MITIGATION ASSESSMENT TEAM REPORT

HURRICANE *Katrina* IN THE GULF COAST

5. Building Envelope Performance

Although Hurricane Katrina's winds were not nearly as powerful as those of other catastrophic hurricanes that have struck the Gulf Coast (such as Hurricane Camille [1969] or Hurricane Charley [2004]), the storm's winds caused widespread damage to building envelopes and rooftop equipment.

The MAT observed building envelope damage as far west as the New Orleans area and as far east as Mobile (see Figure 5-1) and Dauphin Island, Alabama (a west-to-east distance of approximately 140 miles). The MAT also observed building envelope damage as far inland as Poplarville, Mississippi (approximately 40 miles from the Gulf); however, building envelope damage was also reported at least as far inland as Hattiesburg, Mississippi. Although the building envelope damage was less severe than that caused by flooding, the wind-induced envelope damage was significant.

Sections 5.1 through 5.6 describe building envelope performance (e.g., sheathing on the underside of elevated buildings; doors; non-load-bearing walls, and wall coverings and soffits; roof systems; windows, shutters, and skylights; and exterior-mounted mechanical, electrical, and communications equipment) during Hurricane Katrina as observed for residential, commercial, and critical and essential facilities. (Note: see Chapters 3 and 7 for additional photos of damaged building envelopes and rooftop equipment.)

Figure 5-1.
Blow-off of a modified bitumen roof membrane at a service station. Note: The cantilevered canopy over the pumps was flipped upside down (estimated wind speed: 85 mph. Mobile, Alabama[1]).

In addition to the costs associated with repairing building envelope and rooftop equipment damage, even greater costs are typically incurred due to wind and/or water damage to interiors and contents once a building envelope is breached (see Figure 5-2). Because of Katrina's widespread devastation, emergency repairs were not made to large numbers of damaged buildings for many weeks, or even months, after the storm. Thus, during subsequent rains, further wetting of interiors occurred. (Note: At the time the school shown in Figure 5-2 was investigated [about 4 weeks after the hurricane], the damaged roof had not been repaired.) When breached envelopes remain open for several weeks, even small breaches can allow a significant amount of water to leak into buildings and allow mold to develop.

Blow-off of building envelope components and rooftop equipment also frequently results in damage to adjacent buildings and vehicles, as well as the building itself. Common windborne building envelope debris during Hurricane Katrina included roof coverings (particularly aggregate surfacings and asphalt shingles) and vinyl siding. Figure 5-3 illustrates the magnitude of building envelope debris that occurred in some areas.

In addition to the costs associated with repairing damaged building envelopes and subsequent water infiltration damage, when families, businesses, and critical and essential facilities are forced to vacate damaged buildings, the costs associated with the interruption and temporary relocation often exceed the direct costs of repairing the damaged buildings and their contents. Thus, while good structural system performance is critical to avoiding injury to occupants and minimizing damage to a building and its contents, good structural system performance does not ensure occupant or building protection. Good performance of the building envelope is also critical.

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[1] Estimated speeds given in this chapter are based on Figure 1-13. These are for a 3-second gust at a 10-meter elevation for Exposure C. Unless otherwise noted, the buildings for which estimated speeds are given are located in Exposure B. See Table 1-4 for the estimated speed conversion for buildings located in Exposure B. For example, the 85-mph Exposure C speed given for Figure 5-1 is equivalent to 70 mph in Exposure B.

Figure 5-2.
After the roof membrane blew off this school, water saturated the fiberglass insulation and ceiling boards, and several of the ceiling boards collapsed (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 5-3.
A substantial amount of siding (the white lines scattered around the ground) blew off this housing complex (estimated wind speed: 105 mph. Harvey, Louisiana area).

The most notable building envelope issues pertaining to Hurricane Katrina were the widespread poor performance of asphalt shingles, vinyl siding, and exterior insulation and finish systems (EIFS) on several mid- and high-rise buildings. Rooftop equipment anchorage and glazing breakage by aggregate from roof surfaces was also prevalent.

Considering that the estimated actual wind speeds were typically less than the design speeds given in ASCE 7, had the buildings been designed and constructed in accordance with a current model building code such as the International Building Code (IBC), the extent and magnitude of the envelope damage would have been reduced. However, many wind-related issues associated with building envelopes are not addressed or are inadequately addressed in current model codes. Therefore, in order to minimize building envelope damage, in addition to complying with codes, designers and contractors need to voluntarily incorporate a variety of best practices, as discussed in this chapter and in Chapter 11.

5.1 Sheathing on the Underside of Elevated Buildings

Sheathing is typically installed on the underside of lowest-floor joists on elevated buildings. Besides protecting batt insulation that is placed between joists, sheathing can also protect electrical and plumbing lines from floodborne debris. A variety of sheathing materials are used, with vinyl siding and plywood the most common. Because storm surge destroyed most of the buildings along the coast, there were few observations of sheathing on the underside of buildings. Figure 5-4 is an example of one of the vinyl-sheathed buildings observed. Houses with corrugated metal panel and fiber-cement panel sheathings were also observed. The house with the fiber-cement panels was located in Saint Bernard Parish, Louisiana. All of the 1/8-inch-thick 4x8-foot panels were blown off. They had been attached with nails spaced at 7-1/2 to 8 inches on center along the panel edges and ends. Nails were also spaced at 15-1/2 to 16 inches on center along two intermediate rows parallel to the edges.

Figure 5-4.
Loss of vinyl siding from the underside of an elevated residence in Exposure C. Note the large floodborne pole debris near the steel cable "x" brace (estimated wind speed: 130 mph. St. Bernard Parish, Louisiana).

Fast-moving floodwater and breaking waves can cause sheathing loss and floodborne debris can cause gouging. However, the loss of the fiber-cement sheathing appeared to be caused by wind accelerating as it passed beneath the elevated building. Neither ASCE 7, IBC, or IRC provide guidance for determining design wind loads for sheathing on the underside of elevated buildings. Therefore, professional judgment in specifying attachment is needed.

For further information on the performance of sheathing on the underside of elevated buildings, see FEMA 489, *Mitigation Assessment Team Report, Hurricane Ivan in Alabama and Florida.*

5.2 Doors

Failure of an exterior door has two important consequences. First, failure can cause a rapid increase in internal pressure, which may lead to exterior wall, roof, interior partition, ceiling, or structural failure. Second, wind can drive rainwater through the opening, causing damage to interior contents and finishes, and leading to the development of mold. The essential elements of good high-wind door performance include product testing to ensure sufficient factored strength to resist design wind loads (both static and cyclic loading); 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 against windborne debris damage, as discussed in Section 5.5.2.

5.2.1 Personnel Door Damage

Personnel door damage was observed on a limited number of buildings. Observed damage included door frames that detached from the building (likely caused by inadequate fastening to the building) and doors that blew from their hinges (likely caused by use of inadequately sized screws) as illustrated by Figure 5-5. One door on a new residence under construction blew off when the hinges detached from the frame. The door/frame was a pre-hung assembly that used very short screws to attach the hinges to the frame (otherwise, the screws would have projected from the frame and been a potential safety hazard during installation). After the frame was installed in accordance with most manufacturers' instructions, the short screws should have been replaced with stronger permanent screws.

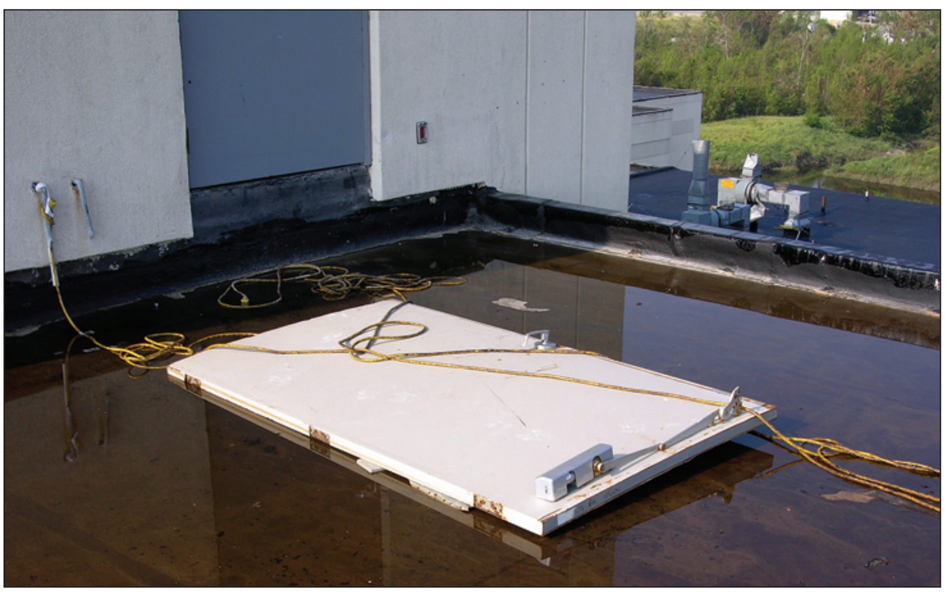


Figure 5-5.
A penthouse door on this hospital blew off its hinges. Blown-off doors allow entrance of rain, and tumbling doors can puncture roof membranes (estimated wind speed: 130 mph. Gulfport, Mississippi).

5.2.2 Garage Door Damage

Several damaged residential garage doors were observed, some of which were damaged by floodwater, while others were damaged by wind. Figure 5-6 shows wind-induced damage at a house under construction. Damaged doors were typically displaced from their tracks, but in some instances the track fasteners were pulled out. (Note: Where breakaway walls are installed, collapse of the garage doors is intended.) For further information on garage door performance, see FEMA 488, *Mitigation Assessment Team Report, Hurricane Charley in Florida*.

Figure 5-6.
Positive pressure blew this garage door from its tracks. At some other residences, negative pressure blew doors outward. Note the damage to the asphalt shingles (estimated wind speed: 110 mph. Belle Chase, Louisiana).

5.2.3 Rolling and Sectional Door Damage

Water- and wind-induced damage to rolling and sectional doors (e.g., service garage doors, loading dock doors, and fire station apparatus bay doors) was observed (see Figure 5-7). In some cases, the doors were dislodged from their tracks, while in others the tracks pulled away from the wall. At a fire station in Gulfport (constructed in 1977), all three windward (eastern) doors were blown in (see Figure 7-8). One of the doors pulled from its tracks, but at the other

Figure 5-7.
Wind-induced damage to several roll-up doors (estimated wind speed: 130 mph. Gulfport, Mississippi)

two doors the tracks pulled from the wall. The tracks were fastened with 1/4-inch diameter lag screws spaced at 2 feet on center. The tracks were lag-screwed to 1x wood framing, which was inadequately nailed to the 6x columns.

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

Hurricane Katrina caused damage to a large number of non-load-bearing walls, wall coverings, and soffits. Non-load-bearing walls included brick veneer/concrete masonry unit (CMU) cavity walls, EIFS, and panelized wall systems. Wall coverings included brick veneer, fiber-cement siding, metal panels, stone veneer, vinyl, and wood. Vinyl was typically used for soffits; however, several metal panel soffits were also observed. The following factors are essential to good, high-wind performance of non-load-bearing walls, wall coverings, and soffits: product testing to ensure sufficient factored strength to resist design wind loads; suitable anchoring of the wall, wall coverings, 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.

5.3.1 Non-Load-Bearing Walls

Non-load-bearing walls that were investigated included brick cavity walls, brick veneer/CMU cavity walls, EIFS over studs, and panelized wall systems. Pre-cast concrete wall panels were also observed and none were damaged by wind. A large number of EIFS failures were observed, including failures as far east as Moss Point, Mississippi. With loss of the EIFS (and other types of coverings), wind-driven rain was often able to enter the wall cavity or the building itself and initiate mold growth. EIFS (and other types of coverings) that became windborne debris were capable of breaking unprotected windows. Figure 5-8 shows typical EIFS assemblies.

5.3.1.1 Exterior Insulation and Finish Systems

Hurricane Katrina produced large areas of EIFS failure on many low-rise and multi-story buildings (see Figure 5-9). In addition to puncture by windborne debris, common planes of failure of EIFS assemblies included (typically as a secondary failure plane) separation of the synthetic stucco from the insulation and (as primary failure planes) detachment of the insulation from the gypsum board substrate, detachment of the gypsum board from the studs, and failure of the studs. When the insulation detaches from the gypsum board, the gypsum board can suffer strength reduction due to wetting from the wind-driven rain, and it too often will then blow off during a hurricane.

Figure 5-10 shows loss of EIFS on a penthouse on a new 13-story building (there was also extensive loss at the main walls). The gypsum board detached from the 8-inch-deep steel studs spaced 16 inches on center. The gypsum board was attached with screws that were irregularly spaced. Along one stud near the corner, the screws were spaced at 8, 25-1/2, and 12-1/2 inches. Along another stud in the corner region, the screws were spaced at 14, 12, and 21-1/2 inches. Away from the corner region, the screws along one stud were spaced at 12, 10-1/2, 12-1/2, and

10-1/4 inches. Along another nearby stud, the screws were spaced at 10, 12, 8-1/4, 4-3/4, and 11 inches. Surprisingly, the screws were typically spaced farther apart in the corner region (where the wind loads are the highest). Away from the corners, the screws should have been spaced in the range of a maximum of 6 inches on center. In the corner areas, the screws should have been spaced in the range of a maximum of 4 inches on center and the studs should have been at a maximum of 12 inches on center. Because contract documents were not available, it is unknown whether the spacing deficiencies were due to design or workmanship errors.

