5

Building Envelope Performance

The ability of the structural system to perform without failure is critical to avoiding injury to occupants and minimizing damage to a building and its contents. It does not, however, ensure occupant or building protection. Good performance of the building envelope is also necessary.

The ability of the structural system to perform without failure is critical to avoiding injury to occupants and minimizing damage to a building and its contents. It does not, however, ensure occupant or building protection. Good performance of the building envelope is also necessary. The envelope includes exterior doors, non-load-bearing walls, wall coverings, soffits, roof coverings, windows, shutters, skylights, and exterior-mounted mechanical and electrical equipment. Historically, poor building envelope performance has been the leading cause of damage to buildings and their contents in weak to moderate intensity hurricanes, with damage to roof coverings and rooftop equipment being the predominant envelope problem. Building structural capacities have improved because of stronger building codes and better enforcement, resulting in less structural damage overall from intense hurricanes such as Hurricane Charley. Consequently, the performance of the building envelope is becoming increasingly important. The following sections describe envelope performance as observed for residential, commercial, and critical/essential facilities.

5.1 Doors

Failure of an exterior door has two important effects. First, failure can cause an increase in internal pressure, which may lead to exterior wall, roof, interior partition, ceiling, or structural damage (as discussed in Chapter 4). Second, wind can drive water through the opening, causing damage to interior contents and finishes, and leading to development of mold. Essentials to effective high-wind door performance include product testing to ensure sufficient factored strength to resist design wind loads; suitable anchoring of the door frame to the building; proper flashing, sealants, tracks, and drainage to minimize water intrusion into wall cavities or into occupied space; and, for glazed openings, the use of laminated glass or shutters to protect openings against windborne missile damage as discussed in Section 5.2.

5.1.1 Personnel Door Damage

There were only a limited number of buildings where personnel door damage was observed. Observed damage included broken window panes (typically caused by missiles) and doors disengaged from their frames (likely caused by over-pressurization). Sliding glass door damage is shown in Figure 5-1, where several doors disengaged from their tracks; this damage was caused by over-pressurization. Water infiltrated the interior of a residence and caused damage because of a lack of weatherstripping between a pair of doors and their threshold. A ⅜-inch gap occurred between the door bottoms and the threshold, apparently allowing a substantial amount of wind-driven water to enter the residence. Double-entry doors were also observed to be damaged even when homeowners tried to support the doors by pushing heavy furniture against them. An example of double-entry door failures was shown previously in Figure 3-20.

Figure 5-1.
Sliding glass doors blown out of their tracks (Punta Gorda Isles)

A limited number of buildings with personnel door damage were observed in commercial and critical/essential facilities. Observed damages included broken window panes (caused by missiles as shown in Figure 5-2) and disengagement of doors from their frames (likely caused by over-pressurization). At one school being used as a shelter, a pair of exterior gym doors reportedly blew open. People pulled the doors shut and held on to the horizontal exit hardware bars for the duration of the hurricane. The right leaf had top and bottom vertical rods, and the left leaf had a horizontal bolt. Therefore, at the latch edge, the door on the right was attached to the frame at the top and bottom of the door. However, the door on the left was attached only at mid-height, where it bolted into the right door (Figure 5-3). If the left door had also been equipped with top and bottom vertical rods, it may not have blown open.

Figure 5-2.
Tempered glass in office building entry door and side windows broken by missiles (Punta Gorda)

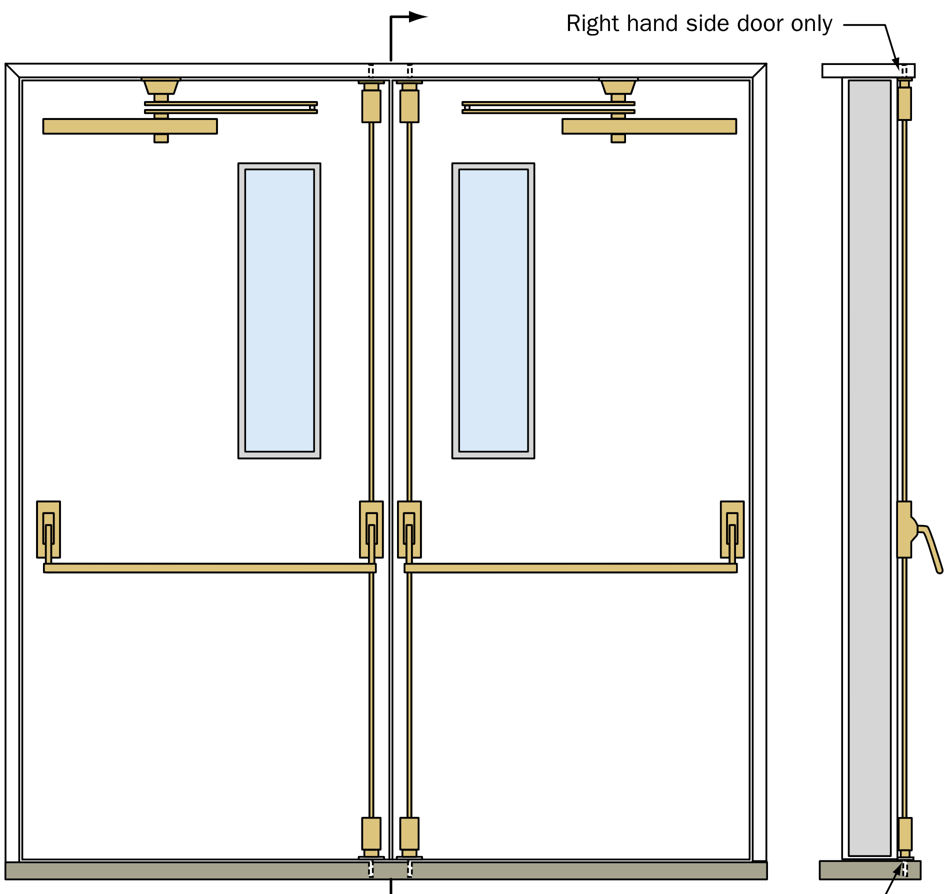

Figure 5-3.
Improper attachment of doors

5.1.2 Garage Door Damage

Damaged garage doors were observed throughout the Port Charlotte and Punta Gorda areas. In some instances, the doors buckled and were pulled outward (suction failures), as shown in Figure 5-4. In other instances, the doors were pushed inward (positive pressure failures), as shown in Figure 5-5. The home in the center of Figure 5-5 had a 5V-Crimp metal panel roof that performed well. Many of the other houses in this area (which typically had asphalt shingle or tile roofs) had roof covering damage. Many of the failures occurred because the doors had inadequate wind resistance. In these cases, the doors buckled inward or outward, and the rollers were often pulled out of the tracks. Other failures were caused by use of weak tracks or inadequate attachment of door tracks to the buildings. It was clear that most of the double car garage doors in older homes were not high-wind or debris-impact rated. In a number of the newer homes, the doors had improved bracing, but the metal gauge was much thinner than that used in Miami-Dade County approved impact-resistant garage doors. In addition, where door failures were observed, the tracks were not of the heavier gauge or braced according to high-wind recommendations. The garage doors approved by Miami-Dade County are constructed of thicker gauge material because they must meet different performance criteria for debris impact than is required by the 2001 FBC in other counties in Florida.

Figure 5-4.
Door lacked sufficient strength to resist the suction load (Deep Creek)

Figure 5-5.
Garage door at the home in the center buckled and the rollers pulled out from their tracks; garage door at the home on the right also failed (Deep Creek).

Some garage doors observed were designed with removable stiffener bars. One garage door with this type of design at a post-2001 FBC residence did not have the stiffener bar in place at the time of the hurricane, and it was damaged by wind pressure (Figure 5-6). There were instances where owners had left their homes for the summer season and had neglected to put into place the stiffener posts required to make their garage doors resist winds as they were designed.

5.1.3 Rolling and Sectional Door Damage

Damage to rolling and sectional doors (e.g., service garage doors and loading dock doors) was observed. Newer doors generally performed well. However, in one instance, a new door failed (the drawings were dated 1997), resulting in the failure of an interior partition wall, as shown in Figures 5-7 and 5-8. The failed door shown in Figure 5-7 was attached with 1¾-inch long by ⅜-inch diameter expansion bolts into concrete that spalled at the bolt locations, likely due to the placement of the bolts too close to the edge. There were no ties between the wall itself and the end wall (Figure 5-8). The drawings indicated continuous angles on each side of the wall, but they were not installed. Another sectional door around the corner and perpendicular to the door shown in Figure 5-7 failed after the door in Figure 5-7 failed. The buildup of internal pressure exerted a positive load on the other door, which was also loaded in suction on its outer surface. One of the expansion bolts along the right track sheared off, and the concrete spalled at the other bolts. The bolts were typically 2 feet on center, but some were closer.

Figure 5-6.
Garage door failed because the removable stiffener bar was not in place at the time of the hurricane (Punta Gorda Isles).

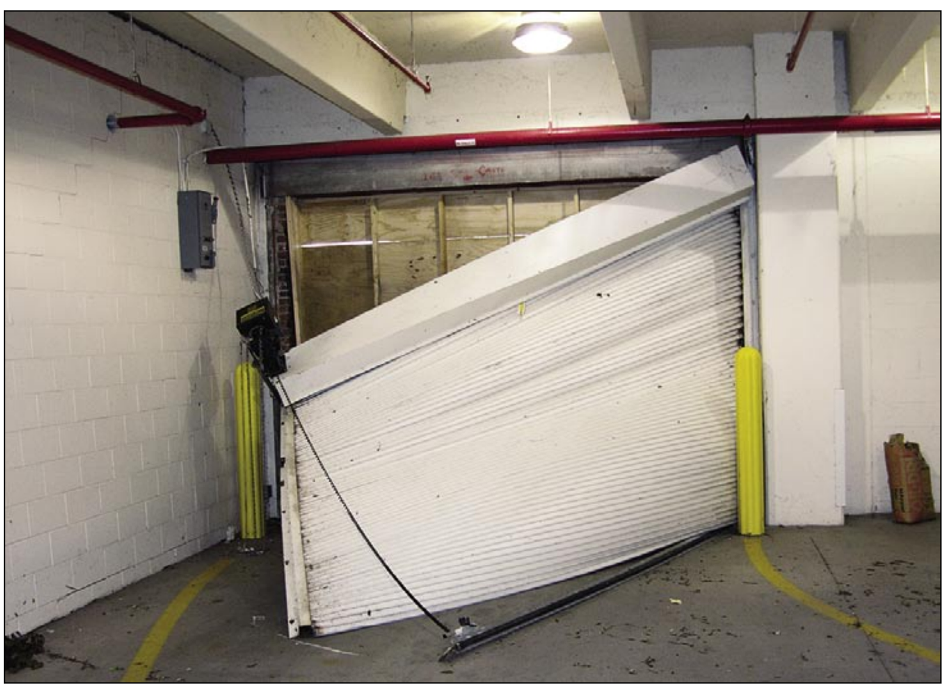

Figure 5-7.
New door that failed. Non-load bearing CMU wall at the left tilted (see Figure 5-8) (Punta Gorda).

