures. Global failures are usually related to overall wind loading of the structure or the very rare impact of an extremely large missile. Falling debris such as elevated mechanical equipment could cause a buckling failure of a roof structure if it impacted near the middle of the roof.

7.3 Commentary on Performance of Wall and Roof Assemblies During Debris Impact Tests

Various wall and roof sections tested at the WERC at TTU have performed successfully during years of testing. To provide an understanding of what type of systems have performed well, this section presents a summary of information on wall assemblies of common materials that have successfully passed missile impacts for the largest missile at the highest test speed (the 15-lb 2x4 traveling horizontally at 100 mph) as discussed in Chapter 3. For more detail on these assemblies, see Appendices E and G.

7.3.1 Impact Resistance of Wood Systems

TTU conducted extensive testing of wall systems that use plywood sheathing. The most effective designs, in terms of limiting the number of layers of plywood necessary, 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 7-7.



a 4x4 stud wall, containing 4-inch concrete block, with one layer of 3/8-inch CD grade plywood on the impact face and two layers of 3/4-inch CD grade plywood on the non-impact face

b Double 4x4 stud wall with 4 layers of 3/4-inch CD grade plywood and 14-gauge steel on the back face

The arrow shows the direction of missile impact and indicates the side of the wall that was impacted.

Figure 7-7. 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 safe room 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 was 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 1½ 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 (OSB) 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.

7.3.2 Impact Resistance of Sheet Metal

Various gauges of cold rolled A569 and A570 Grade 33 steel sheets have been tested in different configurations (see Appendix E for examples of representative wall sections that have been previously tested to resist the 15-lb 2x4 traveling at 100 mph). 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 (safe room side) of the wall, as shown in Figure 7-8.

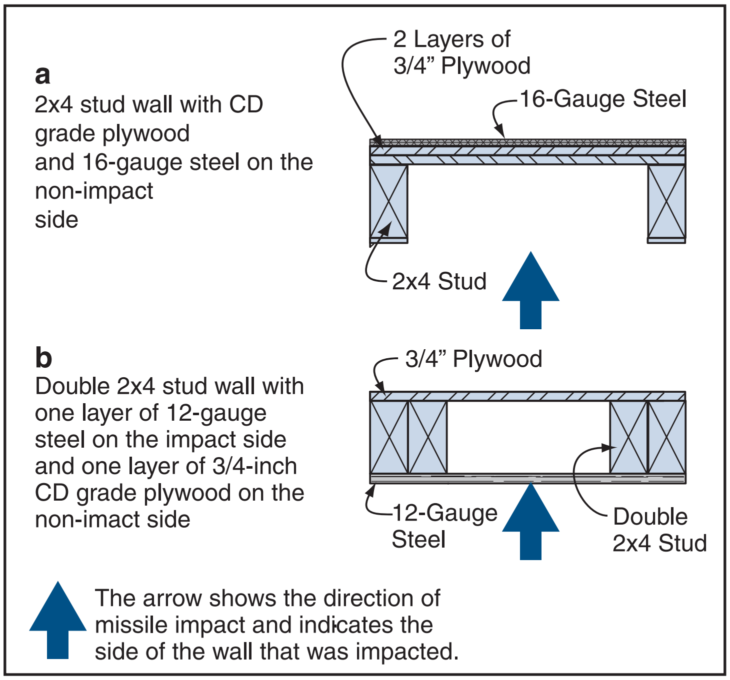


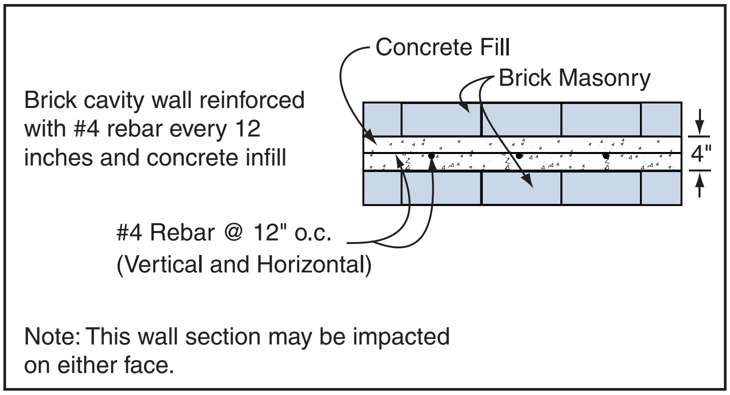
Figure 7-8 Uses of expanded metal (a) and sheet metal (b) in wall sections

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 into the safe room area 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 safe room roof construction. If sheet metal alone is relied on for missile impact protection, it should be 12 gauge or heavier.