Along another wall of the penthouse in an area outside of the corner region, the screws along the end of a gypsum board panel were spaced at 5, 9-1/2, 6, 6, 4, and 4-1/2 inches. Along the next stud, the intermediate row was spaced at 21-1/2, 10, and 13 inches. As shown in Figure 5-11, in one area the molded expanded polystyrene (MEPS) insulation detached from the gypsum board. The MEPS had been adhered with vertical lines of adhesive. Adhesive should have been continuously applied throughout the entire board area.

Figure 5-12 shows a building that had been re-skinned with EIFS (new metal framing had been installed over the original walls). In some areas, the gypsum board blew off the new metal framing, but in other areas the metal framing was blown away because it was inadequately attached to the building.

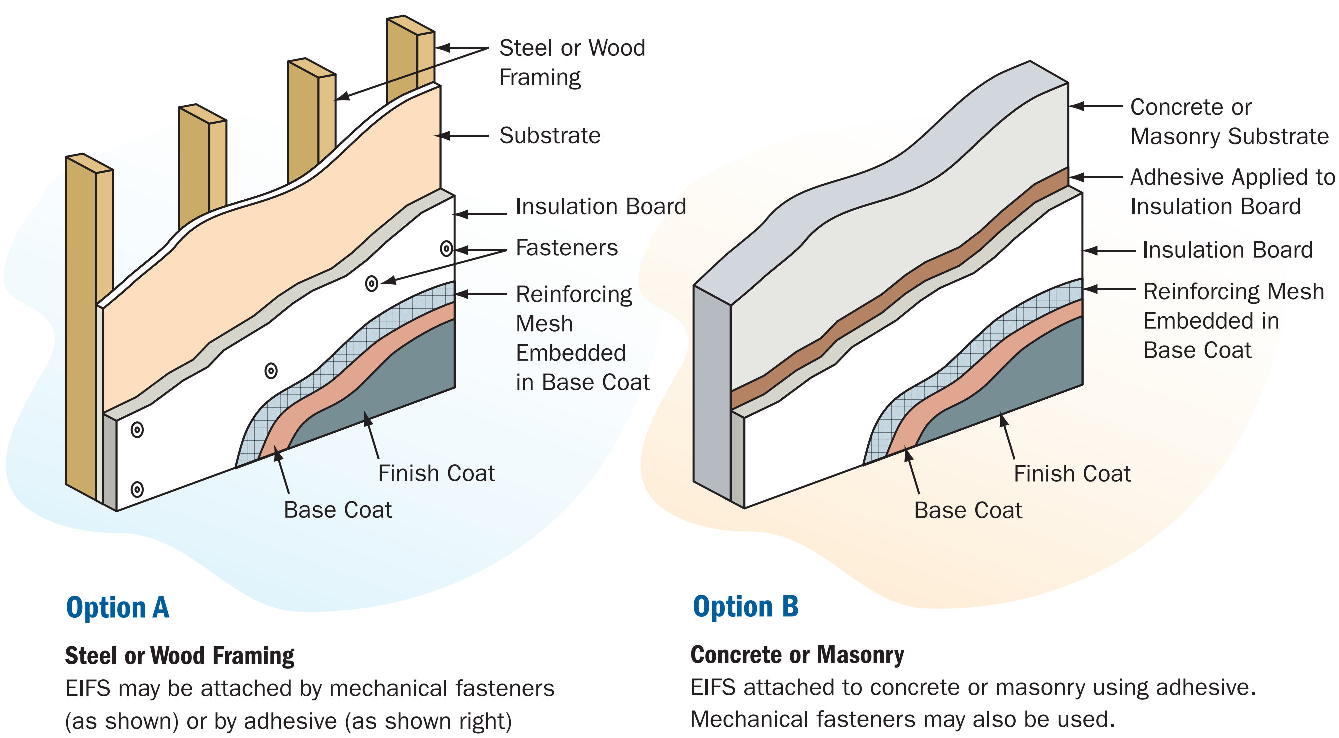


Figure 5-8. Typical EIFS assemblies

Figure 5-9.
Multi-story building in Exposure C, showing severe EIFS damage. The gypsum board typically detached from the studs. In some areas, the gypsum board on the interior side of the studs was also blown away (estimated wind speed: 120 mph. Biloxi, Mississippi).

SOURCE: NIST

Figure 5-10.
Loss of EIFS on penthouse of a new 13-story building in Exposure C. The gypsum board was attached with irregularly spaced screws and detached from the steel studs (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 5-11.
The MEPS had been set in rows of adhesive rather than in a continuous layer of adhesive. Note the inadequate edge distance of the fasteners along the end joint. The building was located in Exposure C (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 5-12.
This building had been re-skinned with EIFS. In some areas, the gypsum board blew off the studs (arrows). In other areas, the metal framing was blown away (square/ inset) (estimated wind speed: 105 mph. New Orleans, Louisiana).

For many buildings, the ramification of damage to EIFS assemblies was significant. With several of these failures, the cost of repairing the EIFS was minor in comparison to the cost of damage to other building components; the cost of rainwater damage and mold remediation to building interiors, furnishings, and equipment; and the cost due to loss of use of the building while repairs were made. EIFS installed over studs is susceptible to disproportional failure, wherein a relatively minor deficiency (such as an inadequate number of screws to attach gypsum board) results in loss of the exterior wall, as shown in Figure 5-9. Typical EIFS assemblies (i.e., studs, gypsum board, insulation, and synthetic stucco) lack redundancy to protect the building from extensive wind and rainwater infiltration when wind initiates failure somewhere within the assembly.

The EIFS damage was primarily related to application and/or design deficiencies. Lack of design guides likely contributed to the design problems. The test method used to determine wind resistance of EIFS assemblies may have also contributed to some of the damage. These issues are discussed below:

- **Application:** In all cases that were investigated where adhered insulation boards separated from the gypsum board, there was a significant lack of adhesive. EIFS manufacturers currently specify that the entire surface of the insulation boards is to be covered with adhesive applied with a notched trowel.

  In all cases that were investigated where gypsum board was mechanically attached, the fasteners were spaced too far apart. Because contract documents were not available, it is unknown whether the spacing deficiencies were due to design or workmanship errors.

- **Testing:** The EIFS industry uses American Society for Testing and Materials (ASTM) E330 to evaluate the wind resistance of EIFS assemblies. Load is applied to the specimen for 10 seconds before being released. The load is then increased and applied for another 10 seconds, and then released. This process is repeated until failure occurs. While none of the investigated failures were specifically attributed to deficiencies in the test method, the test method's load duration of only 10 seconds appears to be inadequate. ASTM E1592 (a test for metal roof and siding panels) specifies that each load increment be maintained for a minimum of 60 seconds and until the gauges indicate no further increase in deflection. The load duration and deflection criteria in E1592 appear prudent for EIFS.

- **Design guides:** The EIFS Industry Members Association (EIMA) has a *Guide to EIFS Construction*, but the guide doesn't discuss wind-related issues. Manufacturers of EIFS materials have specifications, but they are typically lacking in wind-related criteria. For example, to determine fastener spacing for gypsum board (which is a critical element in the load path), designers are referred to gypsum sheathing manufacturers. Also, ultimate load values based on ASTM E330 typically are given, but guidance on the magnitude of the safety factor is often not given to the specifier.

- **Codes:** The IBC does not have specific wind-related criteria pertaining to EIFS. However, the International Code Council's (ICC's) Evaluation Service does have the AC24 *Interim Criteria for Exterior Insulation and Finish System* for evaluating EIFS. AC24 uses ASTM E330 for the wind resistance evaluation. AC24 requires at least six load increments with a 10-second load duration for each increment. AC24 also requires a minimum safety factor of 3. (Note: The Standard Building Code Congress International's Evaluation Service previously used a safety factor of 2. Therefore, systems designed in accordance with those criteria would be much weaker than systems designed in accordance with the ICC criteria.)

5.3.1.2 Panelized Wall Systems

Figure 5-13 shows collapsed wall panels. The tracks at the top of the panels were inadequately anchored to the concrete floor slabs. Figure 5-14 shows collapse of non-load-bearing walls at a hotel. These types of failures can be avoided by designing and constructing the wall panels and their connections to the structure to resist the design wind loads.

Figure 5-13.
Collapse of panelized wall system (estimated wind speed: 115 mph. Slidell, Louisiana)

Figure 5-14.
Collapse of non-load-bearing walls at a hotel (estimated wind speed: 105 mph. New Orleans, Louisiana)

5.3.2 Wall Coverings and Soffits

This section covers wall coverings, which include brick veneer, fiber-cement siding, metal panels, stone veneer, and vinyl siding (and soffits). Soffits included vinyl, aluminum, and lay-in panels in a suspended grid. In some instances, with loss of the coverings/soffits, wind-driven rain was able to enter the wall/attic cavity and initiate mold growth. Some of the blown-off coverings/soffits became windborne debris that was capable of breaking unprotected glazing.

5.3.2.1 Brick

Several buildings with failed brick veneer were observed. The majority of the failed brick veneers were applied over wood stud framing; however, some of the failed veneers were applied over CMU (in some instances, the CMU also failed). Figure 5-15 shows failed brick at a house that was under construction. The ties were typically spaced at 16 inches on center horizontally. Vertical spacing varied. The first row was 19 and 21 inches above the footer. The second row was 22 and 24 inches above the first row, and the third row was 18 inches above the second row. Some of the smooth-shank tie nails pulled from the studs. Many of the ties had never been embedded into the mortar joints, which was a major workmanship error.

Figure 5-15.
Collapsed brick veneer wall that was under construction. Several of the ties had not been embedded into the mortar joints (square/inset) (estimated wind speed: 125 mph. Waveland, Mississippi).

The Brick Industry Association's (BIA's) *Technical Notes 28 (2002) – Anchored Brick Veneer, Wood Frame Construction* specifies a maximum tie spacing of 24 inches in each direction. The ties at the house described previously complied with the spacing specified in *Technical Notes 28*. For this house, the 2005 edition of *Building Code Requirements for Masonry Structures, ACI 530/ASCE 5/ TMS 402*, specifies a maximum vertical and horizontal tie spacing of 16 inches (based on a basic wind speed of 130 mph). Therefore, the ties at this house complied with the ACI 530 specification for horizontal spacing, but did not comply with the vertical spacing requirement.

At a house under construction in Ocean Springs, Mississippi, brick had not been installed, but the corrugated ties had been placed. At a narrow strip of wall between a door and window, the ties were spaced 16 inches apart along one row. A tie along the first row was up 22 inches from the footer. The next row was up 41-1/4 and 42-1/4 inches from the footer. Along another wall, the first row was up 35 inches from the footer. The first tie along this row was 34 inches from the corner. A tie along the second row was up 54 inches from the footer. Ties along this row were 30 and 37 inches apart. The first tie was about 14 inches from the corner. A tie along the third row was up 78 inches from the footer and another was up 80-1/4 inches. These ties were 32 and 31 inches apart. The first tie was about 2 inches from the corner. Figure 5-16 illustrates the layout of ties at this wall.

The ties at this house did not comply with the vertical or horizontal spacing specified in *Technical Notes 28*. This house is located in an area with a basic wind speed of 140 mph; ACI 530-02 does not provide prescriptive tie spacings for this speed. The FEMA Hurricane Katrina Recovery Advisory *Attachment of Brick Veneer in High-Wind Regions* (Appendix E) recommends a maximum horizontal tie spacing of 16 inches and a maximum vertical spacing of 13.7 inches for a 140-mph design wind speed. Figure 5-16 also illustrates location of ties as recommended in the advisory.

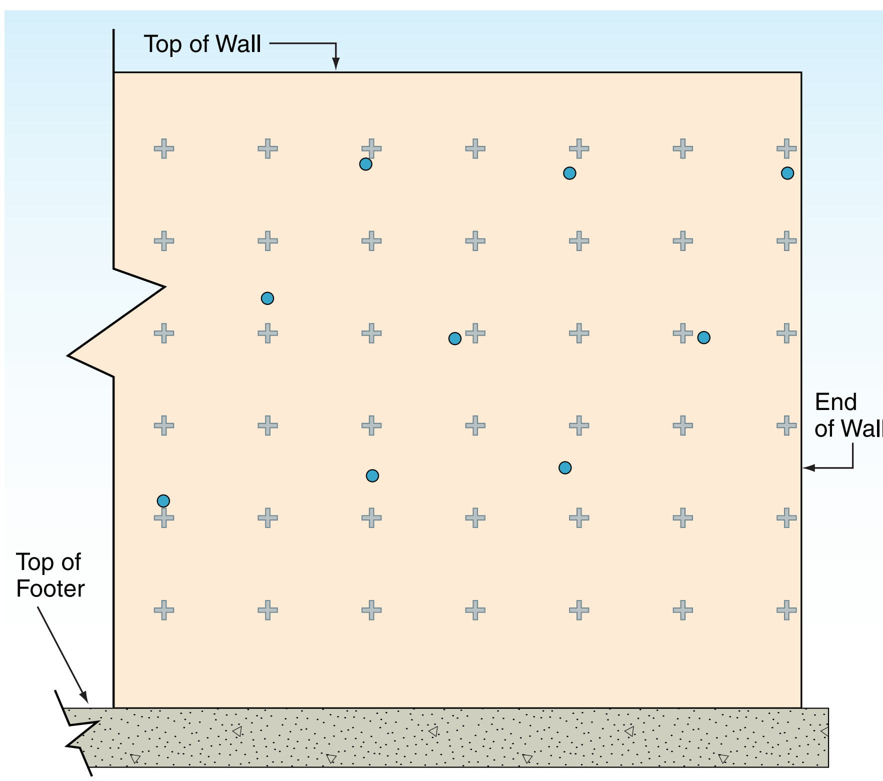


Figure 5-16.
Brick ties at house under construction in Ocean Springs, Mississippi. At this wall, nine ties were installed (blue circles); however, 42 ties ("+" symbol) are needed to comply with the advisory.