The rolling and sectional doors at the older fire stations lacked sufficient wind resistance and typically failed by suction or positive pressure. Common modes of failure observed included doors disengaging from the tracks shown previously in (Figure 3-57), or tracks or track blocking pulling away from the walls, or breakage of glazed or metal panel doors. In several cases, the tracks bent or bowed enough to allow the wheels to disengage from the tracks. Damage to older doors was not surprising, illustrating the need to replace weak doors on these important buildings. However, when doors are replaced, it is important to replace all of the doors and the track hardware as illustrated by Figure 5-9. There were six sectional doors at the fire station shown in Figure 5-9. Five of the doors were damaged. On the leeward side, one door blew out, one buckled, and one had minor outward bowing. On the windward side, two of the doors blew inward as shown in Figure 5-9. The door that did not fail was a newer door. The tracks on the newer door were attached with ¼-inch screws at 18 inches on center. There were two stiffener ribs per 24-inch high door section. It is notable that one of the sidewalls was pushed out when the attachment of the wall angle to the slab failed, likely due to an increase in internal pressure. The wall angle was attached with nail-ins at 3 feet 3 inches on center. The concrete spalled at the fasteners. Because of the door damage, this station was taken off-line after the hurricane.

Figure 5-8.
After the door shown in Figure 5-7 failed, buildup of internal pressure tilted the wall (Punta Gorda).

Surprisingly, sectional doors on two newer fire stations also failed. At the Aqui Esta Fire Station (east of Punta Gorda Isles), five of the six doors were not damaged, but the sixth door pulled out of the track. This station was first occupied in 2000. At a fire station in Deep Creek (Figure 5-10), all three windward doors were blown in. The tracks were attached with ¼-inch lag screws at 24 inches on center. The leeward doors were not damaged, but the roof structure blew off the apparatus bay.

At several of the fire stations, the sectional doors blew inward on the apparatus (i.e., fire engines or ambulances). In some instances, the doors caused damage, such as a broken windshield, but there were no reports of door damage disabling a piece of apparatus.

Figure 5-9.
Windward side of a fire station; two doors blew inward, but the newer center door remained intact (Punta Gorda).

Figure 5-10.
At two of the windward doors, the doors were pushed out of the tracks; at the third door, one of the tracks was pushed from the wall (Deep Creek).

5.2 Windows, Shutters, and Skylights

Exterior windows are very susceptible to missile breakage during hurricanes unless they are protected against windborne debris (via use of laminated glass or shutters). Although the probability that any one window will be struck by windborne debris is typically small (except for manufactured housing in parks), when it does occur, the consequences can be significant. The probability of impact depends upon local wind characteristics and the amount of natural and manmade windborne debris in the vicinity. The greater the wind speed, the greater the amount of windborne debris that is likely to become airborne. Windows can also be broken by over-pressurization, but this damage is not as common as debris-induced damage.

The 2001 FBC defines windborne debris regions (see Figure 2-1) as those specified in ASCE 7-02, except in the Florida Panhandle, where the 2001 FBC has different requirements than ASCE 7. This difference in windborne debris regions is discussed in Section 2.2. In windborne debris regions, the 2001 FBC requires glazing to be impact-resistant or protected by shutters (glazing above 60 feet from grade is exempt). The Port Charlotte and Punta Gorda areas are in the windborne debris region, but inland areas along Hurricane Charley's track (such as Arcadia) are not.

One of the notable successes observed was the greatly increased use of shutters on both residential and commercial buildings, in both the windborne debris region as well as inland areas. Although some windows were shuttered during Hurricane Andrew in 1992 (FEMA FIA-22, *Building Performance: Hurricane Andrew in Florida*, 1992), it was apparent that many residents of Florida now have a greater appreciation of the benefits of protected glazing. The increased glazing protection is likely due to code requirements, development and increased availability of protection products, and the public's awareness of the vulnerability of unprotected glazing.

5.2.1 Residential Buildings

In a manufactured housing park in Zolfo Springs, an area not in the defined windborne debris region, windborne debris broke windows in several homes. The winds (estimated at 100 to 115 mph in Exposure B) generated a large amount of windborne debris. The majority of the windborne debris was from accessory structures and attachments as discussed in Section 4.6. In a manufactured housing park east of Port Charlotte, windows were broken in most of the homes and, in some cases, nearly all of the windows on the windward wall were broken (Figure 5-11). This park was in a windborne debris region, but the windows were not protected. Figure 5-12 illustrates broken windows in a new home that was still under construction. Because this house was still under construction, the contractor may have intended to install shutters in order to meet the windborne debris requirement; however, this was not done before the hurricane arrived. Window breakage was also caused by the failure of attached structures and pool cages. Figures 4-25 and 4-27 illustrated this type of damage.

Figure 5-11.
Most of the windows on this side of a manufactured home were broken by windborne debris (east of Port Charlotte).

Figure 5-12.
Three of four panes broken by windborne debris; other windows in this house also broke (Deep Creek).

Many windows in the windborne debris region were equipped with shutters, although most were not. Shutters were made of wood sheathing, metal panels, or plastic panels of various designs. A common shutter design used metal panels that were held by top and bottom tracks permanently mounted to the wall. Figure 5-13 shows a house with roll-up shutters at the windows and metal panel shutters at the garage (garage door shuttering was rare).

Figure 5-13.
This house, which appeared undamaged from windborne debris, had roll-up shutters at the windows and metal panel shutters at the garage (Deep Creek).

Figure 5-14 shows a common metal awning shutter. These types of shutters provide very limited protection and should not be considered impact-resistant; they have not been tested to 2001 FBC requirements. A plastic roll-up shutter was observed that had been broken by windborne debris. It is doubtful that this shutter met the impact-resistance requirements specified in the 2001 FBC. In one case, windborne debris (a roof tile) was observed to have penetrated a Miami-Dade approved shutter (shown previously in Figure 3-32).

Figure 5-14.
Metal awning shutter penetrated by a missile (Zolfo Springs)

Some of the shutters did not have the strength to withstand the forces of the wind or the impacts of windborne debris. Others may have had sufficient strength, but were improperly installed. Figure 5-15 shows a house that used plastic shutters that blew off.

Figure 5-15.
All of the windows on this house were covered by plastic shutters, many of which were blown off during the hurricane, resulting in several broken windows (North Captiva Island).

The MAT observed some laminated glass windows, but none of them had been impacted by windborne debris, or if they had been impacted, they did not break. Some broken tempered glass windows were observed. Although tempered glass is more resistant to windborne debris than common glazing, when tempered glass breaks, it shatters into small pieces and falls out of the frame. Wind-driven rain could then be driven into the residence and substantially increase the internal pressure. When laminated glass breaks, the glass remains bonded to the plastic film between the panes, and the glazing remains in the frame. Although the glass will need to be replaced, the costly interior water and wind damage is avoided. On North Captiva Island, a house with laminated glass was observed where one sliding glass door panel was broken by impact from porch furniture, but the laminate held without a penetration. However, the impact of debris knocked the glass doors out of their tracks and opened the home to wind and water.

Some power-operated roll-down shutter systems were also observed. In at least one case, the shutter system did not include a manual system for retracting the shutter. As a result, it was impossible for the owner to open the shutters and air out the home after the storm. To minimize the possibility of developing mold, power-operated shutters should have alternate means of operation to allow opening after a storm.

5.2.2 Commercial and Critical/Essential Facilities

Window damage was observed on commercial buildings and critical/ essential facilities throughout the impact area. Figure 5-16 shows a broken window in a mid-rise hotel in the Orlando airport area. Two windows on the same floor were likely broken by the missing plastic lens covers on the hotel sign. Figure 3-33 also showed glass breakage near the Orlando airport. In the Wauchula central business district, windborne debris broke glass in several adjacent buildings (Figure 5-17). The estimated wind speed in this area was 100 to 115 mph. In Punta Gorda, tempered glass in a door and several windows were broken by windborne debris (as shown earlier in Figure 5-2) and a nearby three-story office building had very extensive glass breakage on all sides of the building (Figure 5-18). At least some of the breakage in both buildings was caused by aggregate from a nearby built-up roof (BUR) (Figure 5-19). Other types of windborne debris also impacted the three-story building (one missile penetrated the stucco and underlying metal lath). All of the glazing, including glass spandrel panels, was broken on the long side of the building shown in Figure 5-18.

Figure 5-16. Window most likely broken by missing plastic lens covers on hotel sign (see top of building) (Orlando airport area)

Figure 5-17.
Broken glass in windows and doors in this building. Buildings across the street also had several broken windows caused by windborne debris (Wauchula).

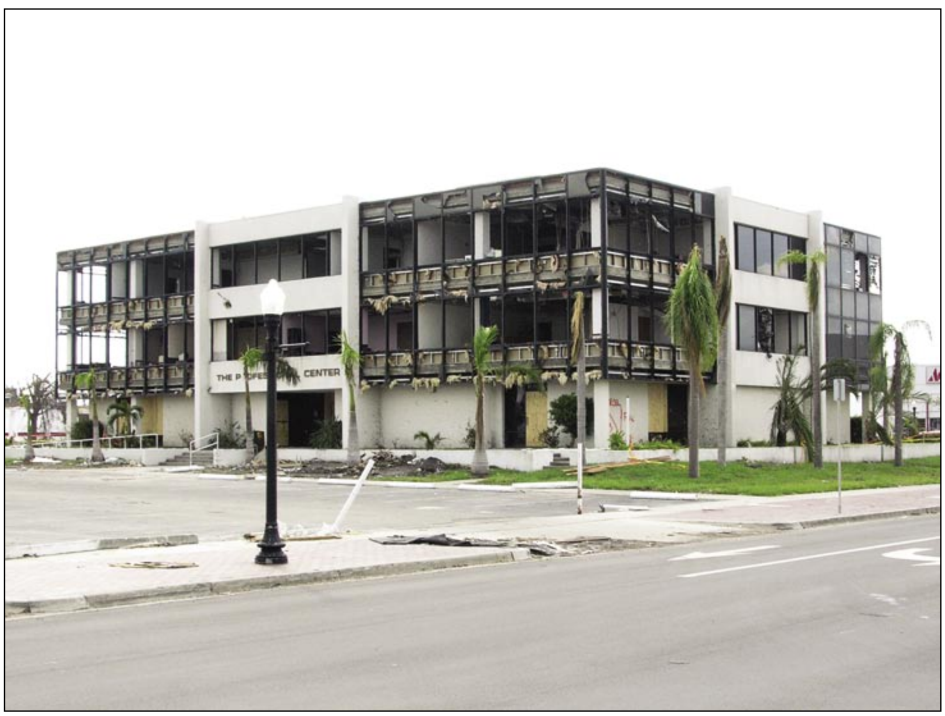

Figure 5-18.
All of the glazing, including glass spandrel panels, was broken on the long side of the building (Punta Gorda).

Figure 5-19.
Windows broken by aggregate from a nearby BUR. Besides impact at the crack intersection, aggregate chipped the glass in three other locations (Punta Gorda).

At a Charlotte County government building in Punta Gorda, a few of the windows were broken by windborne debris. Figure 5-20 shows missing spandrel panels; in other locations, the glass was broken. The windows extended from the floor to the ceiling, so tempered glass was used for personnel protection. Had laminated glass been used instead, any damaged glass would likely have stayed in its frame and would have provided wind and water protection. Glass broken by windborne debris was also observed at a hospital in Arcadia (Figures 3-41 and 6-8) and some of the fire stations in Port Charlotte and Punta Gorda.