7.3.3 Impact Resistance of Composite Wall Systems

Composite wall systems need 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 locations and lengths 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 7-9 for an illustration of a representative composite wall section.



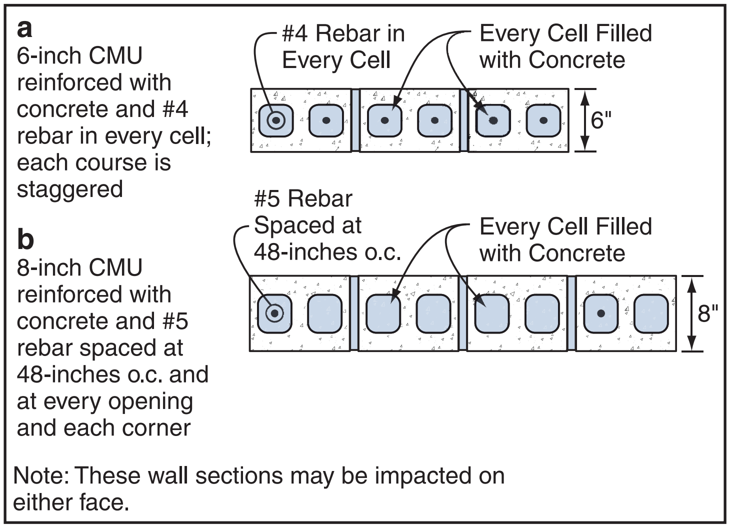
Brick cavity wall reinforced with #4 rebar every 12 inches and concrete infill

Note: This wall section may be impacted on either face.

Figure 7-9. Composite wall section

7.3.4 Impact Resistance of Concrete Masonry Units

Texas Tech research has demonstrated that both 6- and 8-inch-thick concrete masonry units (CMUs) can resist the large missile impact. Six-inch CMU walls that are fully grouted with concrete and reinforced with #4 reinforcing steel (rebar) in every cell (see Figure 7-10) can withstand the impact of a 15-lb 2x4 wood member striking perpendicular to the wall with speeds in excess of 100 mph. Eight-inch CMU walls should be fully grouted but need only be reinforced with #5 reinforcing steel (rebar) in every fifth cell (40 inches o.c.) for debris impact-resistance; however, more reinforcing steel may be required in the masonry wall to carry wind loads, depending upon the design and geometry of the masonry wall.



a
6-inch CMU reinforced with concrete and #4 rebar in every cell; each course is staggered

b
8-inch CMU reinforced with concrete and #5 rebar spaced at 48-inches o.c. and at every opening and each corner

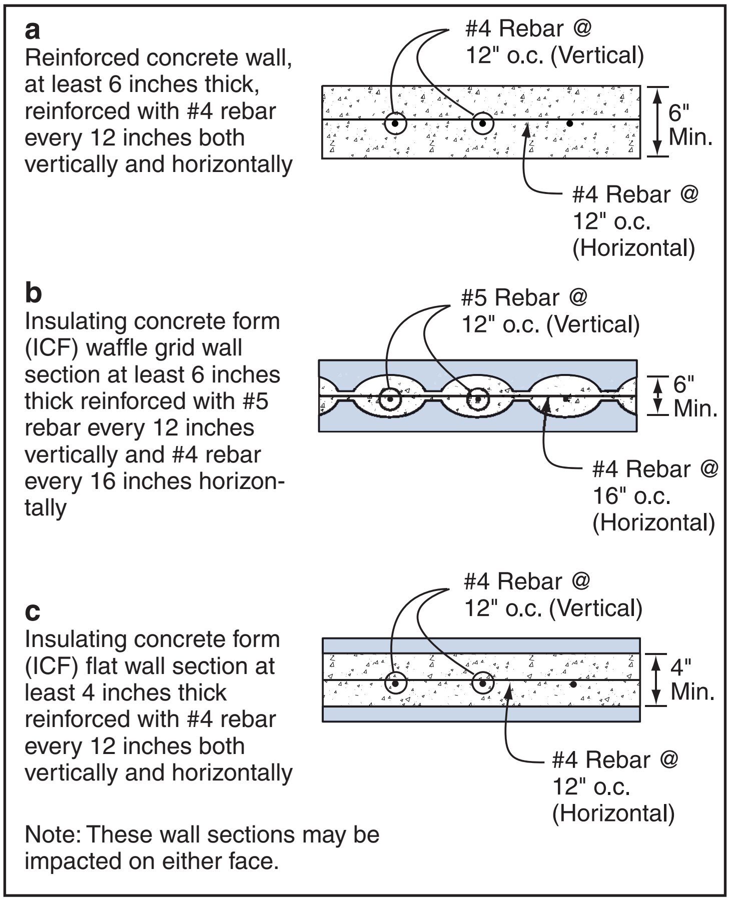
Note: These wall sections may be impacted on either face.