Most of the failed brick veneers that were investigated failed because of inadequate tying between the brick and studs. Inadequacies included excessive vertical and/or horizontal spacing of ties, inadequate pull-out resistance of tie nails (all nails observed were smooth-shank, with a length of either 1-3/8 or 1-3/4 inches), failure to embed ties into the mortar joints, and poor bonding between ties and mortar. However, some of the failures were due to tie corrosion as shown in Figures 5-17 and 5-18. The apartment building shown in Figure 5-17 was occupied at the time of the investigation. The area in the vicinity of the partially collapsed walls had not been barricaded, leaving pedestrians and vehicular traffic susceptible to injury if further collapsing occurred.

Figure 5-17. Partial collapse of brick veneer at an apartment building; the ties were corroded (inset) (estimated wind speed: 115 mph. Slidell, Louisiana).

At the old church shown in Figure 5-18, the ties between the roof framing and brick wall, and the continuous wire truss type horizontal joint reinforcement between the two wythes were severely corroded.

FEMA Hurricane Katrina Recovery Advisory *Attachment of Brick Veneer in High-Wind Regions* (Appendix E) provides recommended practices for brick veneer attachment. This advisory was based on observations from Hurricanes Ivan and Katrina.

Figure 5-18.
The ties and wire truss type horizontal joint reinforcement in this double-wythe cavity wall were severely corroded (inset) (estimated wind speed: 105 mph. Pascagoula, Mississippi).

5.3.2.2 Fiber-Cement Siding

Only a very small number of buildings with fiber-cement siding were observed. Figure 5-19 shows a newly constructed house that experienced wind-induced loss of fiber-cement siding. Along one of the 6-1/4-inch-wide siding panels, the concealed nails were located 1 inch from the end of the panel, then 12, 14, and 12 inches. One of the nails was 5/8 inch from the top of the panel and another was 3/4 inch. At a house in Saint Bernard Parish, Louisiana, along one of the 7-1/4-inch-wide siding panels, the concealed nails were spaced at 8 inches on center and were located 7/8 inch from the top of the panel. At both of these buildings, the siding pulled over the nail heads. The manufacturer recommends that, when using the concealed nailing method, the nails be placed at studs spaced at a maximum of 24 inches on center and that the nails be located 1 inch from the top of the panel.

5.3.2.3 Metal Wall Panels

The MAT observed a limited number of metal wall panel failures. A massive failure occurred at the penthouse on a 15-story office building (Figure 5-20). With loss of the wall panels, the elevators were no longer operational due to wind-driven rainwater damage to the elevator controls.

A few high-rise buildings in New Orleans also lost metal panels from equipment screen walls (see Figure 5-21). Blown-off panels from tall buildings can damage other buildings and vehicles, and cause injury. The panels at one of these buildings were composite panels (i.e., inner and outer metal skins with a plastic foam insulation core).

Figure 5-19.
Blow-off of fiber-cement siding. Note the broken window at the right (arrow) (estimated wind speed: 125 mph. Bay St. Louis, Mississippi).

Figure 5-20.
The metal wall panels blew off the penthouse on this 15-story building. Rainwater infiltration damaged the elevator controls (estimated wind speed: 130 mph. Gulfport, Mississippi).

Figure 5-21.
Loss of metal panels from equipment screen walls (arrow). Note the broken window (circle) (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-22 shows panels at a police station that unlatched and were blown away. The panels were attached with concealed staples to 1x wood nailers.

Figure 5-22.
Loss of metal panels at a police station. In addition to generating windborne debris, loss of panels allowed rainwater infiltration (estimated wind speed: 130 mph. Long Beach, Mississippi).

Another wall panel failure was observed at a university building (Figure 5-23). New metal panels had been installed over older metal panels. The newer panels were attached with concealed clips installed over the older panels. The clips were placed at horizontal girts that were far apart. At a corner area both the newer and older panels blew off; the blow-off may have initiated with failure of the older panels, or the failure of the older panels may have been a secondary failure.

Figure 5-23.
The white metal panels had been installed over a previous metal panel system. Most of the underlying original panels (red arrow) remained in place, but many of the newer panels (yellow arrow) blew off due to inadequate attachment (green double-arrow shows the area that is missing the newer overlying panels). Note that the girts (red double-arrow) were very far apart (estimated wind speed: 125 mph. Waveland, Mississippi).

5.3.2.4 Stone Veneer

Several mid- and high-rise buildings in New Orleans were sheathed with stone veneer. No buildings were observed to have experienced widespread loss of stone veneer; however, a small number of buildings lost a few panels, as shown in Figure 5-24. Blown-off panels can damage buildings and vehicles, and can cause injury.

The tallest building in New Orleans (670 feet to the main roof level) lost several stone panels at the penthouse (see Figure 5-25). The blown-off panels severely punctured the roof membrane. Some of the penthouse panels had loosened a few years earlier and corrective action was planned, but had not been implemented prior to Hurricane Katrina.

5.3.2.5 Vinyl Siding

Vinyl was the predominant siding and soffit material observed on residences in the areas investigated by the MAT. Performance of the siding and soffit was extremely poor (see Figure 5-26) and there were numerous significant failures on both new and old buildings. When vinyl siding was blown off, the underlayment (either asphalt-saturated felt or housewrap) was also often blown away. With loss of the siding and underlayment, wind-driven rainwater was then able to enter the wall cavity, causing water damage and initiating mold growth. Vinyl siding and soffits that became windborne debris were capable of breaking unprotected glazing.

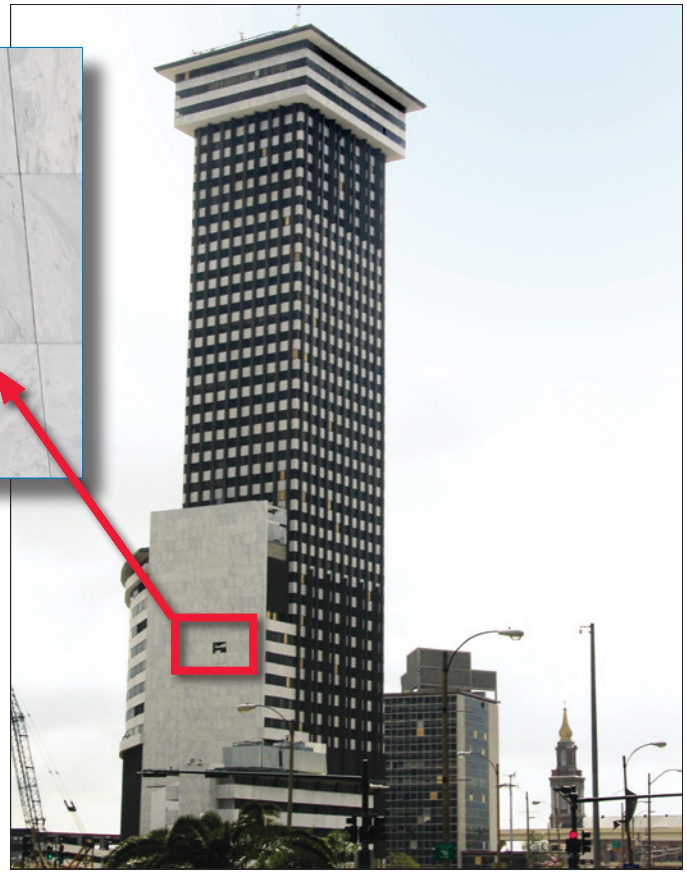



Figure 5-24.
A few stone veneer panels blew off this building. Rainwater was able to enter the interior of the building where the panels shown in the inset were blown off. Note: At least 22 windows were broken on these two façades (estimated wind speed: 105 mph. New Orleans, Louisiana).

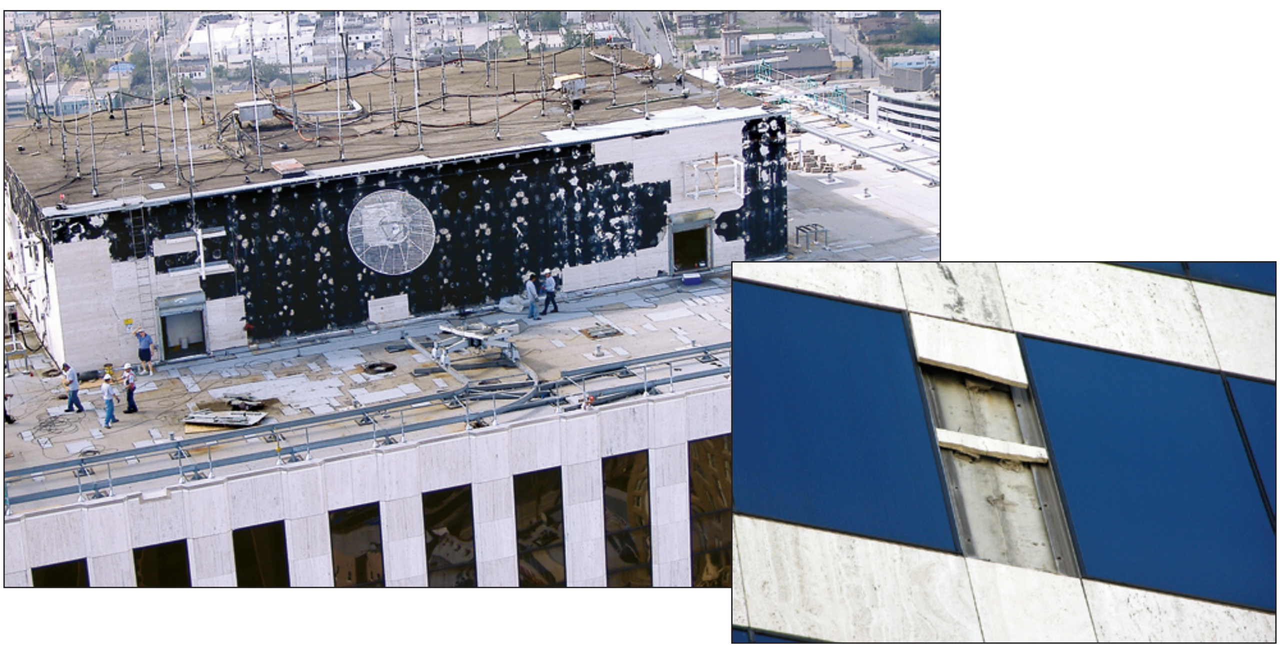


Figure 5-25.
Several stone veneer panels blew off the penthouse and caused significant puncturing damage to the modified bitumen membrane roof. A few panels were also blown off the main walls (inset) (estimated wind speed: 105 mph. New Orleans, Louisiana).

Many of the windows in the apartment complex shown in Figure 5-26 were broken (see Figure 5-27), which is not surprising considering the large amount of vinyl siding, vinyl soffit, and asphalt shingles that were blown off of these buildings.

Figure 5-26.
Many of the buildings in this apartment complex lost a substantial amount of vinyl siding (arrows) and asphalt shingles (circles). Underlayment had not been installed underneath the siding (estimated wind speed: 120 mph. D'Iberville, Mississippi).

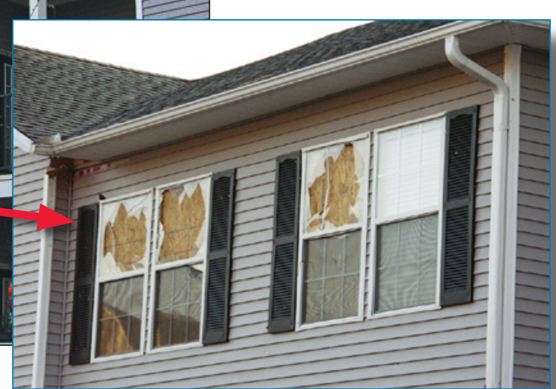


Figure 5-27.
These windows were broken by windborne debris (inset and arrows). Note the missing vinyl siding and soffit (estimated wind speed: 120 mph. D'Iberville, Mississippi).

In several areas investigated by the MAT, siding at gable end walls had been installed over plastic foam insulation (i.e., there was no plywood or oriented-strand board [OSB]). With blow-off of the vinyl siding, the foam insulation was typically also blown away (see Figure 5-28). With loss of both the siding and foam insulation, wind-driven rainwater was free to enter the attic space. When this occurred, typically the attic insulation became saturated and the ceiling collapsed.

On several buildings, siding was also installed over foam insulation at portions of walls, as shown at the apartment complex in Figure 5-29. At this complex, OSB had been installed in corner areas (in order to provide shear walls), but between the corner areas only plastic foam insulation occurred between the studs and vinyl. With loss of both the siding and foam insulation, wind-driven rainwater was free to enter the wall cavity. Also, where the wood sheathing was not present, wind-blown debris of only moderate energy could easily penetrate the building and injure occupants. With the vinyl in place, the center area of the walls shown in Figure 5-29 consisted of vinyl siding, foam insulation, stud cavity, and gypsum board on the interior side of the studs. As shown in the inset in Figure 5-29, in one area the vinyl, foam insulation, and interior gypsum board were blown away and there was no protection of occupants from windborne debris.