Figure 5-20.
Plywood panels installed where aluminum spandrel panels were blown out of the curtain wall (Punta Gorda)

Skylights were not particularly common in the area, but a couple of failures were noted. In one case, the skylight in the bathroom of a manufactured home was broken by flying debris, allowing water to flood the bathroom. In another case, the failure of a skylight and difficulties in getting it replaced resulted in building officials prohibiting the owners from inhabiting their house for 2 months following the storm.

Skylights were observed at a fire station on Pine Island in the service garage area; one of these skylights blew out. It was an old plastic skylight that integrated with an R-panel roof covering. This skylight likely failed due to inadequate resistance to wind pressures rather than by missile damage.

5.3 Roof Systems

Historically, damage to roof coverings and rooftop equipment is the leading cause of building performance problems during hurricanes. Rains accompanying a hurricane can cause water to enter buildings through damaged roofs, resulting in major damage to the contents and interior (Figures 5-21 and 5-22). Unless quick action is taken to dry a building, mold bloom can quickly occur in the hot, humid Florida climate. Drying of buildings was hampered after Hurricane Charley by the lack of electrical power to run fans and dehumidifiers. These damages frequently are more costly than the roof damages themselves. Water leakage can also disrupt the functioning of critical and essential facilities and weaken ceilings and cause them to collapse. Although ceiling collapse is unlikely to result in death, it can cause injury to occupants and further frighten them as they ride out the hurricane.

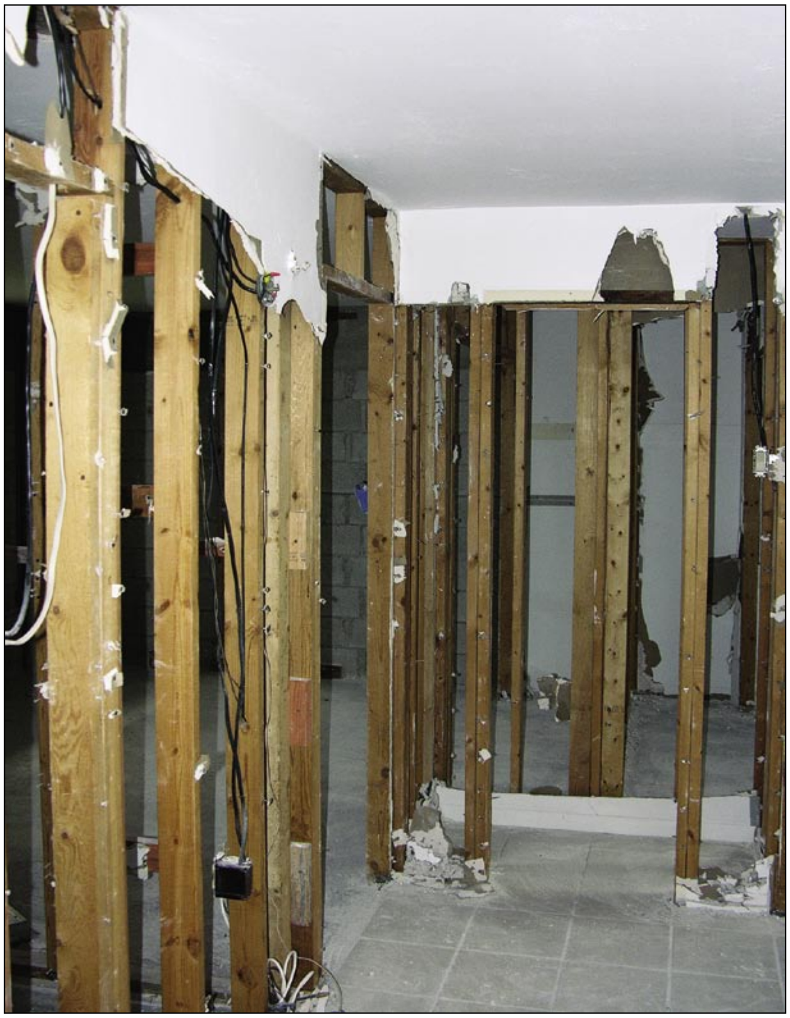

Figure 5-21.
After the attic vent failed, water entered this residence. Wet carpeting and a substantial amount of wet gypsum board had to be removed (Punta Gorda Isles).

Figure 5-22.
The attic vent to the right (temporarily covered with felt) on this foam-set tile roof lifted during the hurricane and allowed water to enter the residence shown in Figure 5-21. The failed vent is like the one on the left (Punta Gorda Isles).

Essentials to good high-wind roof system performance include selection of a suitable system; product testing to ensure sufficient factored strength to resist design wind loads; enhanced design of details; quality application; and timely maintenance and repair. In addition, for critical and essential facilities in hurricane-prone regions, it is important to design a roof system that is likely to avoid water infiltration if the roof is hit by windborne debris (guidance is given in FEMA 424, *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds*).

For steep-sloped roofs, a secondary water penetration barrier that minimizes the water infiltration through the sheathing, if the roof cover fails, offers important backup protection for shingle, tile, and metal panel installations. Figure 5-23 illustrates the installation of self-adhering modified bitumen tape at sheathing joints. The tape is installed at the joints to allow water to shed off the sheathing if the primary roof covering (e.g., shingles) and underlayment are blown off.

In lieu of attaching metal panels directly to structural members, installation of a roof deck between the panels and structure is preferred in hurricane-prone regions. The deck provides increased protection from windborne debris in the event of roof panel blow-off, as well as an opportunity for a secondary membrane.

Figure 5-23. Installation of self-adhering modified bitumen tape at sheathing joints, as part of an enhanced underlayment system on a Fortified…for safer living™ house under construction (IBHS)

5.3.1 Asphalt Shingles

Although damage was observed on several new roofs (Figures 3-14, 4-11, and 5-24), in general it appeared that asphalt shingles installed within the past few years performed better than shingles installed prior to the mid-1990s. The enhanced performance is likely due to product improvements (e.g., availability of greater bond-strength of the self-seal adhesive and availability of greater adhesive surface area) and less degradation of physical properties due to limited weathering time. It is doubtful that any of the observed roofs had been designed in accordance with UL Standard 2390, which was published in 2003. This standard pertains to two main items: 1) it provides a lab test method that manufacturers use to establish pressure coefficients for specific types of shingles; and 2) it provides a calculation procedure for a designer to determine the design wind load on the shingles, which is based on the coefficient from the testing, ASCE 7 criteria such as basic wind speed, and factors developed specifically for shingles. FEMA *Hurricane Recovery Advisories No. 1 and No. 2* (Appendix D) provide recommended practices for asphalt shingles on roofs in hurricane-prone regions. FEMA *Hurricane Recovery Advisories No. 1* and *No. 2* were based on guidance given in the fact sheets for FEMA's *Home Builder's Guide to Coastal Construction* (to be published).

Many shingle roofs in the Port Charlotte and Punta Gorda area were undamaged, while others lost a few hip and/or ridge shingles or a few tabs. Other roofs, including roofs far inland, lost many shingles, as shown in Figures 5-24 and 5-25. The shingles shown in Figure 5-24 were attached with 6 nails per shingle, but the nails were attached about 1½ inches above the nail line. In addition, the shingles were poorly bonded. Though continuous, the self-seal strip was narrow (approximately ½ inch). When shingles were pulled apart during the investigation, many granules from the underlying shingle were pulled up, thus indicating that the granules were not well embedded. The starter course was incorrectly applied, and the nails at the hip shingles were incorrectly located. Note the area where the deck is exposed. Water can flow between the deck and underlayment and leak into the building at the sheathing joints.

Figure 5-24.
Asphalt shingle roof installed on a new residence about 2 months before the hurricane hit; shingles were blown off several areas (Deep Creek).

Hip or ridge shingles were often blown off while the remainder of the shingles were undamaged. The fasteners on all of the hip and ridge shingles that were observed were located in or above the self-seal adhesive, rather than below the adhesive as recommended by the industry. However, the hip and ridge shingles were blown off because of lack of bonding of the adhesive. Sometimes a limited amount of bonding occurred as shown in Figure 5-26, but frequently none of the adhesive had bonded. Lack of bonding of hip and ridge shingles is common. Figure 5-2 shows nails that were improperly installed through the adhesive strip; they should have been driven below it. Use of asphalt cement to bond hip, ridge, and rake shingles (as recommended in FEMA 55, *Coastal Construction Manual*) was observed on only one roof.

Figure 5-25.
Residence with a significant number of asphalt shingles lost. The metal window shutters shown were not designed for windborne debris (Fort Meade).

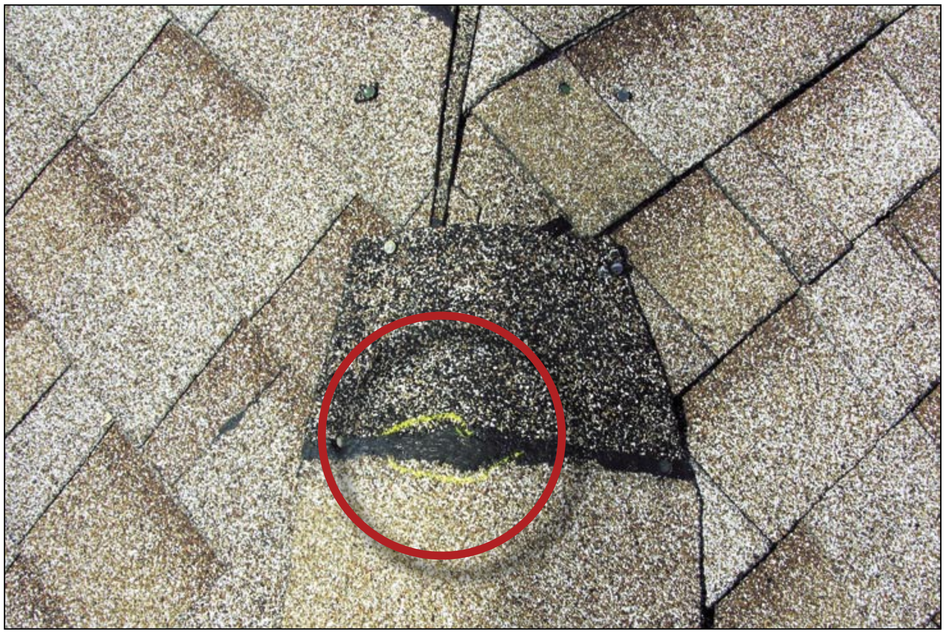

Figure 5-26.
Only the portion of the self-seal adhesive that is indicated in yellow had bonded (within the red circle). No bonding occurred on the right side of the hip line (Deep Creek).

Only one of the observed starter courses complied with industry recommendations. A common practice was to turn the starter shingle 180 degrees, rather than cut off the tabs. By turning the starter 180 degrees, the tabs of the first course of shingles were not bonded to the starter course, thereby making them susceptible to lifting. Use of asphalt cement to bond the first course (as recommended in FEMA 55, *Coastal Construction Manual*) was not observed.

On a few roofs with architectural shingles, instances of blow-off of laminated tabs were observed (Figure 5-27). This type of failure was due to an inadequate amount and/or strength of adhesive used in the manufacturing of the shingles.

Figure 5-27.
Two laminated tabs blown off (Deep Creek)

In many instances where shingles were blown off, the underlayment was not damaged and, therefore, provided some degree of protection from water infiltration. In other instances, the underlayment was also blown off. Rain was then able to enter the building at the sheathing joints. FEMA *Hurricane Recovery Advisory No. 1* (Appendix D) provides recommended practices for underlayments on roofs in hurricane-prone regions, including the use of self-adhering modified bitumen tape at the sheathing joints as shown in Figure 5-23.