Figure 7-10. Concrete masonry unit (CMU) wall sections

7.3.5 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.



Note: These wall sections may be impacted on either face.

Figure 7-11. 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)

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. TTU research indicates that a 6-inch reinforced concrete wall (see Figure 7-11, illustrations a and b) provides sufficient protection from the 15-lb wood 2x4 missile impacting at 100 mph. Reinforced concrete walls constructed with insulating concrete forms (ICFs) with a concrete section 4 inches thick (see Figure 7-11, illustration c) also provide sufficient protection. The TTU 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).

7.4 Commentary on General Performance of Doors, Door Frames, and Windows During Debris Impact Tests

Door failures are typically related to door construction and door hardware. To provide an understanding of what type of systems have performed well, this section presents a summary of information on doors and door hardware that have successfully passed missile impacts for the largest missile at the highest test speed (the 15-lb 2x4 traveling horizontally at 100 mph) as discussed in Chapter 3. For more detail on door assemblies, see Appendix F.

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 safe rooms 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 3 of this manual and ASCE 7-05 for C&C loading. Calculations indicate that the maximum wind

NOTE

The design pressure for a 250-mph wind on doors in wall corner regions of a community safe room is 1.75 psi for 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 safe rooms in FEMA 320 that were assumed to be designed for “enclosed building” conditions (as defined in ASCE 7-05).

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 pounds per square inch (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.

7.4.1 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 have determined that steel doors with 14-gauge or heavier skins that are specially constructed 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 points of locking. 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.

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 safe rooms. Although these systems passed the wind pressure tests, they did not pass the missile impact tests. The maximum wind pressures on any safe room occur at building corners. Therefore, any safe room door system that is not specially constructed for 250-mph wind speeds (of Figure 3-1) should be protected by an alcove or debris barrier. See Appendix F for more detailed guidance.

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 publication:

- 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 14-gauge channel at the top and bottom of the door with a maximum weld spacing of 2½ inches o.c. The interior construction of doors must include internal 20-gauge steel ribs. The door may include fill consisting of polystyrene infill or a honeycomb core between the stiffeners.

- 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 ¼-inch x 1¼-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 edge of the internal door construction should meet the specifications listed above.
- Site-built sliding doors constructed of two layers of ¾-inch plywood and an 11-gauge steel plate attached to the exterior face of the door with ¼-inch x 1¼-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 should be supported by “pockets” capable of transferring loads on the door to the safe room wall. The doors should be suspended by an overhead track system capable of carrying the door weight. Locking can be accomplished by a simple ½-inch diameter pin through the supporting door pocket jamb and the door.

Single-Door Systems Greater Than 36 Inches Wide

Successful pressure and debris impact tests (for 250-mph winds and the 15-lb 2x4 missile traveling at 100 mph) have been conducted on numerous doors up to 48 inches in width and 86 inches in height. These doors were specially constructed similarly to the first bullet of the previous section. For the testing, the door was installed in a 12-gauge frame constructed within an 8-inch reinforced CMU wall and connected to the CMU with steel T-anchors (5 per jamb and 4 per head); note that the void between the frame and the masonry wall was grouted solid. The door was connected to the frame with five 4½-inch heavyweight hinges. The latching hardware on the door tested was the single-lever-operated hardware with two and three points of locking (described in Section 7.4.3).