Vinyl siding manufactured for high-wind areas is available, but was not observed. (With high-wind siding, the nailing flange is folded over, so there is a double thickness of vinyl at the fastener points.) Vinyl siding that was blown off typically tore around the fastener points, which in all the cases investigated were large-headed nails. The 2003 IBC requires a maximum fastener spacing of 16 inches. ASTM D 4756, *Standard Practice for Installation of Rigid Poly (Vinyl Chloride) (PVC) Siding and Soffit*, also specifies a maximum spacing of 16 inches.

The fastener spacing was measured at a few buildings. The spacings on each of the buildings were quite variable. At the complex shown in Figures 5-28 and 5-29, along one of the siding panels, the nails were located 4 inches from the end of the panel, then 29, 14, 18, 31, and 17 inches. At another building in this complex, along one of the panels the nails were located 20 inches from the end of the panel, then 37 and 39 inches (this last fastener was 9 inches from the end of the panel).

Figure 5-28.
Loss of vinyl siding and foam insulation at a gable end wall. Note the missing vinyl soffit (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 5-29.
OSB was installed at the corner areas, but only foam insulation was present over the studs in the field of the wall. Most of the foam was blown away at this end wall (arrow). At some areas in this complex, the gypsum board on the interior side of the studs was also blown away (circle) (estimated wind speed: 130 mph. Long Beach, Mississippi).

ASTM D 4756 specifies that the fasteners are to be driven into framing or furring members, rather than just into plywood or OSB. Most of the fasteners that were investigated by the MAT were merely driven into sheathing. Although this practice did not comply with ASTM D 4756, no fastener pull-out problems were observed. In some cases, the MAT believes that the blow-off was triggered by unlatching of the buttlock, which is the bottom portion of the panel (see Figure 5-30). 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 blown 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.

Underlayment had not been installed at all on some residences (see Figures 5-26, 5-28, and 5-29). Not installing underlayment is a poor practice because vinyl siding (like many other types of wall coverings) does not prevent rainwater from getting behind the siding. Underlayment should always be installed to intercept the leakage and drain it out of the wall. ASTM D 4756 does not currently require underlayment underneath vinyl siding; however, the 2003 IBC does require underlayment.

Some vinyl siding was damaged by windborne debris, and some vinyl soffit damage was observed (see Figures 5-27 and 5-28). Where soffits were blown away, a significant amount of water was often driven into the attics and ultimately into living spaces. (Debris damage and soffit failure was more commonly observed by the MAT that investigated Hurricane Charley. Further discussion and analysis of debris damage and soffits are presented in FEMA 488, *Mitigation Assessment Team Report, Hurricane Charley in Florida.*)

The vinyl siding damage was related to application deficiencies (i.e., excessive spacing between fasteners). However, other factors also likely contributed to the damage. In all of the failures investigated by the MAT, it did not appear that the siding was any stronger than that used in areas of the United States that have a 90-mph basic wind speed. There also appear to be weaknesses in the ASTM product and testing standards. ASTM D 3679, *Standard Specification for Rigid Poly Vinyl Chloride) (PVC) Siding*, which specifies a 1.5 safety factor. Considering the simplicity of the test method and the number of wind failures, the 1.5 factor appears to be too low.

ASTM D 5206, *Standard Test Method for Windload Resistance of Rigid Poly (Vinyl Chloride) (PVC) Siding*, requires holding the test load for only 30 seconds before increasing to the next pressure level. ASTM E 1592 (a test for metal roof and siding panels) specifies that each load increment be maintained for a minimum of 60 seconds and until the gauges indicate no further increase in deflection. The load duration and deflection criteria in E 1592 appear prudent for vinyl siding. Another weakness is that D 5206 is a static test. Static tests can overestimate the wind resistance of systems that experience significant deformations and/or fatigue failure. Considering the flexible nature of vinyl siding and the dynamic nature of wind loading, a dynamic test appears to be prudent for vinyl siding.

**Figure 5-30.
When a panel becomes unlatched, it becomes very susceptible to blow-off (estimated wind speed: 120 mph. Ocean Springs, Mississippi).**

5.3.2.6 Wood Siding

Buildings with wood siding were not investigated by the MAT. However, wood siding was investigated by the Hurricane Ivan MAT. For discussion and analysis of those investigations, see FEMA 489, *Mitigation Assessment Team Report, Hurricane Ivan in Alabama and Florida.*

5.3.2.7 Soffits

Vinyl soffits were discussed in the vinyl siding section, and damaged soffits were shown in Figures 5-27 and 5-28. Figure 5-31 shows loss of metal soffit at a school that was completed in 1997. Some of the soffit panels were perforated. In one area, the soffit support angle was attached to the top row of brick veneer (inset in Figure 5-31). Wind created positive (i.e., upward-acting) pressure on the soffit panels. This load was transferred to the support angle and then to the bricks, which lacked sufficient strength to carry the uplift load. This failure illustrates the importance of soffits being designed and constructed to carry positive and negative pressures, and the importance of load-path continuity. With loss of the soffit, wind-driven rainwater was able to enter the ceiling space, whereupon several ceiling boards became saturated and collapsed. Soffit failure can also increase the magnitude of positive pressure within attics and exert more load on the roof structure and coverings (see Section 10.2.3.1 for further discussion).

Figure 5-31.
Loss of metal soffit at a school. At the area shown in the inset, the soffit support angle was inadequately anchored (estimated wind speed: 130 mph. Gulfport, Mississippi).

Figure 5-32 shows loss of metal soffit from an elevated walkway at a courthouse in downtown New Orleans. Figure 5-33 shows loss of soffit boards from a suspended grid system. The grid system did not have compression struts to resist positive pressure. In addition to the soffit damage itself, windblown soffit panels can break windows.

Figure 5-32.
Loss of metal soffit from an elevated walkway (estimated wind speed: 105 mph. New Orleans, Louisiana)

Figure 5-33.
Loss of soffit at canopy. The grid support did not have compression struts (estimated wind speed: 130 mph. Gulfport, Mississippi).

5.4 Roof Systems

Historically, damage to roof coverings and rooftop equipment is the leading cause of building performance problems during hurricanes. In the rains accompanying a hurricane, rainwater entering a building through damaged roofs can cause major damage to the contents and interior. Unless quick action is taken to dry a building, mold bloom can quickly occur in the hot, humid southern climate. Drying of buildings was hampered after Hurricane Katrina by the lack of electrical power to run fans and dehumidifiers. These types of damage are frequently more costly than the roof damage itself. Rainwater 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.

5.4.1 Asphalt Shingles

Throughout the areas observed by the MAT, most of the residences had asphalt shingle roof coverings. The vast majority of the observed roofs experienced damage, ranging from loss of a few hip trim shingles or tabs to loss of a large number of shingles and underlayment. For example, asphalt shingles were damaged on seven of the houses shown in Figure 5-34. Spotty damage occurred at the house on the upper left of Figure 5-34, while nearly all of the shingles and part of the underlayment were blown away at the house on the lower left.

A large number of relatively new shingle roofs (including several houses still under construction) experienced shingle damage. Figure 5-35 shows a new house that lost many shingles. The starter course was incorrectly installed (as discussed later) and there was no metal drip edge. Some of the shingles were superficially bonded to one another, underlayment was not lapped over a portion of the hip, the underlayment along the hip was cut in several locations (apparently while the shingles were being trimmed), the hip nails were incorrectly located, and several of the hip shingles did not bond, or were only superficially bonded, to one another. These shingles had a 1-1/2-inch-wide nailing strip and the majority of the nails were placed within the strip. The end nails were too far from the end (ranging from about 2 to 4 inches rather than 1 inch from the end). The field nails were somewhat uniformly distributed between the end nails; however, the manufacturer's literature indicates a different nailing pattern. These shingles had a Miami-Dade County (Florida) product approval label.

Figure 5-34. Asphalt shingles were damaged on seven of these houses. The two houses on the lower right had built-up or modified bituminous cap sheets. The blow-off at the lower right was likely initiated by blow-off of a deck panel from the corner (estimated wind speed: 105 mph. New Orleans, Louisiana area).

Figure 5-35.
An incorrectly installed starter course was the likely cause of failure at the left and right portions of the damaged roof. Water was able to leak into the building where the underlayment was not lapped over a portion of the hip (estimated wind speed: 130 mph. Long Beach, Mississippi).

Performance of the self-seal adhesive is a key factor. If the bonding is inadequate to prevent the shingle tab from lifting, winds of even moderate speed can lift the tabs. Depending upon physical properties of the shingle, number of fasteners, and fastener location, when tabs are lifted they are susceptible to being torn off, or entire portions of shingles being blown away. New Underwriters Laboratories (UL) and ASTM standards have been developed in recent years to provide better evaluation of wind resistance of shingles. UL has also implemented a new wind classification; however, it is unlikely that most of the damaged roofs that were observed were constructed with shingles that met the new classification system.

While sufficient bonding of the tabs is a critical performance factor, there are other key issues that influence wind performance. Throughout the areas observed by the MAT, failures of hip/ridge trim shingles, and failures along the eaves and rakes were common. Enhancement of hip/ridge, eave, and rake details, such as that shown in the FEMA 55, *Coastal Construction Manual* (2000), were not observed (see Technical Fact Sheet No. 20 in FEMA 499, *Home Builder's Guide to Coastal Construction*, for these details and other items pertaining to shingle roof coverings). Fastener mislocation and an inadequate number of fasteners were also common. These issues are discussed in the following paragraphs.

5.4.1.1 Hips/Ridges

Hip or ridge shingles were often blown off while all or many of the remaining shingles were undamaged (Figures 5-34 to 5-36 and 5-39). 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, but frequently none of the adhesive had bonded (Figure 5-37). Lack of bonding of hip and ridge shingles is common due to substrate irregularity along the hip/ridge line. Use of asphalt roof cement, as recommended in Technical Fact Sheet No. 20 in FEMA 499, ensures bonding.

Figure 5-36.
Loss of hip shingles. The underlayment above the dormer was likely blown off due to increased turbulence caused by the dormer (estimated wind speed: 115 mph. Slidell, Louisiana).

Figure 5-37.
At the hip on the left, the self-seal adhesive only made contact at a small area on the right side of the hip (red circle). At the hip at the right, no adhesive bonding occurred. The nails at both of these hips were above, rather than below, the adhesive line (estimated wind speed: 105 and 130 mph. Pascagoula and Gulfport, Mississippi, respectively).

5.4.1.2 Eaves

None of the observed starter courses of damaged roofs complied with industry recommendations. The typically observed practice was to turn the starter shingle 180 degrees, rather than cut off the tabs (see Figure 5-38). 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 and progressive peeling (see Figures 5-39 and 5-47). One recently installed roof used a factory precut starter strip and did not experience any damage along the eaves (however, the wind speeds in this area were only about 120 mph). On this roof there was some limited hip damage, loss of one shingle from the field of the roof, and some loss of laminated tabs (see Figure 5-42).

Figure 5-38.
Rather than cutting off the tabs of the starter, the starter was rotated 180 degrees (red arrow). The exposed portion of the first course of shingles (yellow arrow) was unbonded because the self-seal adhesive (dashed line) on the starter was not near the eave (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 5-39.
These two failures likely initiated at the eave due to an incorrectly installed starter course. Note that, at both roofs, a portion of the underlayment and some of the hip shingles were blown away (estimated wind speed: 115 and 105 mph. Slidell, Louisiana, and Pascagoula, Mississippi, respectively).

In addition to correctly installing the starter, use of asphalt roof cement to ensure bonding along the eave is recommended in Technical Fact Sheet No. 20 of FEMA 499. Due to substrate irregularities along the eave line, even when the starter is correctly installed, insufficient tab bonding can occur unless asphalt roof cement is applied.

Another commonly observed problem was excessive overhang. The *Residential Asphalt Roofing Manual* (published by the Asphalt Roofing Manufacturers Association [ARMA]) recommends that the shingles overhang the eave and rakes by 1/2 to 3/4 inch. Eave overhangs of 3/4 to 1-1/2 inches were often observed. The greater the overhang, the greater the uplift load on the shingle. Therefore, Technical Fact Sheet No. 20 in FEMA 499 recommends a 1/4-inch overhang at eaves and rakes.

5.4.1.3 Rakes

As with eaves, lifting and peeling failure often initiates at rakes and propagates into the field of the roof, as shown in Figure 5-40. Rakes are susceptible to failure due to the additional load exerted on the overhanging shingles (thus it is important to minimize the overhang as discussed above) and the configuration of the self-sealing adhesive. Along the long dimension of the shingle (i.e., parallel to the eave), the tab is sealed with self-sealing adhesive that is either continuous or nearly so. But along the rake, the ends of the tab are only sealed at the self-seal lines; therefore, the tabs are typically sealed at about 5 inches on center. Therefore, under high-wind loading, the adhesive at the rake end is stressed higher than the adhesive farther down along the tab. With sufficient wind loading, the corner of the tab at the rake can begin to lift up and progressively peel.

Figure 5-40.
These shingle blow-offs likely were initiated by lifting and peeling of shingles along the rake. Note the loss of vinyl siding at the right photograph (estimated wind speed: 130 and 115 mph respectively. Long Beach, Mississippi, and Slidell, Louisiana, respectively).

To enhance the wind resistance of shingles along the rake, Technical Fact Sheet No. 20 in FEMA 499 recommends application of asphalt roof cement along the rake. By adding dabs of cement, as shown in Technical Fact Sheet No. 20 (and Figure 5-41), uplift load across the ends of the rake shingles is distributed to the cement as well as the self-seal adhesive, thus minimizing the possibility of tab uplift and progressive peeling failure.