On many residences that had been re-covered (i.e., new shingles had been installed on top of old shingles), large numbers of the re-cover shingles were blown away and the underlying older shingles remained in place. Some of these blow-offs may have been due to use of nails that were too short, although on the building shown in Figure 5-28, the nails had adequate sheathing penetration, but the newer shingles were poorly bonded (likely due to substrate irregularities). When re-covering versus tearing off the old shingles down to the sheathing, more substrate irregularity occurs, which can interfere with bonding of the self-seal adhesive of the new shingles. Most of the re-cover blow-offs were likely due to bonding problems associated with substrate irregularities.

Figure 5-28. Re-covered apartment building (the newer shingles are grey and the older shingles are brown) (Deep Creek).

The shingles on the roof of the elementary school shown in Figure 5-29 were installed over underlayment over two layers of gypsum board atop a steel deck. The shingles were attached with a split-shank self-locking nail. At the rakes, the shingles were set in asphalt roof cement over the metal edge flashing (somewhat similar to the detail shown in FEMA *Hurricane Recovery Advisory No. 2* (Appendix D)). The 4½-inch vertical flange of the edge flashing was not cleated. At this rake and another rake, the edge flashing lifted. Because the shingles were well bonded to the flashing, they progressively failed. The shingle end nails at the rake were well inward of the industry's recommended 1-inch placement. One of the end nails was 4 inches in from the edge of the shingle. Adhering the shingles to the edge flashing was a good practice, but the end nails should have been much closer to the edge, and the edge flashing should have had a much shorter vertical flange or the flange should have been face-fastened or cleated. Several of the laminated tabs at this school were blown off (similar to Figure 5-27). This type of failure was due to an inadequate amount and/or strength of adhesive used in the manufacturing of the shingles.

A portion of the shingles at the fire station in Cape Coral (constructed in 1991) also blew off. Water leaked into the room housing the Emergency Management Services (EMS) computer equipment, resulting in minor damage. Minor damage also occurred at a post office on Pine Island that was constructed in 1993. Performance was quite good except for the loss of a few hip shingles and laminated tabs (similar to Figure 5-27). At a fire station in Punta Gorda, many of the three-tab shingles were blown off, and many of the staples were incorrectly oriented. This was one of the few roofs observed that had been attached with staples.

Figure 5-29.
Edge flashing that caused a progressive failure of the shingles (Deep Creek)

Several instances of ridge vent blow-off were observed. The performance of ridge vents with respect to prevention of wind-driven rain infiltration during the hurricane was not evaluated.

The use of a larger number of nails (six instead of four) to attach shingles may have also played a role in the improved resistance of some of the newer roofs, but this was not verified through detailed inspections of the installations because it would have required access to the attics. The fasteners on all of the damaged shingles that were observed were located too high above the nailing line (i.e., the line printed on the shingle by the manufacturer). Fasteners were typically located 1 to 2 inches above the nailing line. End fasteners were often 2 to 3 inches from the end, rather than the industry-recommended 1 inch. Nails rather than staples were used to attach most of the shingle roofs that were investigated.

5.3.2 Tiles

Clay and concrete tiles were observed, with concrete being the most common. A variety of tile profiles (e.g., S-tile and flat) were also observed, but no significant wind performance differences were attributed to profile. Mortar-set, mechanically attached, and foam-set (adhesive-set) attachment methods for tile roofs were observed during the assessment. Tile damage was observed along the path of the hurricane from the Port Charlotte/Punta Gorda area to Orlando. For the areas east of Port Charlotte and Punta Gorda, damage was typically limited to blow-off of hip and ridge tiles and blow-off of tiles along eaves. In the areas of Port Charlotte and Punta Gorda that received very high winds, there were larger areas of blown-off tiles. Tile underlayments were generally not blown off, with few exceptions (Figure 5-30). Therefore, many buildings with significant tile damage likely experienced little, if any, water infiltration from the roof.

Figure 5-30.
A large area of underlayment at this mortar-set flat tile roof blew away. The loss of tile underlayment was atypical (Punta Gorda).

5.3.2.1 Mortar-Set Tile Roofs

The size of the blow-off area of tile roofs attached using mortar-set systems was typically much greater than for tile roofs attached using foam-set and mechanically attached systems. Figure 3-31 showed a mortar-set roof with a large area of blown-off tiles.

On the roof shown in Figure 5-31, some of the tiles debonded from the mortar patties; other tiles debonded from the underlayment; and, in other instances, the underlayment tore off with the mortar. Mixed failure modes also occurred on the roof shown in Figure 5-32. Mixed failure modes also occurred in Hurricane Andrew (FEMA FIA-22, 1992). The mortar patties at the roofs shown in Figures 5-31 and 5-32 were incorrectly located, and most of them were too small.

On the roof shown in Figure 5-32, most of the mortar-set hip and ridge tiles blew off. Some of the mortar-set flat tiles were also blown off, and other field tiles were broken by windborne debris (likely other tiles from this roof). Figure 5-33 shows three tiles from the roof shown in Figure 5-32. The mortar paddy on the left debonded from the underlayment. For the other two tiles, the underlayment tore away. The paddies were incorrectly located near the head of the tiles, which offers reduced uplift resistance.

Figure 5-31.
Mixed failure modes occurred on this mortar-set tile roof (Port Charlotte).

Figure 5-32.
Most of the mortar-set hip and ridge tiles blew off this house (Port Charlotte).

Figure 5-33.
Tile debris from the roof shown in Figure 5-32 (Port Charlotte)

5.3.2.2 Mechanically Attached Tile Roofs

Both direct-to-deck and batten-attached systems were investigated. Figure 5-34 shows a batten-attached system where the roof is attached with nails. According to 2001 FBC (Table 1507.4.7), the attachment method observed on the roof shown in Figure 5-34 is suitable for buildings with a mean roof height up to 40 feet in areas with a design wind speed of 100 mph.[1] The building (which has a mean roof height of less than 15 feet) is located in an area that is now mapped with a wind speed of approximately 110 mph; therefore, the installed attachment at this older residence was inadequate to meet the current code. The estimated speed at this Exposure B location was in the range of 110 to 120 mph. If the speed was in the lower portion of this range, the tiles did not perform as predicted by 2001 FBC (i.e., the tiles should have been good for 100 mph at a roof height up to 40 feet).

[1] In this chapter, basic wind speeds cited from the 2001 FBC are 3-second peak gust wind speeds, Exposure B, unless otherwise noted.

Figure 5-34.
Each tile on this building was attached to battens with a single 3$^{1}/_{8}$-inch long smooth shank nail (Arcadia)

The building shown in Figures 5-35 and 5-36 is located in an area with a basic wind speed of approximately 120 mph. The 2001 FBC, therefore, requires compliance with the calculation method given in Section 1606.3.3. Load and resistance data can be found in the March 1, 2003, Addendum to the 3rd edition of the *Concrete and Clay Tile Installation Manual* (published by the Florida Roofing, Sheet Metal and Air Conditioning Contractors Association [FRSA] and Roof Tile Institute [RTI]). The roof in Figures 5-35 and 5-36 was attached with one 2½-inch long screw per tile directly to the deck. According to Table 12 of the Addendum, the attachment of this roof is suitable for buildings with a mean roof height up to 40 feet in areas with a basic wind speed of 150 mph. The estimated speed at this Exposure B location was in the range of 125 to 140 mph; therefore, the tiles did not perform as predicted by the *Concrete and Clay Tile Installation Manual*.

At a residence near the one shown in Figure 5-35, missiles (likely tiles from its roof) broke a few field tiles. The field tiles were attached with one screw per tile directly to the deck.

Figure 5-35.
Windborne debris (likely tiles from this roof) broke several of the field tiles (Deep Creek).

Figure 5-36.
Loss of mortar-set hip tiles and several of the field tiles. Some of the screws remained in the deck, while others had been pulled out (Deep Creek).

Figure 5-37 shows several areas where batten-attached tiles on a fire station were damaged. The tile debris on the lower roof is from the upper roof. The tiles were installed when the building was re-roofed in the mid- to late-1980s. According to the 2001 FBC (Table 1507.4.7), the attachment method observed on this roof is suitable for buildings with a mean roof height up to 40 feet in areas with a basic wind speed of 100 mph. The building (which has a mean roof height of less than 30 feet) is located in an area that is now mapped with a basic wind speed somewhat less than 110 mph; therefore, the installed attachment at this pre-2001 FBC building does not meet the current code. The estimated speed at this Exposure B location was in the range of 95 to 110 mph. The tiles did not perform as predicted by the code (i.e., the tiles should have been good for 100 mph at a roof height up to 40 feet).

Figure 5-37.
Fire station with at least three battens blown off. Some tiles remained attached (Fort Meade).

5.3.2.3 Foam-Set Tile Roofs

The foam-set attachment method was developed after Hurricane Andrew in response to the widespread poor performance of mortar-set systems. Hurricane Charley was the first hurricane to deliver at or near-design wind speeds to this new attachment method. One- and two-part specially formulated polyurethane foam tile adhesives are available. Depending upon design uplift pressures and tile profiles, a variety of proprietary paddy schemes are available, including single paddy placement (with either small, medium, or large paddies) and two paddy placements. Although large areas of blow-off were unusual with this attachment method, they were observed on some residences.

A large number of damaged foam-set systems were observed as shown in Figures 5-38 through 5-45. Significant installation problems were observed with the size and/or location of the foam paddies. The side of the residence shown in Figure 5-38 was the side the damaging winds came from. Assuming the intent was to provide a small paddy placement, according to the foam manufacturer's literature, this attachment would have been suitable for a basic wind speed of 135 mph in Exposure B (assuming proper application). According to the 2001 FBC, the basic wind speed where this residence is located is approximately 125 mph; therefore, this small paddy placement meets code. The estimated Exposure B wind speed at this site was in the range of 125 to 140 mph. If the foam paddies had been properly sized and located according to the manufacturer's literature, the tiles should not have blown off.

In Figure 5-39, to meet the small paddy placement criteria, the paddy should have been 3 inch by 3 inch minimum, with approximately 8 to 9 square inches of foam contact with the tile near the head. As shown in the photo, clearly there was very insufficient contact area. The paddies were rectangular rather than square; perhaps a medium paddy placement was intended. To meet the medium paddy placement criteria, the paddy should have been 2 inch by 7 inch minimum, with approximately 12 to 14 square inches of foam contact area. The small round paddies shown in Figure 5-39 were placed after the down-slope tiles were set. Foam from these paddies occurred between the tile end laps. These round paddies are not shown in the foam manufacturer's installation instructions. Although failed tiles typically debonded from the paddies, in at least one location, the paddy debonded from the cap sheet underlayment.

Figure 5-38.
In addition to the damage shown in this photo, this one-story roof lost virtually all of the hip and ridge tiles (see Figures 5-22, 5-39, and 5-40) (Punta Gorda Isles).

Figure 5-40 is a close-up of the eave area of the roof shown in Figure 5-38. The manufacturer's installation instructions do not require screws, but they do require foam paddies.