Double-Door Systems (with Center Mullions)

Double-door systems (with fixed, removable, or no center mullions) were tested for resistance to damage from wind pressures and missile impact. For the test, both doors were equipped with panic bar mechanisms. 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 under Single-Door Systems Less Than 36 Inches Wide (presented earlier in this section). The doors were mounted in a 12-gauge steel frame with a 4¾-inch-

NOTE

Heavy-gauge steel doors have been successfully tested for resistance to wind and blast pressures. Testing has shown that the weak link in available door products is the door hardware. Testing has shown that the weak link in available door products is resistance to debris impacts and failure of the door hardware. See Section 7.4.3 for testing of door hardware systems.

deep frame. Doors with removable mullions were bolted to the frame at the top and the sill and were either a structural steel tube section or contained a structural steel reinforcement within the mullion. Non-removable mullions were similarly constructed but were fixed at the head and the sill. Finally, the frame was attached to an 8-inch, fully reinforced, CMU wall with steel T-anchors, a minimum of five in each jamb and three in each head opening, and the void between the frame and masonry wall was grouted solid. No grout was placed in the center mullion.

The double-door systems were tested with pressures associated with the 250-mph design wind and for the 15-lb design missile. Also, for some door missile impact tests, it was not uncommon for one door to withstand the impacts and remain closed, but the hardware on that particular door (with the panic bar hardware) was no longer operational. For life-safety considerations, these results meet the missile impact criteria since the missile did not enter the safe room area. However, when functionality is a requirement (such as in the Dade County Florida impact test criteria), this result does not meet those impact requirements.

7.4.2 Door Frames

Fourteen-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 should be taken in the installation of the frame so that it works properly and does not hinder the rest of the safe room construction. Frames used in stud construction should be attached to the main wind force resisting system (MWFRS). This attachment is achieved with five 3/8-inch lag screws in the jamb and three 3/8-inch lag screws in the head, installed 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. A minimum of five T-anchors in the jamb and three T-anchors in the head are typically needed to secure the jamb effectively.

Frames for large single doors should be constructed of at least 12-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 Double-Door Systems (with Center Mullions) in the previous section.

7.4.3 Door Hardware

Door hardware consists of latching and locking mechanisms, hinges, door coordinators, door closers, view windows, and ”peep” sights. In all cases, following pressure and impact tests, the door should remain closed and locked and none of the hardware mechanisms should have been disassociated from their attachment to the door and frame. Two points of locking should remain engaged following the conclusion of the pressure or impact tests. Three points of locking are recommended so that, if a debris impact close to one destroys it, two latches will be left to carry the loads. Latching and locking hardware is further described in this section. Hinges should be heavy duty 5-knuckle types that are attached with American-made, “fullhead” screws. Some doors with heavy duty hinges have been successfully tested to 250-mph standards. Door closers and coordinators must remain attached to the door and frame following the tests. View windows and “peep” sights have not been successfully tested in any assemblies and should not be included in the door.

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. Further testing proved that doors with these latching Grade 1 mechanisms and two additional Grade 1 mortised, cylindrical deadbolts (with solid ½-inch-thick steel throw bolts with a 1-inch throw into the door jamb) above and below the original latch would meet the criteria of the wind pressure and missile impact tests. It is important to note, however, that hollow deadbolts containing rod inserts, and residential grade deadbolts, failed the pressure and impact tests.

However, it is important to note that the use of a door with three individually operated latching mechanisms may conflict with code requirements for egress for areas with large occupancies. Additional information on appropriate door hardware for larger occupancies is presented later in this section. Further guidance on door and egress recommendations is provided in Section 7.4.4.

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. Two systems were selected and tested. These systems consisted 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)

WARNING

Maintenance problems have been encountered with some three-point latching systems currently in use. If the door system uses a latch that engages a floor mounted catch mechanism, proper maintenance is needed if the latch is to function properly. Lack of maintenance may lead to premature failure of the door hardware during an extreme-wind event. Some tested manufacturers now offer a low jamb bolt in lieu of a sill bolt to solve these maintenance issues.

NOTE

Most doors evaluated by FEMA prior to January 2000 were equipped with latching mechanisms composed of three individually activated deadbolt closures. Since that time, multiple latching mechanisms activated by a single lever or by a panic bar release mechanism have been tested and shown to resist the wind loads and debris impacts of the most stringent criteria in this publication (pressures associated with the 250-mph safe room design wind speed and impacts from a 15-lb 2x4 traveling horizontally at 100 mph).

at the top and bottom 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, but only the externally mounted assembly was tested. The mortised lock complies with ANSI/BHMA 115.1 standard mortise lock and frame preparation (1¼-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 previously. Each of the doors was fitted with the panic bar hardware and three-point latches. This system was tested to 1.75 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.