On several damaged roofs, including the one shown on the left side of Figure 5-40, bleeder strips had been installed. Bleeder strips are shingles that are applied along the rake, similar to the starter course at the eave, as shown at Figure 5-41. A bleeder provides an extended straight edge that can be used as a guide for terminating the rake shingles. At first glance, it might be believed that a bleeder enhances wind resistance along the rake. However, it does not significantly enhance resistance because the concealed portion of the overlying rake shingle is the only portion than makes contact with the self-seal adhesive on the bleeder. As can be seen in Figure 5-42, the tab does not make contact with the bleeder. Hence, if the tab lifts, the shingle is placed in a peel mode, which can easily break the bond with the bleeder. Also, if the tabs are not cut from the bleeder and the cut edge placed along the rake edge (which was seldom done on the observed roofs), the bleeder's adhesive is too far inward to be of value.

If bleeder strips are installed for alignment purposes, use of asphalt roof cement, as shown in Technical Fact Sheet No. 20 of FEMA 499, is still recommended.

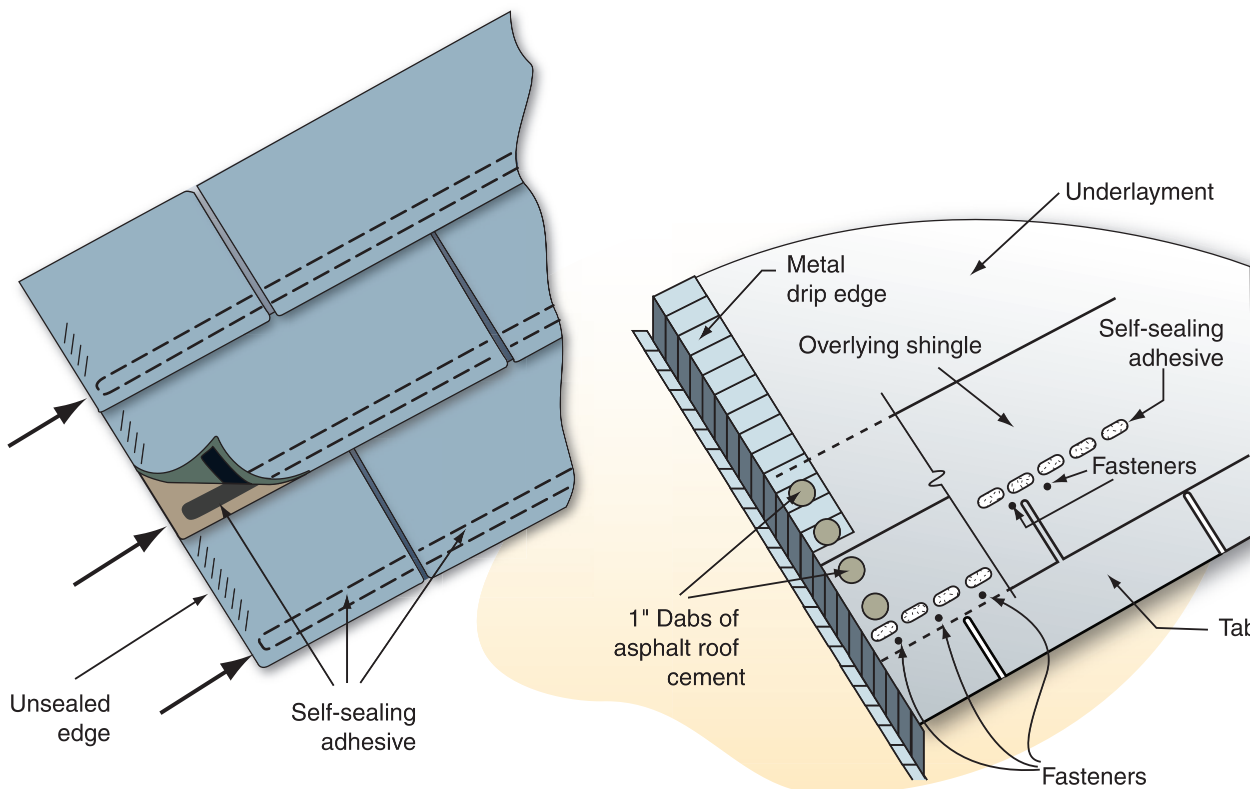


Figure 5-41.
Uplift loads along the rake are transferred (illustrated by the arrows) to the ends of the rows of self-sealing adhesive. When loads exceed resistance of the adhesive, the tabs lift and peel. The detail at the right is from Technical Fact Sheet 20 in FEMA 499. It shows installation of asphalt roof cement along the rake. The cement adheres the unsealed area shown by the hatched lines of the drawing to the left.

Figure 5-42.
Blow-off of shingles at a new house under construction. A bleeder strip (double-arrow) was used along the rake. Note that the tab of the overlying shingle cannot make contact with the bleeder's self-seal adhesive (upper arrow) (estimated wind speed: 125 mph. Waveland, Mississippi).

5.4.1.4 Fasteners

Where fasteners were visible due to shingle blow-off, it was found that roofing nails were typically used. Several of the damaged roofs had been installed with six nails per shingle, but it was more common to see four or five nails per shingle. (Use of five nails per shingle is not a recognized practice.) ARMA advises that six nails per shingle "should be considered" in high-wind areas. (All of the areas investigated by the MAT are high-wind areas.)

Significant fastener mislocation occurred on nearly all of the damaged roofs observed (see Figures 5-43 and 5-44). Fasteners were typically located 1 to 2 inches above the nailing line (i.e., the line printed on the shingle by the manufacturer). End fasteners were often 2 to 3 inches from the end, rather than the industry-recommended 1 inch. Minor deviations from intended fastener locations should be expected; however, the deviations on nearly all of the damaged roofs were excessive.

When nails are too high above the nail line, they can miss the underlying shingle headlap or have inadequate edge distance as shown by the nail that is right of the circle in Figure 5-43 and illustrated in Figure 5-45. When using laminated shingles, high nailing may miss the overlap of laminated shingles; if the overlap is missed, the nail pull-through resistance is reduced (see Figure 5-46). High nailing may also influence integrity of the self-seal adhesive bond by allowing excessive deformation (ballooning) in the vicinity of the adhesive.

Shingles manufactured with a wide nailing zone, such as those installed on the house shown in Figure 5-35, provide roofing mechanics with much greater opportunity to apply the fasteners in the appropriate locations.

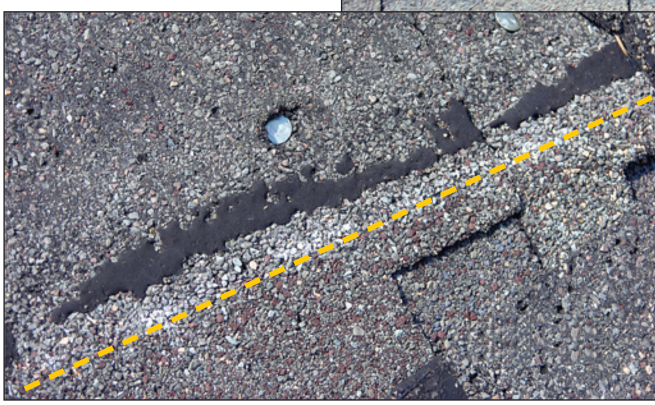


Figure 5-43.
The nails at this house under construction were too far above the nailing line (underscored by dotted yellow line in inset) and too far from the ends (circle). They were also over-driven (square and inset) (estimated wind speed: 125 mph. Waveland, Mississippi).

Figure 5-44.
The nails at this house under construction were placed quite close to the nailing line. However, some of the end nails were too far inward (the nail in the oval was several inches from the end). Distribution along the nail line was also a problem (the nails in the circles were much too far apart) (estimated wind speed: 115 mph. Slidell, Louisiana).

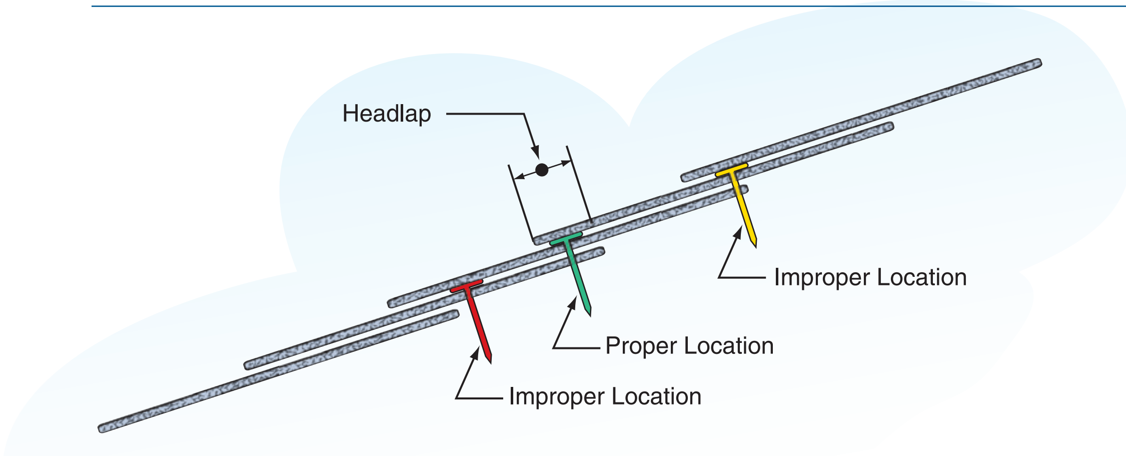


Figure 5-45.
When properly located, the nail engages the underlying shingle in the headlap area (green nail). When too high, the nail misses the underlying shingle (red arrow) or is too close the to edge of the underlying shingle (yellow nail).

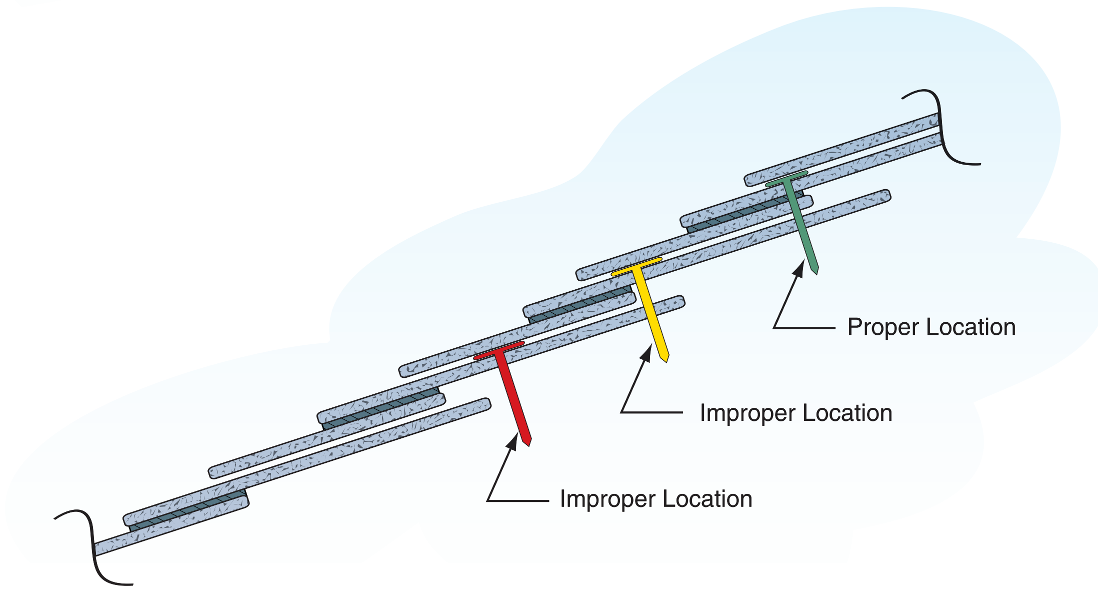


Figure 5-46.
With laminated shingles, properly located nails engage the underlying laminated portion of the shingle, as well as the headlap of the shingle below (green nail). When too high, the nail can miss the underlying laminated portion of shingle but engage the headlap of the underlying shingle (yellow arrow), or the nail can miss both the underlying laminated portion of the shingle and the headlap of the underlying shingle (red nail).

The number of nails (i.e., four versus six) and their location likely plays little role in wind performance, as long at the shingles remain bonded. However, if they are unbonded prior to a storm, or debonded during a storm, the number and location of nails and the shingles' nail pull-through resistance likely play an important role in the magnitude of progressive damage, as illustrated by Figure 5-47.[2]

[2] If the wind speed is extremely high, extensive progressive damage is likely, regardless of the number and location of fasteners and pull-through resistance.

Figure 5-47.
The starter course was incorrectly installed at this recently completed roof. The starter course and eave course lifted. A progressive peeling occurred because there was inadequate nailing attachment to resist the peel forces (estimated wind speed: 105 mph. Pascagoula, Mississippi).

5.4.1.5 Raking

Several of the damaged roofs were installed with the raking installation method. With this method, shingles are installed from eave to ridge in bands about 6-feet wide (see Figure 5-48). Where the bands join one another, at every other course, a shingle from the previous row needs to be lifted up to install the end nail of the new band shingle. Sometimes installers do not install the end nail; in these applications, the shingles are vulnerable to unzipping at the band lines, as shown in Figure 5-49. At a nursing home in Gulfport, Mississippi, a limited amount of spot checking found three shingles that were missing the right end nail (see Figure 5-50). Blown-off shingles broke some of the windows in the nursing home (see Figure 5-51), and were the likely cause of glazing damage at a building across the street.