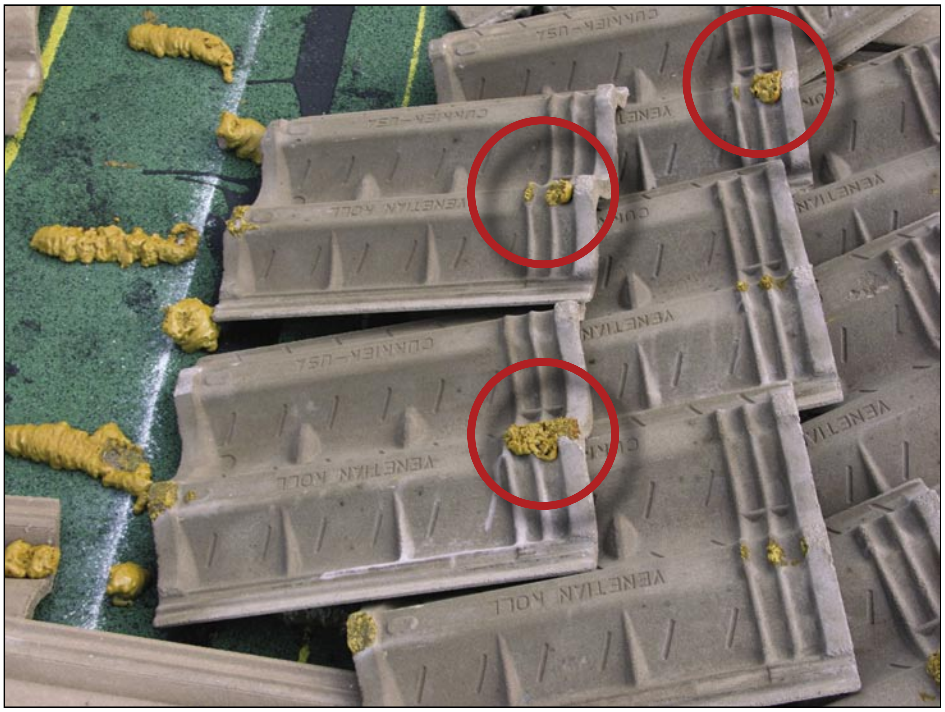

Figure 5-39.
Note the very small contact area of foam at the tile heads (left side of the tiles) and very small contact area at the tails. The long narrow paddies were intended to be underneath the pan portion of the tile (Punta Gorda Isles).

Figure 5-40.
View of the eave. The first row of tiles was attached with two screws per tile; foam was not used to adhere this row (Punta Gorda Isles).

The residence shown in Figures 5-41 and 5-42 was located in an area identified in the code with a basic wind speed of approximately 125 mph. Assuming the intent was to provide a small paddy placement, according to the foam manufacturer's literature, this attachment would have been suitable for a basic wind speed of 135 mph in Exposure B (assuming proper application). The estimated speed at this Exposure B location was in the range of 125 to 140 mph. Therefore, had the foam paddies been properly sized, located, and installed according to the manufacturer's literature, the tiles should not have blown off.

To meet the small paddy placement criteria, the paddy should have been 3 inch by 3 inch minimum, with approximately 8 to 9 square inches of foam contact with the tile near the head. The paddies were typically about the correct size, but they did not achieve the required contact area (see inset in Figure 5-42). The paddies were also typically located too close to the upslope end of the tile. In Figure 5-42, the first row of tiles at the eave was attached with one nail and a foam paddy. Most of the nails remained in the deck. The foam manufacturer's instructions do not require nails at the eave. (The dark spots on the tile are rain drops.) An attic vent also rolled back and allowed water to enter the building.

Figure 5-41.
In addition to field tile blow-off, most of the hip tiles and several ridge tiles were also blown off this house (Punta Gorda Isles).

Figure 5-42.
The paddy on the tile at the lower left debonded from the asphalt bleed-out near a cap sheet lap. Only the center portion of the paddies made contact with the tiles, as shown in the inset (Punta Gorda Isles).

Several foam-set tiles were blown off a one-story bank (Figures 5-43 through 5-45), primarily due to insufficient contact area of the paddies. To meet the small paddy placement criteria, the paddies should have provided approximately 8 to 9 square inches of foam contact with the tile near the head. The paddies were observed to be about the correct size, but they did not achieve the required contact area. The paddies were also typically located too close to the upslope end of the tile. Though not required, a very small paddy was placed at the tile overlaps (red arrow in Figure 5-43). The tiles typically debonded from the paddies, but the two paddies shown at the bottom of Figure 5-43 debonded from the cap sheet. Many mortar-set hip and ridge tiles were also blown off. The bank was located in an area identified in the code with a basic wind speed of approximately 125 mph. Assuming the intent was to provide a small paddy placement, according to the foam manufacturer's literature, this attachment would have been suitable for a basic wind speed of 135 mph (assuming proper application). The estimated speed at this location was in the range of 125 to 140 mph. Therefore, had the foam paddies been properly sized and located, according to the manufacturer's literature, the tiles should not have blown off.

Figure 5-43.
This photo clearly shows insufficient contact area of foam-set paddies on the bank's roof (Punta Gorda Isles).

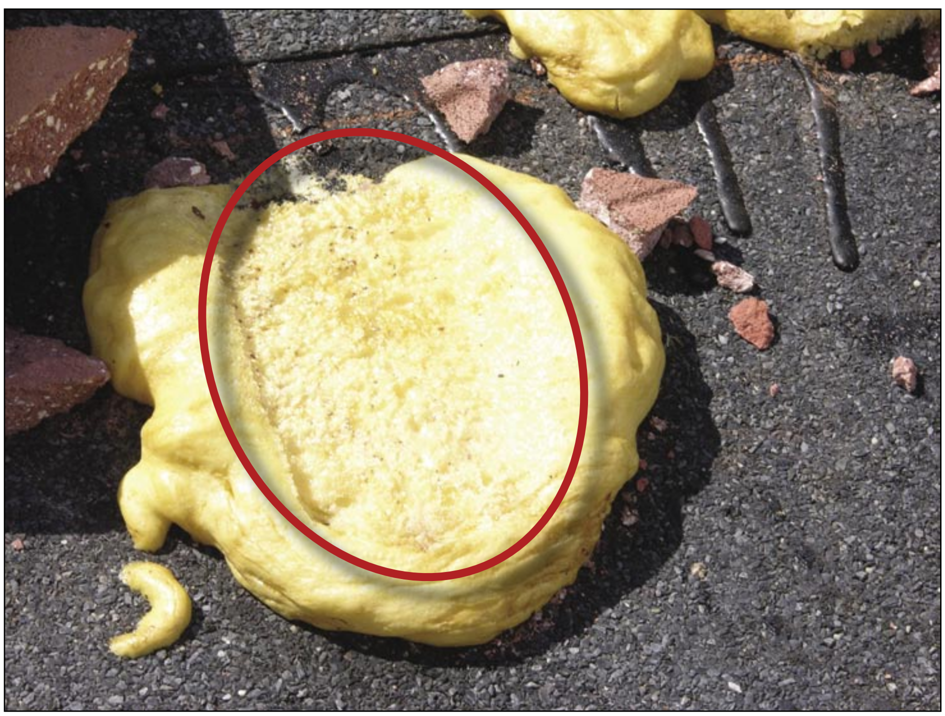

Figure 5-44.
In this photo, the portion of the paddy that made contact with the tile is clearly visible (Punta Gorda Isles).

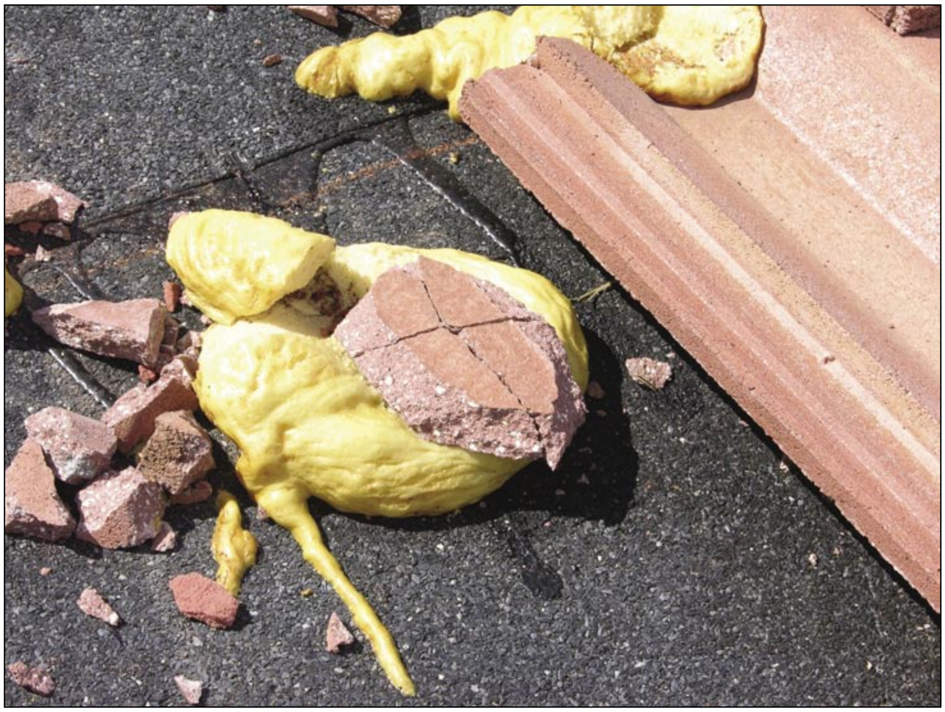

Figure 5-45.
Tile remained bonded to the paddy, but, except where bonded, the tile blew away. A large portion of the paddies shown in Figure 5-43 and this figure failed to make tile contact, which was a typical observation (Punta Gorda Isles).

5.3.2.4 Hip and Ridge Tiles

Blow-off of hip and ridge tiles as shown in the previous figures was very common, even in areas with only moderate wind speeds. Most of the hip and ridge tiles that were investigated were attached with mortar, although a few were attached with mortar and a single nail. The installation of a nail near the head of the hip and ridge tiles did not greatly improve blow-off resistance. Because the hip and ridge tiles project several inches above the adjacent field tiles and form a transition between different roof surfaces, the raised hip/ridge line of tiles may be subjected to higher wind loads than expected on the field tiles due to turbulence. This research issue is worthy of future investigation. The vulnerability of hip and ridge tile blow-off was documented following Hurricane Andrew (FEMA FIA-22, 1992). It was reported that the current design guidelines were inadequate (T.L. Smith, 1994).

5.3.2.5 Sprayed Polyurethane Foam

A few tile roofs that had been covered with sprayed polyurethane foam (SPF) were investigated by the MAT. Figure 5-46 shows one of these roofs. A missile had impacted the foam and gouged it in several locations, but no tile debris was blown off. The SPF appeared to provide some protection for the tiles. However, SPF applications may not improve the uplift resistance. Figure 5-47 shows a roof that lost SPF covered tiles. In this instance, the SPF bonded tiles together and, as a result, large sections of tiles were lifted off the roof. Although the larger fragments should not fly as far as smaller fragments, because they are more massive, they could be more damaging (depending upon their velocity) if they were to become windborne.

Figure 5-46.
This residence had a tile roof that had been covered with SPF. A missile gouged the foam, but no tile debris was blown off (Punta Gorda Isles).