7.4.4 Doors and Egress Recommendations

All doors should 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). These codes often require panic bar hardware, single-release mechanisms, or other hardware requirements. For example, the IBC and the NFPA life-safety codes 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 deadbolts, 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 safe room areas, but also rooms and areas adjacent the safe room. For example, in a recent project in North Carolina, a school design was modified to create a safe room 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 considered not to be a problem when the students were in the hallway that functioned as a safe room, but it was a violation of the code for the normal use of the classrooms by the local building department. 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 safe room area, thereby providing egress that met the requirements of the code. Currently, one manufacturer has been identified that offers a single action three-point locking hardware with a “Classroom Function” that has been successfully tested to resist pressures associated with a 250-mph safe room design wind speed and impacts from a 15-lb 2x4 traveling horizontally at 100 mph.

Another option for protecting doors from missile impacts and meeting the criteria of this manual is to provide missile-resistant barriers. The safe room designs presented in Appendices 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 safe room 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 7-12.

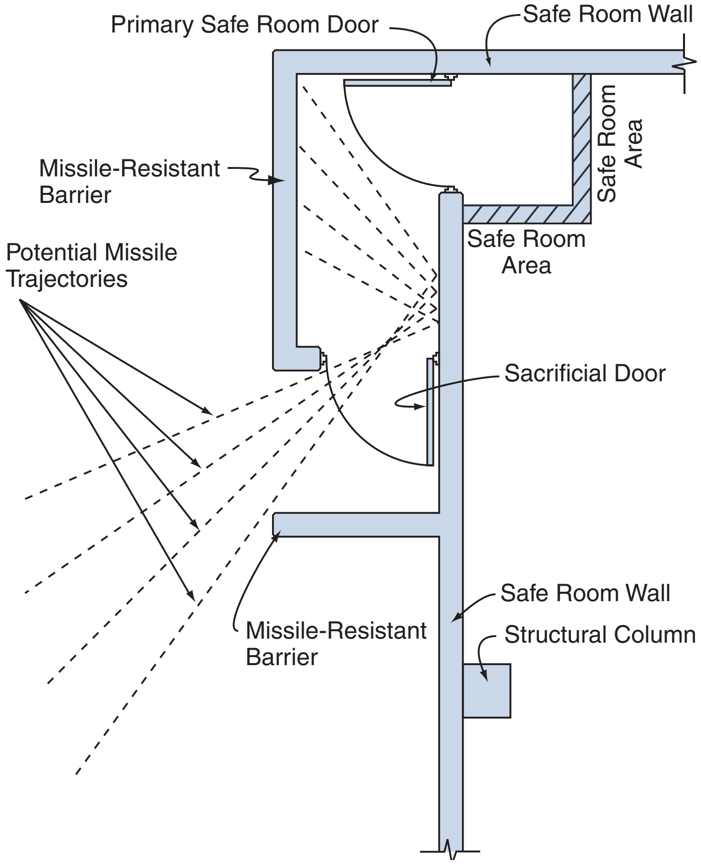


Figure 7-12. The door of the safe room in Case Study I (Appendix C) is protected by a missile-resistant barrier. Note: the safe room roof extends past the safe room wall and connects to the top of the missile-resistant barrier to prevent the intrusion of missiles traveling vertically.

Finally, the size and number of safe room doors should be determined in accordance with applicable fire safety and building codes. If the community or governing body where the safe room 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.

7.4.5 Performance of Windows During Debris Impact Tests

Natural lighting is not required in small residential safe rooms; 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 extreme-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 safe room area).

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, and the glazing often popped out of the frame in which they were mounted.

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 polyvinylbutyral (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 safe room 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 safe rooms. The thickness and weight of the glass systems needed to resist penetration and control glass spall, coupled with the associated expense of these systems, make them impractical for inclusion in safe room designs. To date, FEMA is aware of only one product that has been tested to meet the large missile criteria of this publication, a 15-lb wood 2x4 traveling at 100 mph.

It is therefore recommended that glazing units subject to debris impacts not be included in safe rooms until products are proven to meet the design criteria. Should the safe room design specify 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 should be as identified in Chapter 8 of the ICC-500. In general, this means that a “PASS” should show the following: 1) the missile did not perforate the glazing, 2) the glazing remained attached to the glazing frame, and 3) glass fragments or shards remained 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.