The National Roofing Contractors Association (NRCA) recommends that the raking method not be used and that shingles should be laid one course at a time from rake to rake starting at the eave.

Figure 5-48.
This house was being reroofed after the hurricane using the raking method. The starter course was incorrectly installed (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 5-49.
The vertical lines of missing tabs are indicative of installation by the raking method. When raked, end nails are frequently not installed. Some shingles and underlayment were also blown from the eave and rake (estimated wind speed: 125 mph. Waveland, Mississippi).

Figure 5-50.
Many shingles were blown from a nursing home. Limited checking found three shingles that were missing the right end nail (see inset for one of these). The nails that were installed were placed very high (red arrows); many missed or just nicked the underlying headlap (estimated wind speed: 130 mph. Gulfport, Mississippi).

Figure 5-51. Windborne asphalt shingle debris broke several windows in this nursing home. A piece of shingle debris is embedded in the frame (estimated wind speed: 130 mph. Gulfport, Mississippi).

5.4.1.6 Laminated Tabs

On a few roofs with architectural shingles, instances of blow-off of laminated tabs were observed (see Figure 5-52). This type of failure was due to an inadequate amount and/or strength of adhesive used in the manufacturing of the shingles.

Figure 5-52. Two laminated tabs were lifted (circles) at a house under construction (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

5.4.1.7 Recovering

On some residences that had been recovered (i.e., new shingles had been installed on top of old shingles), large numbers of the recovered shingles were blown away and the underlying older shingles remained in place. When recovering 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 recover blow-offs were likely due to bonding problems associated with substrate irregularities. Some of these blow-offs may have been due to use of nails that were too short, although this failure mode is atypical.

5.4.1.8 Ridge Vents

A few instances of ridge vent blow-off were observed, but detailed investigations were not made. (Ridge vents were investigated by the Hurricane Ivan MAT. For discussion and analysis of those investigations, see FEMA 489, *Mitigation Assessment Team Report, Hurricane Ivan in Alabama and Florida*.) The performance of ridge vents with respect to prevention of wind-driven rain infiltration during the hurricane was not evaluated.

5.4.1.9 Roof-to-Wall Flashing

In a few instances, continuous metal flashing rather than step flashing was observed at roof-to-wall intersections (see Figure 5-53). Although continuous flashing is cheaper to install, this application method is susceptible to leakage and subsequent dry rot of the deck sheathing (this type of failure was observed by the Hurricane Ivan MAT). The ARMA *Residential Asphalt Roofing Manual* recommends the use of step flashings at roof-to-wall intersections. Technical Fact Sheet No. 24 in FEMA 499 provides recommendations for enhancing the roof-to-wall flashing in high-wind areas.

Figure 5-53. Continuous metal flashing at the roof-to-wall intersection of a house under construction. This detail is susceptible to leakage and subsequent dry rot of the deck sheathing (estimated wind speed: 115 mph. Slidell, Louisiana).

5.4.1.10 Underlayment

In some instances where shingles were blown off, the underlayment was not damaged and, therefore, provided some degree of protection from water infiltration. But in many other instances, the underlayment was also blown off (see Figure 5-54). Rain was then able to enter the building at the sheathing joints. In general, wind performance of exposed underlayment observed by the

Hurricane Charley and Ivan MATs in Florida and Alabama, respectively, was significantly better than the performance of underlayment in Louisiana and Mississippi in Hurricane Katrina, and was primarily due to enhanced nailing of the underlayment.

Technical Fact Sheet No. 19 in FEMA 499 provides recommended practices for underlayments on roofs in high-wind areas.

Figure 5-54. Widespread loss of underlayment. With loss of underlayment, water is free to leak into the building and cause extensive interior damage (estimated wind speed: 115 mph. Slidell, Louisiana).

5.4.2 Fiber-Cement, Slate, and Tile

Fiber-cement and slate roof coverings have very limited market shares in the southeastern United States and there is limited information in the literature on the wind performance of these products. The MAT observed one roof with fiber-cement that simulated slate and one slate roof. Figure 5-55 shows the fiber-cement roof. It experienced damage in several areas, including many of the hip lines. The simulated slates were attached with two nails. The manufacturer's literature states the nails are to be placed between 1/2 and 1-1/2 inches above the exposure so that the nail penetrates the underlying simulated slate in the headlap area. However, the nails were typically placed a few inches above the exposure and they missed the headlap. Some of the nails pulled out of the deck, but many remained in place. In several instances, the simulated slates broke at the nail line.

In 2004, the manufacturer issued high-wind attachment recommendations, which consisted of placing 1-1/2x3/8 inch beads of adhesive over the nail heads. Adhesive was not used on the roof shown in Figure 5-55; however, that roof may have been installed prior to distribution of the 2004 recommendations.

Figure 5-56 shows a slate roof. It too experienced damage in several areas, including many of the hip lines. The slates were 9-1/2 inches wide by 15-3/4 inches long, with a 7-inch exposure. They were attached with two 2-inch-long copper slating nails, located about 1-3/4 inches in from the edges and about 2-3/4 inches from the upper end. *The NRCA Roofing and Waterproofing Manual* recommends the nails be 1-1/4 to 2 inches from the edges; therefore, the application complied with that recommendation. However, the NRCA manual recommends the nails be 1/4 to 1/3 the length of the slate from the end.[3] With a 15-3/4-inch-long slate, the nails should have been about 4 to 5-1/4 inches from the end, rather than the 2-3/4 inches. The NRCA manual also recommends use of four nails per slate in high-wind areas; therefore, the application did not comply with that recommendation. In addition, the NRCA manual recommends dabs of asphalt roof cement or polyurethane sealant at the eave in high-wind areas. It was unclear whether or not the eave slates had the recommended adhesive enhancement.

Figure 5-55.
Fiber-cement simulating slate. Note the loss of underlayment and the simulated slates broken at the nail line (circle). This house was located in Exposure C (estimated wind speed: 105 mph. Pascagoula, Mississippi).

Figure 5-56.
Damaged slate roof. The nails typically pulled out of the deck. However, as shown in the square/inset, some of the slates broke and small portions remained nailed to the deck. This house was located in Exposure C (estimated wind speed: 130 mph. Gulfport, Mississippi).

[3] The NRCA manual has a typographical error. The manual states the holes should be 1/4 inch to 1/3 inch the length of the slate from the upper end. The word "inch" should not have been included (i.e., the holes should be 1/4 to 1/3 the length of the slate).

Few tile roofs were seen in the areas in Louisiana and Mississippi that were struck by Hurricane Katrina. The tile roofs that were observed were typically damaged (see Figures 5-57 and 5-58). (Many tile roofs were investigated by the Hurricane Charley and Ivan MATs. For discussion and analysis of those investigations, see FEMA 488, *Mitigation Assessment Team Report, Hurricane Charley in Florida* and FEMA 489, *Mitigation Assessment Team Report, Hurricane Ivan in Alabama and Florida*. Both of those documents include a Hurricane Recovery Advisory on tile, and that Advisory became Technical Fact Sheet No. 21 in FEMA 499.)

Note: The tile Advisory and Technical Fact Sheet No. 21 references the third edition of the *Concrete and Clay Roof Tile Installation Manual*. The fourth edition of that manual was published in August 2005 in response to the 2004 hurricanes. FEMA's tile Advisory and Technical Fact Sheet No. 21 are still applicable, but the fourth edition of the manual should be used.

Figure 5-57. Damaged tiles at roof perimeter (estimated wind speed: 120 mph. VA Hospital Chapel, Biloxi, Mississippi)

Figure 5-58. Wind turbulence behind parapet resulted in uplift of ridge tiles. Tile was also damaged along the eave (estimated wind speed: 120 mph. VA Hospital Patient Building, Biloxi, Mississippi).

5.4.3 Metal Panels and Shingles

A variety of exposed fastener and standing seam panel systems was observed, as well as metal shingles. The performance of metal roofing varied greatly.

5.4.3.1 Exposed Fastener Panels

Exposed fastener panels generally performed well, as illustrated by Figure 5-59, although in several instances, hip and/or ridge flashings were blown away. Most of the exposed fastener panels were of the R-panel design, although a few 5V-Crimp roofs were observed. (A substantial number of 5V-Crimp roofs were observed by the Hurricane Charley MAT. For discussion and analysis of those investigations, see FEMA 488, *Mitigation Assessment Team Report, Hurricane Charley in Florida.*)

Success or failure of exposed fastener panels was likely dependent upon fastener spacing (see Figure 5-60) and type, and whether or not the substrate lifted, as discussed later. Panel gauge may have also had some influence. Screws provided greater pull-out resistance than ring-shank nails, and were more resistant to dynamic loading. Another key element of good performance is the spacing of fasteners along the eave and at hip and ridge flashings. Close spacing at the flashings and eave is important to keep the flashings and panel ends from billowing during high winds.

Figure 5-59.
This R-panel roof was not damaged. This house was located in an area that received some of the highest winds (estimated at 125 mph). The damage at the first and second floors was caused by storm surge. The surge pushed the first floor to the right. This "leaner" is considered to be a "survivor" (estimated wind speed: 125 mph. Bay St. Louis, Mississippi).

Figure 5-60.
The R-panel roof on this house located in Exposure C was very well attached. The screws were closely spaced horizontally and vertically, and at the panel side laps. The flashing fasteners were too far apart (12 inches on center), but the attachment was sufficient for these winds (estimated wind speed: 115 mph. Slidell, Louisiana).

Several of the R-panel failures were caused by failure of the substrate to which the panels were attached. The panels on the house shown in Figure 5-61 were likely a reroofing application. The panels were installed over underlayment over plywood. On the backside of the house, one or more plywood panels were blown off from along two locations at the eave. The decking blow-off resulted in a progressive lifting and peeling failure of the panels. At the house shown in Figure 5-62, 2x4 nailers had been attached to the plywood decking and then the R-panels were attached to the nailers. The right half of the third nailer from the eave was blown away. Inadequate nailer attachment was the likely cause of this failure. Nailer failure also caused R-panels to be blown away on a few residences where nailers had been installed over existing asphalt shingles. The panels were screwed to the nailers at 12 inches on center, but the nailers were nailed to the sheathing at spacings that exceeded 12 inches. Therefore, the nailer attachment was the weak link in the load path.

Figure 5-61. Blow-off of decking caused these panels to progressively fail (estimated wind speed: 105 mph. Pascagoula, Mississippi).

Figure 5-62. Blow-off of one of the nailers (dotted line) caused these panels to progressively fail. Note the cantilevered condenser platform (arrow), a good practice, and the broken window (circle). The house was located in Exposure C (estimated wind speed: 130 mph. St. Bernard Parish, Louisiana).

Figure 5-63 shows an apartment complex that did not incorporate roof decking. The trusses had 2x4 nailers installed directly over them. Several of the nailers were blown away, which resulted in a progressive failure of the R-panels. Since there was no roof decking, it was not possible to install underlayment. Thus with loss of the metal panels, the living units were exposed to massive rainwater infiltration.

An advantage of exposed fastener panels (versus panels with concealed clips) is that, after installation, it is easy to verify that the correct number of panel fasteners were installed. However, if the panels are attached to nailers or decking that is inadequately attached, such deficiency will not be apparent after panel application.

Figure 5-63.
Blow-off of nailers caused these panels to progressively fail. The nailers were installed directly over the trusses and, with loss of the panels, rainwater was free to enter the building (estimated wind speed: 105 mph. Pascagoula, Mississippi).

5.4.3.2 Standing Seam Panels

A variety of architectural and structural standing seam panels was also observed. As with the exposed fastener panels, some of the roofs were undamaged, others lost hip or ridge flashings, and others lost a large number of panels (see Figure 5-64). Performance of standing seam 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.

Figure 5-64.
Loss of architectural standing seam panels. The panels were installed over 2x4 nailers over underlayment and wood sheathing panels. Much of the exposed underlayment was blown away, thereby allowing rainwater infiltration (estimated wind speed: 130 mph. Buras, Louisiana).

Two unusual installation practices were observed. At the school shown in Figure 5-65, the standing seams were not continuously seamed together. Rather, they were crimped at an erratic spacing (in one area, it was about 4 feet between 6-inch-long crimps). Lack of continuous seaming reduces uplift resistance of the panels and makes them susceptible to leakage. Some of the copings were blown off, and several suspended ceiling boards collapsed after becoming saturated from roof leakage.

The other unusual installation practice occurred on a police station that was reroofed. The concealed clips were installed with a single screw, rather than two screws, as intended for the clips that were used. With only a single screw, the clip was eccentrically loaded (see Figure 5-66), thus making the panels susceptible to failure. However, with this building, the greater problem pertained to inadequacies of the support structure, as shown in Figure 3-54.

Figure 5-65.
The architectural standing seam panels on this school were not continuously seamed. Note the coping damage. This portion of the school was completed in 1988 (estimated wind speed: 125 mph. Waveland, Mississippi).

Figure 5-66.
The clips for this structural standing seam panel were intended to be attached with two screws. With only one screw, the clips were eccentrically loaded (estimated wind speed: 130 mph. Long Beach, Mississippi).

When metal panels or hip/ridge flashings blow off (see Figure 5-67), 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.

Figure 5-67.
The steep-slope roof coverings on this high-rise building appear to be tile; however, they actually were metal panels that simulated tile. Several panels were blown off (estimated wind speed: 120 mph. Biloxi, Mississippi).