Figure 5-47.
The other side of the roof shown in Figure 5-46 with a portion of the underlayment and several tiles blown off (Punta Gorda Isles)

5.3.2.6 Tile Missiles

There were many reports of tiles or tile fragments hitting occupied buildings and flying through windows (shown previously in Figures 3-31 and 3-32). The owner of one residence reported that six of their windows were broken by tiles from a neighbor's house (Figure 5-48). The homeowner's metal roof was not damaged, but wind-driven rain forced through the broken windows caused extensive interior wind and water damage.

Figure 5-48.
Tiles that flew through windows of an occupied residence (Deep Creek)

In addition to becoming windborne debris and further damaging the roof on which they were installed, many tile roofs were damaged by other types of windborne debris. One of the advantages of foam-set, according to one of the manufacturer's literature, is that foam-set installation is supposed to result in "high resistance to damage from missile impact," meaning that the "tile may break but remains adhered to the roof." Although this may be true for the portion of the tile that is adhered, the MAT observed that broken portions that are not adhered are vulnerable to being blown away as shown in Figure 5-49.

It is important to note that other types of roofing systems are also capable of generating windborne debris (Figure 3-34); however, missiles are most problematic with tiles. FEMA *Hurricane Recovery Advisory No. 3* (Appendix D) provides recommended practices for tiles on roofs in hurricane-prone regions. This Advisory was based on observations from Hurricanes Charley, Frances, and Ivan.

Figure 5-49.
A view of the roof on the back side of the residence shown in Figure 5-41. Tiles (including a hip tile) from the front garage roof landed in this area and broke several field tiles (Deep Creek).

5.3.3 Metal Panel Roofs

Although small in number compared to houses with asphalt shingle and tile roofs, several residences in the Port Charlotte, Punta Gorda, Pine Island, and Sanibel and North Captiva Island areas had metal roof coverings. Many of these coverings were 5V-Crimp metal panels. This type of panel uses exposed fasteners (Figure 5-50). The majority of the 5V-Crimp metal panel roofs observed were not damaged, or only experienced hip or ridge flashing damage. However, significant panel loss was observed at a few residences. At a fire station on Pine Island, the 5-V Crimp metal panels blew off the main building and the plywood panels blew off with the panels. Furring strips (1x) occurred between the plywood and the trusses. The furring strips, which had been stapled to the trusses, were lifted off with the plywood and likely were the cause of the panel loss. There was significant water infiltration; however, a temporary roof had been installed after the hurricane, and the station was occupied at the time of the investigation.

Success or failure of the 5-V Crimp metal roof coverings was likely primarily dependent upon fastener spacing and type, although panel gauge may have had some influence (panels are available in 24 to 29 gauge). Screws provided greater pull-out resistance than ring-shank nails and were more resistant to dynamic loading. One of the failed roofs that were investigated was attached with ring-shank nails.

Another key element of good performance is the spacing of fasteners along the eave and at hip and ridge flashings. Only a single fastener occurred at the eave between the rib fasteners shown in Figure 5-50; considering the basic wind speed of 125 mph 3-second peak gust in this location, use of two fasteners between the ribs would have been prudent. Note that the hip flashing is bowed; two fasteners between the ribs would have also been prudent at the flashings. Close spacing at the flashings and eave is important to keep the flashings and panel ends from billowing during high winds. Although the roof in Figure 5-50 did not fail, the flashing and eave fasteners were too far apart.

Figure 5-50.
The number of fasteners was not increased at the corner, perimeter, hip, or ridge areas (close-up of the residence shown in Figure 5-5). Also note that several of the soffit panels were blown away (Deep Creek).

Most of the 5V-Crimp panels that blew off failed as a result of the panel fasteners pulling out of the sheathing. However, plywood substrate blow-off and wood nailer failures were also observed (Figure 5-51). The upper asphalt shingle roof shown in Figure 5-51 had been re-covered with 5V-Crimp panels attached to nailers. The nailers were inadequately attached to the sheathing. Note that the hip flashing on the lower roof blew off.

Figure 5-51.
These panels blew off the upper roof and landed on the lower roof of this house (Bokeelia, north end of Pine Island).

All of the 5V-Crimp roofs that were observed were unpainted galvanized or aluminum-zinc alloy ("Galvalume") panels. Aluminum-zinc alloy panels are very resistant to corrosion. No significant corrosion problems were observed. An advantage of 5V-Crimp (and other types of exposed fastener) panels (versus panels with concealed clips) is that, after installation, it is easy to verify that the correct number of fasteners were installed.

A variety of architectural metal panels were also observed. As with the 5V-Crimp panels, some of the roofs were undamaged, others had lost hip or ridge flashings, and others lost a large number of panels. Performance of architectural panels is a function of the strength of the panels and their interlock with the clips, clip spacing and attachment, and strength of the flashing attachments. Some of the failed hip and ridge flashings were attached with cleats rather than exposed fasteners. Cleat attachment is not as reliable as exposed fasteners.

When metal panels or hip/ridge flashings blow off, they can become high-energy windborne debris that can damage buildings and other property and cause injury. These types of windborne debris can travel a considerable distance.

A variety of exposed fastener and architectural and structural metal panels were observed on commercial and critical/essential facilities. Figures 5-52 through 5-54 show a medical office building that lost approximately 75 percent of the superstructure supporting the architectural metal panel roof that encircled the perimeter of the building. This building experienced significant water damage. Although much of the aggregate roof covering remained in the center portion of the roof, temporary roof covering (Figure 5-53) was installed to minimize water intrusion after the metal panel structure blew away.

Figure 5-52. Medical office building (Port Charlotte).

Figure 5-53. The wood and metal framed superstructure blew away and exposed the lightweight insulating concrete roof deck (Port Charlotte).

Figure 5-54.
View of the canopy ridge at the building shown in Figure 5-52. The ridge flashing fasteners were placed too far apart. A significant amount of water leakage can occur when ridge flashings are blown away (Port Charlotte).

Figure 5-55 shows a roof on a school in Arcadia that performed fairly well; the building was located inland in an area that experienced approximately 110 to 120 mph wind speeds. Temporary repairs to the roof covering had been made prior to this photo taken by the MAT.

Figures 5-56 and 5-57 show an architectural panel roof on a fire station in the Deep Creek area that performed poorly, with metal panels that were blown off. At this station, the 2-inch high ribs had a 16-inch spacing. The panels had a single-lock fold. There were two screws per clip. Typically the clips remained attached to the deck, but some did not. Clip spacing varied widely across the roof and from panel to panel with spacings ranging from 2 feet 4 inches to 3 feet 3 inches. The eave clips shown in Figure 5-57 should have been located near the edge. It would have been prudent to install double clips along the eave.

At the headwall flashing, the flashing was pop-riveted to the panels at 16 inches on center. Along one side of the hip, the flashing was attached at 2 feet 2 inches; on the other side of hip line, they were at 1 foot 10 inches. The hip and headwall flashing fastener spacing was excessive; for the building code design requirements in Charlotte County, a fastener spacing of 4 to 6 inches on center is typically used, depending on the design wind speed at one site. Some panels on another roof area were damaged by windborne debris (OSB panels), and water entered the building at the penetration location.

Figure 5-55.
This standing seam metal roof had a 16-inch rib spacing. There was some rake flashing damage, and a few rake panels were also damaged (Arcadia).

Figure 5-56.
Several of the architectural panels and hip flashings blew off this fire station (Deep Creek).

Figure 5-57.
This photo provides a view of the eave of the building shown in Figure 5-56. The clip at the left was 13 inches from the edge of the deck. The other clip was 17 inches from the edge (Deep Creek).

Several structural standing-seam trapezoidal panel system failures were observed, including the panels on the Turner Agri-Civic Center in Arcadia, which partially collapsed (see Section 6.5.1.1. and Figures 6-17 and 6-18). It was reported that the roof covering was lifting prior to the collapse. The panels were installed over fiberglass batts over a vapor retarder atop the light-gauge purlins.

Figure 5-58 shows an exposed fastener R-panel roof on two old pre-engineered metal buildings that had been re-covered with SPF. A large wall section blew out of one of the buildings, and the edge flashing was torn away, but the metal roof panels remained in place. At an adjacent building with a similar roof, the metal panels on a canopy were blown away, but the failure did not propagate into the roof panels on the main building. The SPF covering likely prevented progressive failure at both of these buildings due to the stiffness that it imparted to the panels.

Figure 5-59 shows a mansard with metal shingles simulating tiles. The metal shingles performed well. However, metal shingles can also experience significant damage as discussed in FEMA 489, *Hurricane Ivan in Florida and Alabama.* Note that the rooftop mechanical equipment in Figure 5-59 remained attached to the support stands. Also note the lightning protection system on the parapet in the foreground. One of the conductor connectors detached from the roof and the conductor pulled out of some of the connectors.

Figure 5-58. The metal wall panels and metal edge flashing on this building blew away, but the exposed fastener R-panels with an SPF covering did not progressively fail (Wauchula).

Figure 5-59. Metal shingles (simulating tile) that performed well (Port Charlotte)

5.3.4 Low-Slope Membrane Systems

The MAT observed several types of low-slope roof systems. These systems included BURs, modified bitumen, and single-ply, which are described below.

5.3.4.1 Built-Up Roof (BUR) and Modified Bitumen

A BUR failure was observed at one of the terminals at the Orlando International Airport. Portions of its BUR blew off, resulting in water infiltration. To dry out the interior and to avoid mold growth, the airport used large air dryers to remove the moisture.

At a hospital in Arcadia, several windows at the intensive care area were broken by windborne debris (Figure 6-8). Most, if not all, of the windborne debris was aggregate from the hospital's roofs. Three of the eight intensive care rooms were taken out of service due to the glass breakage and windows were broken in other patient rooms. Gutters and walkway pads were also blown off (Figure 5-60). The gutters and pads possessed sufficient mass to be very damaging missiles and may have caused some of the glass breakage observed.

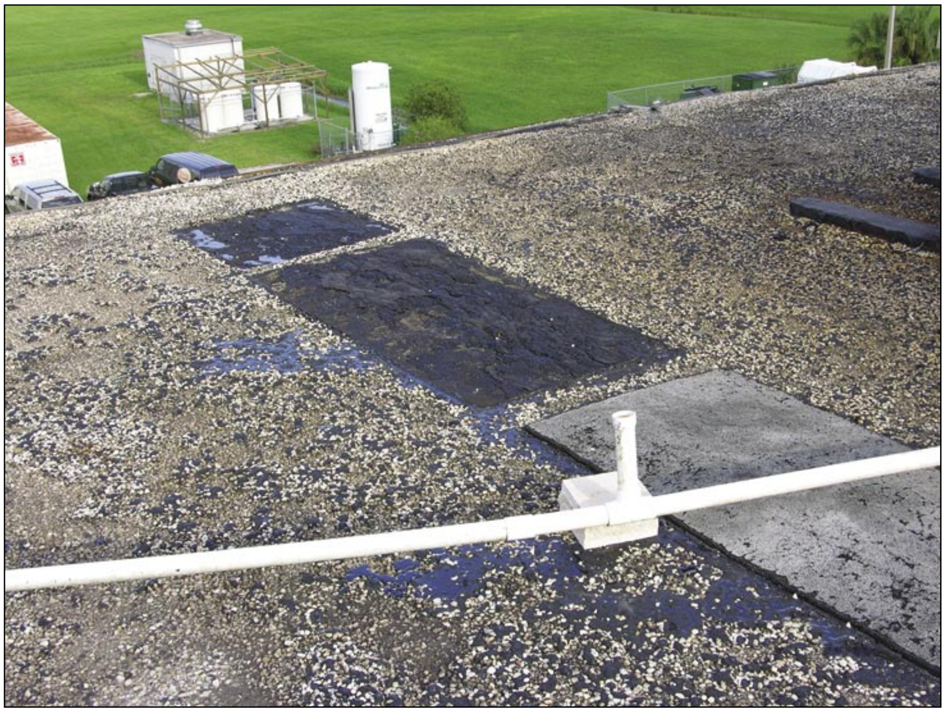

Figure 5-60.
This view of the back side of the upper roof of a hospital (see Figure 6-8) shows that the missing gutter and asphalt plank walkway pad were blown away (Arcadia).