NOTE

Few window or glazing systems tested for resistance to missile impact have met the missile impact criteria recommended in this manual.

7.5 Commentary on Soil Protection From Debris Impact

As discussed in Chapter 3, soil cover on or around safe rooms can help to protect the safe room from debris impact. Should all or portions of safe rooms be below-ground or covered by soil, missile impact resistance may not be required. Safe rooms with at least 12 inches of soil cover protecting horizontal surfaces, or with at least 36 inches of soil cover protecting vertical surfaces, do not need to be tested for resistance to missile impact as though the surfaces were exposed. Soil in place around the safe room as specified above can be considered to provide appropriate protection from the representative tornado safe room missile impact. Figure 7-13 (based on ICC-500 Figure 305.2.2) presents this information graphically.

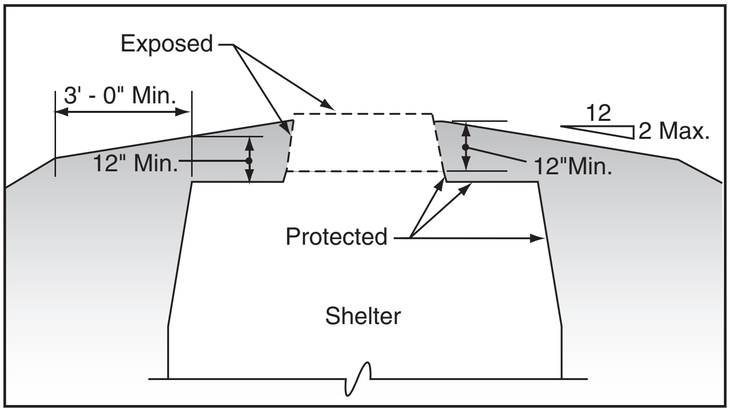


Figure 7-13. ICC-500 Figure 305.2.2 Soil cover over a safe room relieving the requirement for debris impact-resistance

It is also important to note that the soil conditions described above assume the soil is compactable fill. When fill is placed on top of or around a safe room, the soil should be compacted to achieve 95 percent compaction of the dry density of the soil as defined by a Modified Proctor Test. The fill cannot be the soil type used in “green buildings” on the roof or sides of the safe room unless it can be shown to be compactable fill.

7.6 Commentary on Large Falling Debris

The design recommendations for the wind speed selected from Figures 3-2 and 3-3 and the representative missile impact criteria outlined in Sections 3.3.2 and 3.4.2 provide most safe room 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 safe room 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 safe room is located where falling debris may be a hazard. In this testing, two types of safe room 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 pounds. Semi-deformable debris included barrels filled with sand weighing between 200 and 600 pounds, while deformable debris included heating/ventilation/and air conditioning (HVAC) components and larger objects weighing from 50 to 2,000 pounds. 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 Appendices 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, should 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 safe room occupants from large impacts on safe room roof systems if siting the safe room 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 safe rooms to resist the forces created by large falling debris.

Falling debris also creates 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 safe room, the designer should consider placing the safe room away from a taller building or structure so that, if the structure collapses, it will not directly impact the safe room. When this cannot be done, the next best alternative would be to site the safe room in such a way that no large structure is within a zone around the safe room defined by a plane that is 1:1 (vertical to horizontal) for the first 200 feet from the edge of the safe room.

If it is not possible to site the safe room away from all the potential falling debris hazards, the designer should consider strengthening the roof and wall systems of the safe room for the potential dynamic load that may result from these large objects impacting the safe room.

The location of the safe room has an influence on the type of debris that may impact or fall on the safe room. For residential structures, the largest debris generally consists of wood framing members. In larger buildings, other failed building components, such as steel joists, pre-cast concrete members, or rooftop-mounted equipment, may fall on or impact the safe room. Chapter 5 discusses how to minimize the effects of falling debris and other large object impacts by choosing the most appropriate location for a safe room at any given site.

When using the designs provided in FEMA 320 for residential and small, community safe rooms, the safe room user/operator should be aware that falling debris was considered during the design of these prescriptive design solutions. As such, it should be noted that the use of the FEMA 320 safe room within low-rise buildings (typically 60 feet in height and less), even though it may collapse upon the safe room during an extreme-wind event, is considered appropriate.