5.4.3.3 Metal Shingles

A limited number of metal shingles were observed. Figure 5-68 shows an aluminum shingle that has been used on many fast-food restaurants throughout the United States. These shingles are attached with two stainless steel clips per shingle. Because these shingles are quite flexible, they deformed and lost engagement with the clip. Poor performance with this type of shingle has been observed in several previous hurricanes, dating back to Hurricane Hugo in 1989. Another aluminum shingle of somewhat similar design to that shown in Figure 5-64 also deformed and lost engagement with its clips. Some batten-attached metal shingles were also observed, but detailed investigations were not performed to determine the failure mode.

Figure 5-68.
These aluminum shingles disengaged from their clips (estimated wind speed: 115 mph. Slidell, Louisiana).

5.4.4 Low-Slope Membrane Systems

The MAT observed several types of low-slope roof systems that included built-up roofs (BURs), modified bitumen, and single-ply. Membrane damage was typically caused by membrane lifting and peeling after lifting of the gutter, edge flashing, or coping, and by puncturing and tearing by windborne debris. Deck failure also caused membranes to lift and peel, and aggregate blow-off caused substantial glazing damage. In addition to these failure modes, which are discussed below, walkway pads were blown away. Walkway pads have sufficient mass to be very damaging windborne debris.

Roof membranes can successfully resist very high-wind loads but, to do so, attention needs to be given to system and component selection, detailing, and application. This is illustrated by the 670-foot tall building in New Orleans (see Figure 5-25). The penthouse roof was reroofed around 1997. It was a modified bitumen membrane over perlite insulation set in hot asphalt. This membrane blew off during Hurricane Katrina and was attributed to inadequate uplift resistance of the perlite insulation. The main roof was reroofed around 2000. The modified bitumen membrane was reportedly installed over glass mat gypsum roof board set in hot asphalt over polyisocyanurate insulation set in hot asphalt over the concrete deck. This membrane was punctured by stone veneer panels that detached from the penthouse walls; however, neither the edge flashing or membrane lifted.

5.4.4.1 Edge Failure

Lifting of metal edge flashings typically results in progressive lifting and peeling of the roof membrane. Lifting of copings can also result in progressive failure of the membrane, and blown-off copings become windborne debris that can puncture roof membranes and cause other damage. Metal edge flashing and coping lifting can be caused by inadequate attachment of the flashing or coping, inadequate attachment of nailers, or lifting of gutters. The vital importance of edge flashing and coping securement has been widely recognized since the early 1980s; however, code criteria were not incorporated into a model code until the 2003 edition of the IBC.

Some of the investigated roofs (including two of the EOCs discussed in Section 7.1) had uncleated metal edge flashings. Because of lack of securement of the vertical face, uncleated flashings are particularly susceptible to wind blow-off. However, as discovered during Hurricane Hugo (1989) investigations, presence of a continuous cleat does not ensure adequate performance. Gauge of the cleat and flashing/coping, length of cleat hem (the amount of interlock between the cleat and flashing/coping), and number, type, and location of cleat fasteners influence wind performance.

At the Federal courthouse shown in Figure 5-69, the coping had a 6-1/2-inch vertical face, but the hem on the continuous cleat was only 7/16 inch long.[4] High-wind loads caused deformation of the coping and cleat. Because of the limited engagement with the cleat, the outer face of the coping unlatched from the cleat. At several areas, the unlatched coping lifted, but remained attached to the parapet; however, some of the sections of coping were blown from the parapet. The courthouse was completed in 2003.

[4] The 2001 edition of *The NRCA Roofing and Waterproofing Manual* recommends a ¾-inch long hem.

Figure 5-69.
This coping unlatched from the cleat because the cleat hem was too short. Two sections of detached coping are resting on the roof (red arrows) (estimated wind speed: 130 mph. Gulfport, Mississippi).

At the school gym roof shown in Figure 5-70, the modified bitumen membrane was set in hot asphalt over 4x4-foot perlite set in hot asphalt over mechanically attached polyisocyanurate insulation and glass mat gypsum roof board over metal deck. The membrane peeling was caused by failure of the edge flashing nailers. Rather than stacking continuous 2x nailers, a 2x nailer about 12 inches long was attached to the deck, followed by another 2x nailer of the same length on top of it. The upper nailer was attached with two power-driven fasteners. These discontinuous stacks were spaced at 4 feet 7 inches on center. A continuous top nailer was then attached to the stacks. The continuous top nailer lifted with the metal edge flashing and caused the membrane to lift and peel. This school was completed in 1998.

Figure 5-70.
The modified bitumen membrane failure at this school was caused by lifting of the edge nailer (estimated wind speed: 130 mph. Pass Christian, Mississippi).

5.4.4.2 Puncture

Membranes were also commonly punctured and torn by windborne debris (see Figure 5-71). A substantial amount of water can leak into a building at small punctures and tears unless there is a secondary membrane (as discussed in FEMA 424, *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds*) or a monolithic concrete deck. Membrane puncture is a routine occurrence in hurricanes. When a large number of buildings are damaged, emergency repairs are often not made for many weeks. In these cases, relatively minor membrane damage can cause wetting of large areas of roof insulation, resulting in damage to interior finishes and equipment.

During prolonged wind loading, as is often the case with hurricanes, membrane tears can propagate and lead to detachment of the membrane from its substrate, which can lead to blow-off of a large portion of the membrane.

Figure 5-71.
This modified bitumen membrane was punctured in several locations by windborne debris. This building was located in Exposure C (estimated wind speed: 120 mph. Biloxi, Mississippi).

5.4.4.3 Deck Failure

Failure of the roof deck or the roof deck support structure sometimes occurs, particularly with buildings designed when the building code did not account for increased uplift loads at the roof perimeter and corners. Deck failure can be caused by inadequate attachment of the deck to the deck support structure, as shown in Figures 3-48 and 5-72. Deck failure can also be caused by corrosion or dry rot, as shown in Figure 5-73.

Figure 5-72.
The BUR on this school was blown off after one of the cementitious wood-fiber deck panels detached from the joists. Older cementitious wood-fiber deck attachments typically offered limited uplift resistance (estimated wind speed: 120 mph. Biloxi, Mississippi).

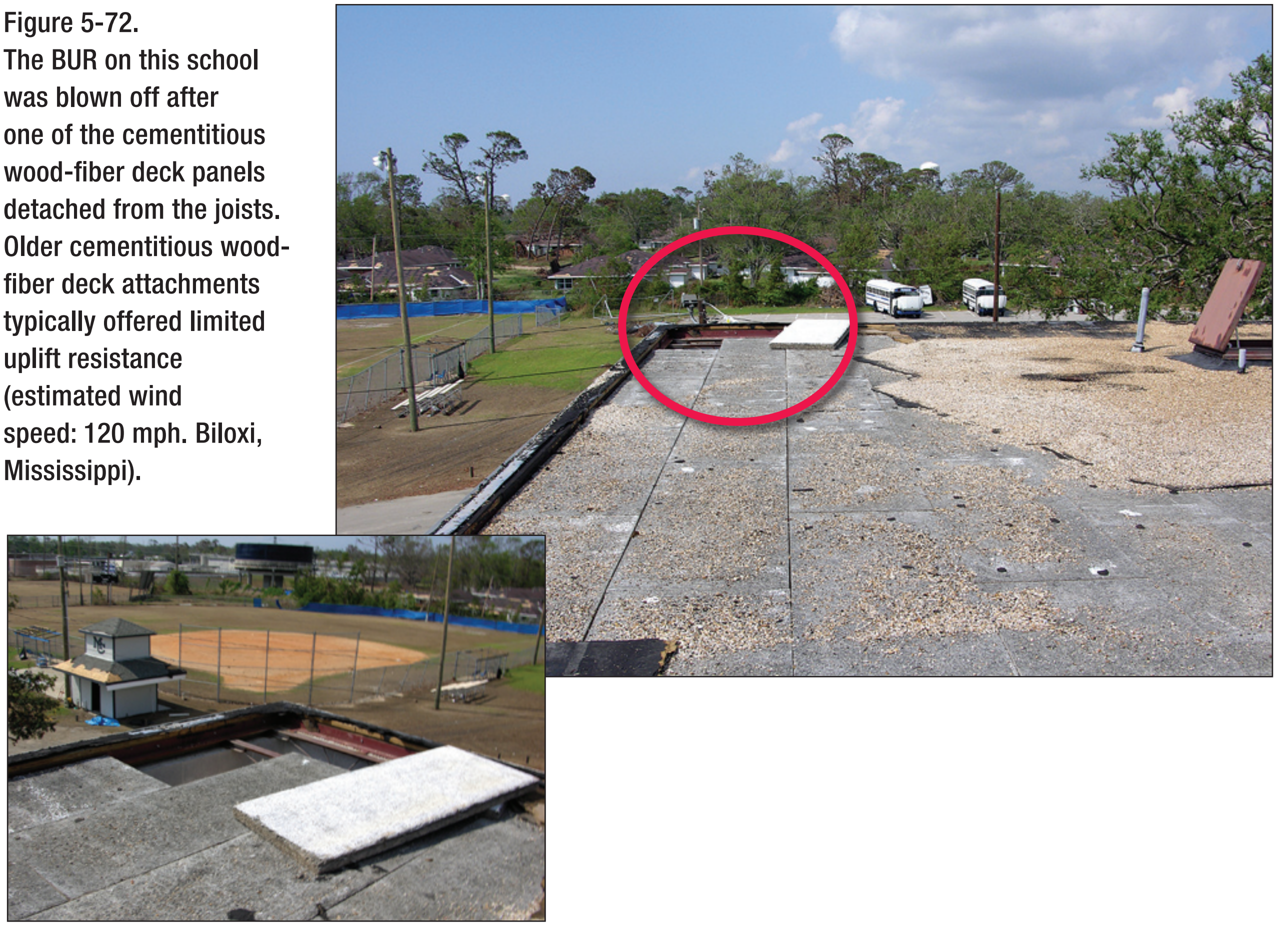


Figure 5-73.
The BUR on this school was blown off after a few of the rotted wood planks detached from the joists (estimated wind speed: 120 mph. Biloxi, Mississippi).

When buildings in hurricane-prone regions are reroofed, it is prudent to tear off the existing roof system down to the deck, so that the entire deck surface can be checked for attachment and deterioration. If inadequately attached or deteriorated decking is discovered, remedial action should then be taken as part of the reroofing project. By doing so, future wind damage associated with deck deficiencies can be avoided.

Figure 5-74 illustrates another type of deck and deck support failure. This school originally had a low-slope BUR. As part of a reroofing project, a steep-slope conversion was made, wherein sloped wood framing was installed over the BUR, followed by plywood decking and a modified bitumen membrane. The wood framing blew away due to inadequate attachment. This illustrates the importance of load path and connections when steep-slope conversions are made.

Figure 5-74.
The wood superstructure that was installed on this school as part of a steep-slope conversion blew away because of inadequate attachment (estimated wind speed: 125 mph. Port Sulphur, Louisiana).

5.4.4.4 Aggregate Blow-off

Many windows (including windows of critical and essential facilities) were broken by aggregate blown from roofs, as shown in Figures 3-29, 3-47, and 3-59 and discussed in Section 5.5.1. The glazing damage in downtown New Orleans was extensive and very costly. Most of the aggregate was from built-up roofs, but some of the aggregate was from ballasted single-plies.

In addition to causing damage to unprotected glazing, wind-blown aggregate can injure people who are outside during a hurricane. Although few people are normally outside during a hurricane, common exceptions are people who arrive late to shelters and those seeking care at hospitals. It is therefore prudent to avoid aggregate surfacings on critical and essential facilities.

A new section in the 2006 edition of the IBC now prohibits the use of aggregate surfaced roofs in hurricane-prone regions.

5.5 Windows, Shutters, and Skylights

Exterior windows are very susceptible to windborne debris breakage unless they are impact resistant (via use of laminated glass or shutters). The probability that any one window will be struck by windborne debris is typically small; however, 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. This section addresses debris damage to unprotected glazing, performance of protected glazing, problems caused by over-pressurization, window installation issues, and skylights.

If glazing is cracked by debris, but remains in the frame as shown in Figure 7-8, the ramifications of damage are limited to the cost of replacing the glazing and perhaps some water infiltration. However, if glass is blown from the frame, the shards become debris that can cause injury or damage, the internal pressure within the building can be substantially increased or decreased and thus lead to structural failure as discussed in Section 4.2, building envelope damage, interior partitions and ceilings can be damaged, and a substantial amount of wind-driven rain can enter the building. Figure 5-75 illustrates consequences of breached glazing at a hotel. In addition to the cost of the damage to the glazing and interior finishes and furnishings, business interruption costs can be substantial.

Figure 5-75. Interior view of the hotel shown in Figures 3-47 and 5-82. After the exterior glazing broke, wind knocked down the partitions between the guest rooms and water entered the building (estimated wind speed: 105 mph. New Orleans, Louisiana).

In addition to the performance problems discussed in this section, leakage problems were also reported, but this failure mode was not investigated by the MAT. Leakage can occur between window frames and the exterior wall, and between glazing and glazing gaskets due to sealant and/or flashing failures or gasket deterioration. However, leakage more commonly occurs around the frames of operable window units. Leakage around operable units can be caused by deterioration of weatherstripping or installation of window units that have inadequate resistance to wind-driven rain. The maximum test pressure that is used in the current ASTM test standard for evaluation of resistance of window units to wind-driven rain is well below design wind pressures. A change is being considered to increase the maximum test pressure for water resistance from 12 psf to 15 psf. Test duration time may also be an issue, but a change has not been proposed.