Aggregate commonly used on BUR systems was blown off many buildings. One example is shown in Figure 5-61 where the school was being used as a shelter. There was no other apparent damage to the roofs at the school, including the mechanically attached single-ply membrane on a courtyard building. The boarded-up broken windows at the residence across from the school in Figure 5-61 were likely broken by aggregate from this roof. Roofing aggregate was found at the far side of the street in front of the house. The inner leg of the coping in Figure 5-61 was attached with screws spaced at 3 feet 5 inches, 2 feet 11 inches, and 3 feet 1 inch; the coping was not damaged. Aggregate also blew off a new portion of a hospital in Port Charlotte, but no missile damage was observed. At another roof area of the hospital, a portion of the mineral surface cap sheet roof was blown off. The metal edge flashing had improperly been installed underneath the membrane; therefore, the flashing was unable to clamp the roof edge. Wind lifted the gutter and metal edge flashing and peeled the roof membrane. Figure 5-62 shows an area of the hospital roof that nearly failed. With the flashing in a lifted position, the membrane was very susceptible to peeling. Apparently the winds subsided before this occurred.

Figure 5-61.
Although this roof had an 11-inch high parapet, aggregate was blown off (Port Charlotte).

Figure 5-62.
The edge flashing at this mineral surface cap sheet roof lifted (Port Charlotte).

An edge flashing failure also occurred at a middle school in Cape Coral, first occupied in 1998 (Figure 5-63). This metal edge flashing had also been improperly installed underneath the membrane. The flashing should have been installed over the modified bitumen cap sheet and then stripped in to clamp the edge of the membrane. Wind lifted the gutter and metal edge flashing and peeled the modified bitumen membrane. The gutter was not designed for uplift resistance. A portion of a middle school in Port Charlotte also had a mineral surface BUR cap sheet roof, and the metal edge flashing had also been improperly installed underneath the membrane. However, none of the edge flashings lifted. Except for some missile damage, the BUR on this roof performed very well.

Figure 5-63.
The edge flashing had a 2-inch vertical flange that extended into the gutter. The flashing was not cleated (Cape Coral).

A high school in Arcadia had an aggregate surface BUR over lightweight insulating concrete (LWIC) over steel form deck that had been installed in the mid-1970s. Two areas over the cafeteria blew off, as did a portion over the gym. Repairs had been made by the time the MAT inspected, so it was not possible to definitively determine the cause of the failures. The failures at the cafeteria occurred several feet from the parapet. These failures may have been due to base sheet rupture around the fasteners (which may have been due to spacing problems, fastener corrosion, or deterioration of the base sheet), or deformation or cracking of the LWIC. At the gym roof, the blow-off area extended to the parapet, but it was unclear if the blow-off originated at the parapet. This roof may have failed for the reasons given at the cafeteria, or this failure may have been related to the coping or base flashing attachment. The 13½-inch-wide coping was attached only at each coping joint with three nails in the horizontal flange and one in the vertical flange. There was significant water infiltration in the cafeteria and gym.

5.3.4.2 Single-Ply

One aggregate ballasted system was observed in the Orlando airport area. Some aggregate was blown off the roof, but this may have been due to gutter blow-off. A detailed investigation was not performed. In addition to the BURs discussed above, one of the hospitals in Port Charlotte had single-ply membranes at two different areas. There was no apparent damage to the mechanically attached ethylene propylene diene monomer (EPDM) membrane roofs on the lower levels. However, there was extensive damage to the mechanically attached polyvinyl chloride (PVC) membrane (with 6-foot 3-inch row spacing) on the fourth floor roof (the highest roof), as shown in Figure 5-64. Emergency repairs had been made, so it was not possible to definitively determine the cause of the failure. Mechanical equipment was missing and portions of the lightning protection system (LPS) had become detached. It is possible that a piece of equipment or LPS conductor cut the membrane, and a progressive failure occurred. Extensive water damage was observed on the fourth floor and some on the third floor. The fourth floor was evacuated after the roof membrane blew off.

Figure 5-64.
View of a portion of the fourth floor roof of a hospital after installation of an emergency roof (the black area). The deck was concrete (Port Charlotte).

In addition to the BUR discussed above, the middle school in Port Charlotte also had single-ply membranes on two roof areas. Wind likely lifted the gutter and metal edge flashing and peeled the membrane on the gym (Figure 6-21). At a lower roof, the mechanically attached PVC alloy membrane with 4-foot 3-inch row spacing was installed over polyisocyanurate insulation over an old BUR over LWIC over a steel form deck (shown previously in Figure 3-59). The failure of this roof was also likely initiated by gutter failure. However, it may have been initiated by progressive tearing after missile impact (there were numerous missile tears), or by pull-out of membrane fasteners. Several membrane fasteners near the edge of the roof had been pulled out, which is not surprising. Metal form decks are typically thinner and therefore offer less pull-out resistance than standard steel decks.

At a county building in Punta Gorda, the mechanically attached PVC alloy membrane was punctured in several areas. Because the roof was much taller than surrounding buildings, the punctures were likely caused by rooftop equipment that was blown away and by the LPS components that became detached. The membrane peeled back at a corner area, but since emergency repairs had been made at the time the MAT visited, it was not possible to definitively determine the cause of the failure. The membrane fastener rows were at 4 feet 6 inches on center in the field of the roof. At the perimeter, the rows were 1 foot 11 inches on center. The perimeter width was 11 feet 8 inches. The corners appeared to be attached in the same manner as the perimeter.

5.3.5 Gutters and Downspouts

Gutters and/or downspouts were blown off many buildings. In most cases, loss of gutters caused little or no damage to the steep-slope roof coverings to which they were attached; however, the gutters and downspouts that were blown off became windborne debris. As discussed in Section 5.3.4, loss of gutters often resulted in lifting and progressive failure of low-slope membrane systems.

5.4 Wall Coverings, Non-Load Bearing Walls, and Soffits

Hurricane Charley caused wall covering, non-load bearing walls, and a significant amount of soffit damage throughout the hurricane path. The following factors are essential to resist high winds: product testing to ensure sufficient factored strength to resist design wind loads; suitable anchoring of the wall coverings, non-load bearing walls, and soffits to the building; use of moisture barriers (e.g., asphalt saturated felt or housewrap) where appropriate; and proper flashing, sealants, and drainage to minimize water intrusion into wall cavities or into occupied space.

5.4.1 Wall Coverings

Wall covering damage was observed by the MAT primarily on houses with vinyl siding. There were several instances of vinyl siding failure as shown in Figures 5-65 and 5-66 (and previously in Figure 3-24). Wall covering failure was more commonly observed in manufactured home parks than elsewhere in the hurricane's path. When vinyl siding was blown off, the underlayment (either asphalt-saturated felt or housewrap) was also typically blown away. With loss of the siding and underlayment, wind-driven rain was then able to enter the wall cavity, causing water damage and initiating mold growth. Vinyl sidings that became windborne debris were capable of breaking unprotected windows.

Vinyl siding that was blown off typically tore around the fastener points. Vinyl siding manufactured for high-wind areas is available. With high-wind siding, the nailing flange is folded over, so there is a double thickness of vinyl at the fastener points. None of the failures that were observed used high-wind siding.

In some cases, the MAT believes that the blow-off was triggered by unlatching of the bottom portion of the panel (Figure 5-65). Once the panel unlatches from the retainer slot just below the nailing flange, the panel is free to rotate outward where it can be caught by the wind and blow off. The magnitude of the unlatching issue, compared to the strength of the nailing flange and fastener spacing, is unknown. When unlatched, panels are very susceptible to blow-off.

Figure 5-65.
The vinyl siding panel with the red arrow is unlatched. The panel above and several others are also unlatched (Zolfo Springs).

Vinyl siding is quite susceptible to windborne debris damage as shown by Figure 5-66. Because the vinyl siding cannot resist debris impact, resistance to debris impact is provided by the wall sheathing (if any) between the siding and the wall studs. On some of the residences, plastic foam sheathing was used instead of wood sheathing between the vinyl and the studs. The walls of these buildings offered very little resistance to windborne debris penetration, as they were composed only of vinyl siding, underlayment, foam sheathing, fiberglass batt insulation in the wall cavity, and gypsum board on the interior side of the studs. Residents who rode out the hurricane in their homes were quite susceptible to injury from windborne debris penetrating the light exterior walls.

Underlayment had not been installed at all on some residences and at the Bokeelia Post Office on Pine Island (constructed in 1993). Not installing underlayment is a poor practice because vinyl siding (like many other types of wall coverings) does not prevent water from getting behind the siding. Underlayment should always be installed to intercept the leakage and drain it out of the wall. The 2001 FBC does not currently require underlayment underneath vinyl siding. Further discussion and analysis of vinyl siding is presented in FEMA 489, *Hurricane Ivan in Florida and Alabama.*

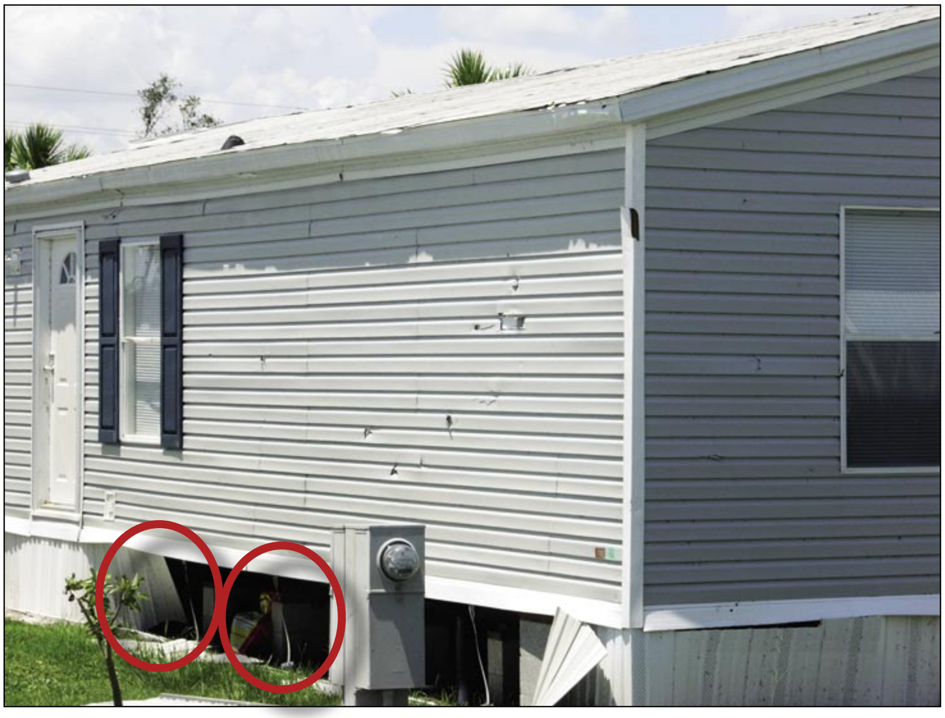

Figure 5-66.
The vinyl siding on this manufactured house was ruptured in several locations by windborne debris (most of which were likely building envelope components from other nearby manufactured houses). Note the missing skirt and loose foundation anchor straps (Zolfo Springs).

A variety of wall coverings other than vinyl siding were observed. They also typically performed well, but there were exceptions. There were several instances of metal wall panel failures; these typically occurred on older pre-engineered metal buildings. The key to achieving good performance of metal panels is selecting an appropriate panel system and installing an adequate number and type of fasteners. Figure 5-67 shows good attention to attachment of metal fascia panels on a school. Stitching the termination of panels with closely spaced fasteners as shown in Figure 5-67 prevents the end of the panel from billowing and becoming detached from the concealed clips.

Figure 5-67.
Standing seam metal panels with a 16-inch rib spacing were used at the fascia and secured with closely spaced exposed fasteners (Arcadia).

5.4.2 Non-Load Bearing Walls

Exterior non-load bearing walls generally performed well, but there were notable exceptions. Figure 3-25 showed a collapsed unreinforced masonry wall. Figures 3-33 and 5-68 show extensive EIFS failure on a hotel near the Orlando airport. Other EIFS damage was shown in Figure 3-26. Further discussion and analysis of EIFS failures is given in FEMA 489, *Hurricane Ivan in Florida and Alabama*, where this type of damage was prevalent.

5.4.3 Soffits

Many buildings lost some or all portions of their soffits (shown previously in Figure 3-21). The damaged soffits were typically vinyl or aluminum. Some of the soffits failed by suction (i.e., downward pressure), while others failed by positive pressure (i.e., they were pushed upward). In many instances where soffits were lost on residences, water was driven into the attics and ultimately into living spaces. The wind also displaced attic insulation and blew it out of attics (much of the insulation was blow-in insulation, rather than insulation batts). Figure 5-69 shows ceiling damage adjacent to soffit loss at a residence on North Captiva Island.

Figure 5-68.
This hotel experienced significant EIFS failure on several sides (Orlando). EIFS debris broke several windows (Figure 3-33).

Figure 5-69.
An exterior eave with soffit failure, which resulted in water intrusion (North Captiva Island)

Figure 5-70 shows a damaged soffit at a bank drive-through canopy. Figure 5-71 shows damaged soffits at the Aqui Esta Fire Station. Most of the gutters and downspouts at the fire station blew away, but the 5V-Crimp metal roof had only minor damage at a hip flashing lap. The soffit panels were connected to the building only at their ends. A substantial quantity of wind-driven rain blew into the attic space and caused ceiling boards to collapse. Because of the water infiltration, this station was taken off-line after the storm.

Figure 5-70.
Loss of soffit at a bank drive-through. Note the coping damage (Port Charlotte).

Figure 5-71.
Essentially all of the perforated aluminum soffit on this fire station was blown away (Aqui Esta, east of Punta Gorda Isles).

5.5 Exterior Mechanical and Electrical Equipment Damage

The MAT observed many damages to mechanical and electrical devices mounted on the exterior of buildings. The devices attached to residential, commercial, and critical/essential facilities are typically different from each other; for this reason, the following section presents information according to building type.

The following factors are essential to good high-wind performance of exterior mechanical and electrical equipment: determining design wind loads on equipment and designing suitable attachments to resist the loads; special anchoring of fan cowlings and access panels; and special design of LPS anchorage. Guidance for these design factors is provided in FEMA 424, *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds.*

5.5.1 Damage to Exterior Equipment Attached to Residential Buildings

Typically, the types of exterior equipment attached to residential buildings included air-conditioning condenser units and TV satellite dishes; however, this report focuses on condensers.

Condenser units were generally not anchored to their support pad, which resulted in their being displaced off the support pad by wind (Figure 5-72). In some instances, the condensers broke free from the electrical and copper tube connections and were blown away entirely.

In several cases, the condensers were fastened and remained anchored throughout the hurricane (Figure 5-73). Typically, where anchors were used, the clips were often very thin and the screws quite small. Although the condensers did not move during this hurricane, additional precautions to prevent wind damage should be taken. In some cases, corrosion of fasteners was observed; this can result in failure in a future hurricane event. In high-wind areas, clips and screws with high strength and corrosion resistance should be used.

Figure 5-72.
This condenser was not anchored to the concrete pad. The electrical and copper tube connections kept it from blowing farther away (Deep Creek).

Figure 5-73.
Condenser on the elevated platform attached with four angle brackets. The other condenser, located adjacent to it on the ground, should also have been on an elevated platform to account for storm surge (Pine Island).

5.5.2 Damage to Exterior Equipment Attached to Commercial and Critical/Essential Facilities

Commercial and critical/essential facilities typically have a wide variety of mechanical and electrical equipment attached to their rooftops and elsewhere. Equipment lost included fan units and HVAC units, electrical and communications equipment, and LPS systems. There are several effects due to loss of this equipment: in many instances, the displaced equipment left large openings through the roof and/or punctured the roof membrane; equipment loss often affected the operational functions of the facilities; and blown-off equipment became high-energy windborne debris in some cases. The equipment observed on hospitals, fire stations, and schools was not anchored more effectively than the equipment on common commercial buildings.

5.5.2.1 Condensers

Condenser problems like those discussed in Section 5.5.1 were also observed at commercial and critical/essential facilities (Figures 5-74 and 5-75). A complete lack of anchor systems or inadequate or deteriorating fasteners resulted in the loss of many compressors. Installation methods observed were not standardized. In Figure 5-75, although the condenser did not move off its rail, it would have been prudent to use two side-by-side screws, with more edge distance between the screw and strap end.

Figure 5-74. Condenser unit displaced from the elevated platform (Port Charlotte)

Figure 5-75.
Rooftop condenser anchored to a support rail, but with only one small screw (which was corroded) used to connect the strap (Port Charlotte).

5.5.2.2 Fan Units and HVAC Units

Figure 5-76 shows the loss of fan cowlings on a roof. Two of the three cowlings had blown off. At one curb, which was 2 feet 4 inches square, the fan unit was attached to the curb with two small screws at two sides and three small screws on the other two sides (total of 10 screws). Attachment was not checked at other fans. No fans were blown off this building. This success was likely the result of using multiple screws to secure the fasteners (unlike many other buildings, where often only two screws per fan were used).

Figure 5-76.
Cowlings blown off two exhaust fans in the foreground. Note also the loose LPS conductors and missing walkway pad (Punta Gorda).

Loss of HVAC units was also observed as shown in Figure 5-77. A number of these large units were blown off their supports. Additional damage to equipment included loss of access panels on package units, debris impact damage to relief air hoods, and damaged rooftop ductwork. Figure 5-78 shows a unit that was marginally anchored.

Figure 5-77.
A large HVAC unit blew off this curb. Note the loose LPS conductors (this side of the curb). This school had significant damage to several pieces of rooftop equipment (Port Charlotte).

Figure 5-78.
A thick angle bracket was used to anchor this unit. Although two screws attached the angle to the support beam, only one screw was used at the unit (Port Charlotte).

5.5.2.3 Electrical and Communications Equipment

Rooftop electrical and communications equipment were also observed to be inadequately anchored. Problems included blow-off of satellite dishes (Figures 5-79 and 5-80), antenna collapse (shown previously in Figure 3-44), and displacement of LPS (Figures 5-59 and 5-81 through 5-85). Four buildings with LPS were investigated, and the systems on all four buildings were damaged. Three of the buildings had two or more roof levels and damage occurred at several of the different levels. Consequences of the damage included loss of communications, damage to the roof covering, and loss of lightning protection, the latter of which is significant, considering the frequency of lightning storms in Florida.

Figure 5-79.
This satellite dish at a hospital was held down only with CMU. Note the loose LPS conductors and displaced air terminal at the corner (Arcadia).

LPS failures were typically the result of poorly anchored systems. Connectors often fail by opening up and releasing the conductor cable or they debond from the roof (Figure 5-82). In other cases, the air terminal base plates debond from the roof (Figure 5-83). In Figure 5-84, a prong-type conductor splice connector (approved for roof heights up to 75 feet) failed. Bolted-type connectors are prudent in hurricane-prone regions because they are less likely to pull apart and cause damage to the roof (Figure 5-85).

Figure 5-80.
A satellite dish previously sat in this location. It was held down only with CMU and blew off the five-story building (Punta Gorda).

Figure 5-81.
The LPS conductor on this hospital blew away, but the air terminal was still attached. A lightning strike to this air terminal would not be safely dissipated (Port Charlotte).

Figure 5-82.
The LPS conductor pulled away from the conductor connector at the top of the photo. The conductor was also attached to the membrane with poorly welded strips of PVC (Port Charlotte).

Figure 5-83.
The conductor connectors detached from the cap sheet on a hospital's BUR. The air terminal was also displaced (Port Charlotte).

Figure 5-84.
A failed prong-type splice connector with prongs permitted for roof heights up to 75 feet caused roof damage at this facility (Cape Coral).

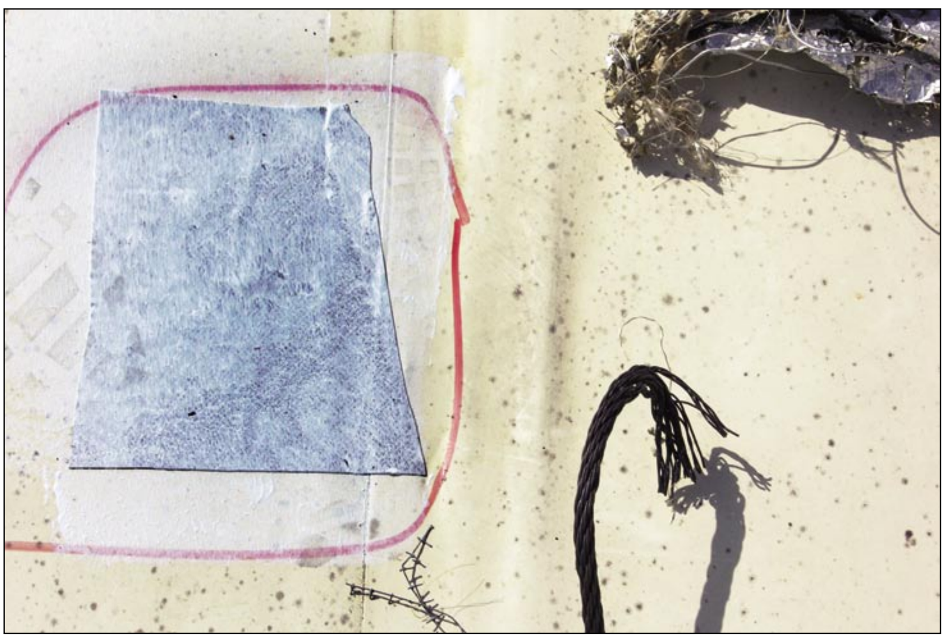

Figure 5-85.
When LPS conductors detach, the conductor ends can whip around and puncture and tear the roof membrane. The patch near this frayed conductor is likely a repair of damage caused by a whipped conductor (Punta Gorda).