5.5.1 Unprotected Glazing

5.5.1.1 New Orleans Area and Mississippi

When the MAT observed broken glazing, often only one or a few of a building's windows were broken. This type of isolated damage occurred when there was a limited amount of natural or manmade debris (such as tree limbs or building components) flying in the vicinity of the building. For example, it appeared that a cosmetic shutter was blown from the window shown in Figure 5-76 and broke the glazing. In other instances, when the MAT observed broken glazing, a large number of a building's windows were broken. In these instances, the building was pummeled with vinyl siding, asphalt shingles, or aggregate from roofs. Glazing damage associated with siding and shingles is shown in Figures 5-26, 5-27, and 5-51. Although siding and shingle debris can damage many windows, the greatest threat is aggregate from roofs. Unprotected glazing that is downwind of an aggregate surfaced roof is very susceptible to breakage due to aggregate blow-off. According to ASCE 7, during hurricanes aggregate can travel up to 1,500 feet with sufficient momentum to break unprotected glazing. The remainder of this section discusses some of the buildings the MAT observed that experienced glazing damage that was attributed to roof aggregate.

Figure 5-76.
This window was broken by a fragment from a shutter (estimated wind speed: 105 mph. New Orleans, Louisiana).

At the hospital shown in Figure 3-59, approximately 400 windows and spandrel panels were broken by aggregate blown from the hospital's own roofs. This hospital complex had several different roof areas, some of which had aggregate-ballasted single-ply membranes and some had aggregate surfaced BURs. The aggregate that caused the glazing damage shown in Figure 3-59 was from an aggregate-ballasted single-ply roof. At another roof area (see Figure 5-77), aggregate from a ballasted single-ply also broke several windows. ANSI/SPRI RP-4 *Wind Design Standard for Ballasted Single-ply Roofing Systems* (which is referenced in the IBC) prescribes aggregate requirements. Several of the aggregates shown in Figure 5-77 equal or exceed the 1-1/2 inch-nominal dimension for #4 aggregate; however, the number of aggregates that were 3/4 inches or smaller exceed that allowed by RP-4. However, more importantly, RP-4 does not permit aggregate ballast (even #2 ballast, which is 2-1/2-inches nominal) on this building, considering its design wind speed, low parapet height, and importance factor.

Figure 5-77. Aggregate from this ballasted single-ply broke several of the windows in the wall beyond. The concrete pavers at the perimeter were not displaced. The aggregate (inset) does not comply with RP-4 requirements (estimated wind speed: 130 mph. Gulfport,

The majority of the windows in the mid-rise building shown in Figures 5-78 and 5-79 were broken by aggregate from BURs. Most of the damage to the lower level windows was likely caused by aggregate from the podium roof adjacent to the tower (roof "A" in Figure 5-78). The south edge of the podium roof (the edge near the arrowhead in Figure 5-78) had a metal edge flashing. The roof sloped toward the tower; therefore, a parapet occurred along the east-west walls. The maximum height of the parapet was about 6 inches. Most of the aggregate that had been embedded in the flood coat was still embedded, but most of the loose aggregate had been blown away.

Wind in this area blew from two primary directions, from the southwest and east/southeast. Therefore, aggregate from the roofs on building "B" in Figure 5-78 likely impacted the tower glazing. Several of the second-story windows in building "B" were also broken by roof aggregate. Aggregate from the roof of building "C" also likely impacted the tower. Portions of the BUR membrane and some of the wood plank decking on the five-story portion of building "C" also blew off, but there was no indication that membrane or deck debris struck the tower. Aggregate from building "D" may have also impacted the tower. Around the main roof of this seven-story building, there was a parapet in the range of 3 to 4 feet high. Aggregate on this roof was scoured, but because of lack of roof access it was not determined if aggregate was blown from the main roof. However, the parapet on the penthouse roof was about 18 inches high; therefore, aggregate was likely blown from this roof.

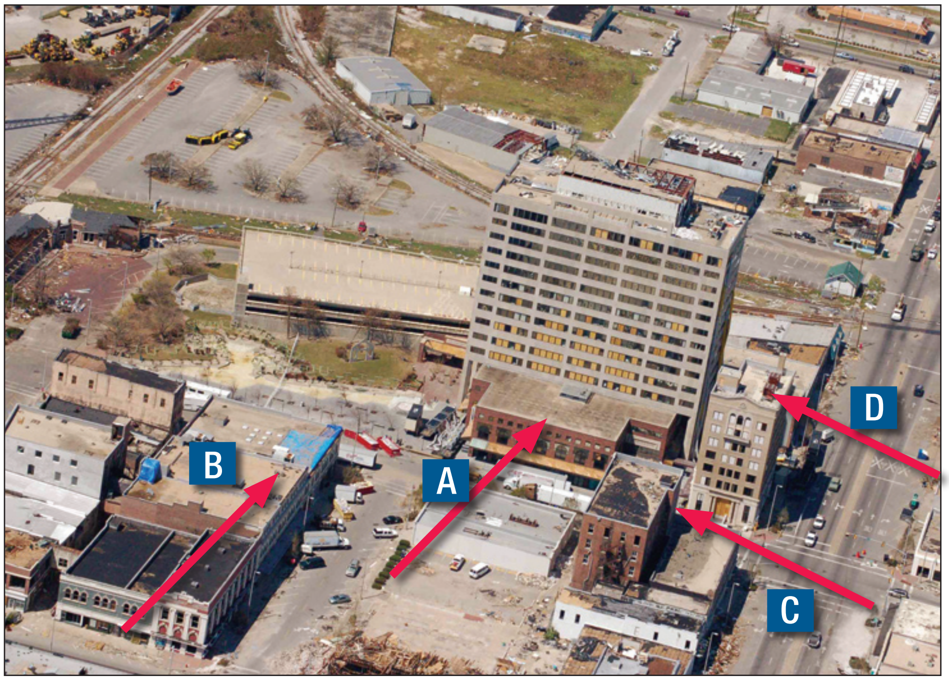


Figure 5-78.
The south façade of the 15-story building had a large number of windows broken by aggregate from BURs. Damage was caused by aggregate from roof A, and likely from roofs B and C. Damaging aggregate may have also been blown from roof D (estimated wind speed: 130 mph. Gulfport, Mississippi).

The tower windows were double glazed. Tempered glass was used for the outer pane. At some windows, only the outer panes were broken (the windows in Figure 5-79 that appear black and those that appear white [due to window blinds] are where the outer panes broke and the inner panes are still in place). However, at most of the broken windows, both the outer and inner panes were broken (at these windows, the openings were covered with OSB after the storm). With loss of both panes of glass, wind and water were able to enter the building. Ceiling boards were blown from their support grid and there was significant water damage to interior finishes and furnishings.

At the 15th (top floor), the outer pane at the west end broke, and the inner and outer panes broke at seven other windows as shown at Figure 5-79. As discussed in the ASCE 7 Commentary, during its flight, aggregate blown from roofs can be lifted 30 feet above the roof from which it blew. The 15th floor windows are well above the penthouse roof on the seven-story building "D"; therefore, it is unlikely that the 15th floor windows were broken by aggregate from roofs "A" - "D." The main roof on the tower was also aggregate surfaced. The parapet around this roof was 30 inches high; therefore, aggregate was likely blown from this roof.

Aggregate blown from a roof can be blown back toward the leeward side of the building and cause glazing damage. However, it did not appear that sufficiently strong winds blew from the north to cause glazing damage on the south facade. Some of the 15th floor windows may have been weakened by scratches and failed when over-stressed by wind pressure, which would have been greatest at the top floor.

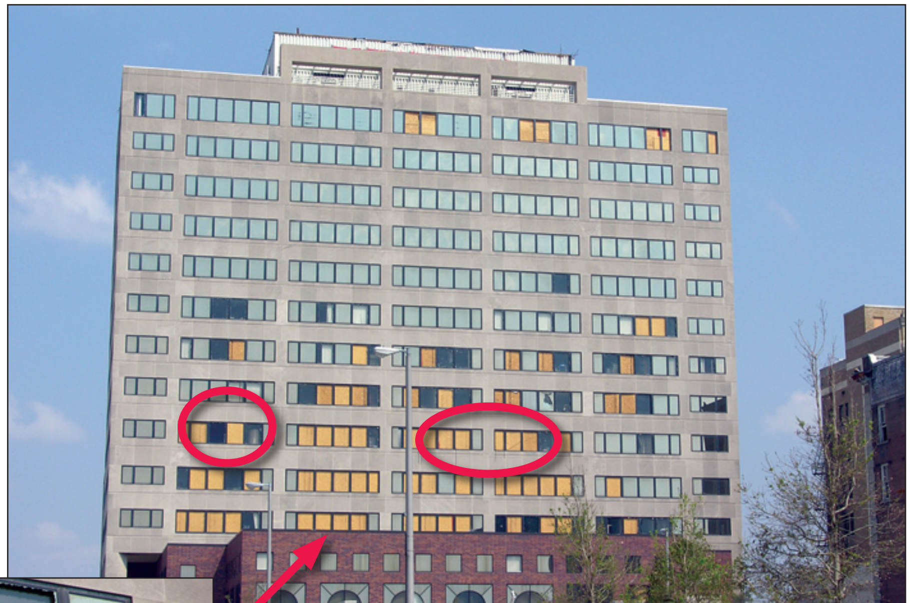


Figure 5-79.
Another view of the tower shown in Figure 5-78. Roof "A" is shown by the arrow. At the black and white (circled) window areas, the outer pane broke. Temporary OSB enclosures were installed where the inner and outer panes broke (see inset) (estimated wind speed: 130 mph. Gulfport, Mississippi).

5.5.1.2 Downtown New Orleans

Several buildings in downtown New Orleans had isolated window breakage such as that shown in Figure 5-21. These windows may have been broken by windborne debris or they may have been weakened by scratches and failed when over-stressed by wind pressure. However, nine buildings along or near Poydras Street had extensive glazing damage (see Figure 5-80) that was indicative of damage caused by windborne roof aggregate. Except for two of these buildings, virtually all of the glazing damage occurred on the windward facades. These buildings are discussed below.

Cluster A: The buildings in circle A in Figure 5-80 are shown in Figure 5-81. Wind in this area blew from two primary directions, from the north and west. Buildings T1 - T4 and S4 experienced extensive glazing damage. Buildings T1, T2, and S4 are office buildings; T3 is a hotel;

and T4 is a large skylight. These buildings are shown in Figure 5-82, and T2 and T3 are shown in Figure 3-48. Figure 3-29 is a ground-based view of T1, T3, and S4. The white areas at T1 and T3 are where plastic sheeting was installed at broken windows and spandrel panels. The brown areas at T1, T2, and S4 are where plywood was installed after the storm. Figure 5-83 is a close-up view of T1, Figure 5-84 is a close-up view of S4, Figure 5-85 is a closeup view of T2, and Figure 5-86 is a view of T4.

Building S1: This was an aggregate ballasted membrane. The aggregate appeared to be #4 (1-1/2 inch nominal). A stone-protection mat occurred between the aggregate and membrane. Because of lack of roof access, the membrane type could not be definitively determined; however, it appeared to be a modified bitumen membrane. Two rows of concrete pavers occurred around the roof perimeter; they appeared to be about 18 x 18 inches. A band of concrete about 3 feet wide was adjacent to the pavers. The concrete was cast over insulation. At the windward (north) corner, several of the concrete pavers were lifted and broken (see Figure 5-87 inset). It was unclear whether or not pavers or paver fragments were blown off the roof. A substantial amount of aggregate was scoured. Aggregate was ramped against a portion of the parapet (which appeared to be around 12 inches high) adjacent to Poydras Street, but there was no significant windrowing (i.e., piling up) of aggregate. It was therefore apparent that a substantial amount of aggregate was blown from the roof. A few of the metal panels from the equipment screen were blown away and a gooseneck was blown from its curb, but it remained on the roof (see Figure 5-87).

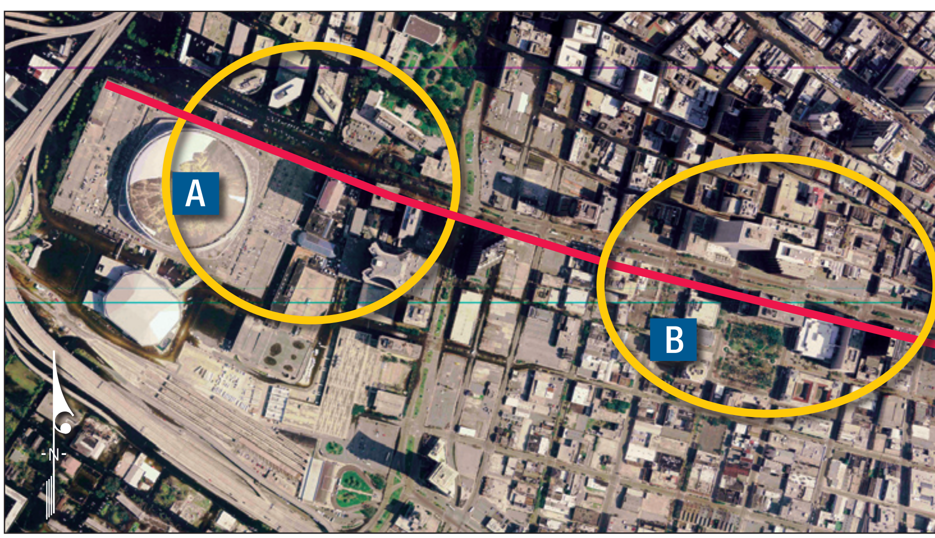


Figure 5-80.
General locations of buildings (highlighted by yellow circles) along Poydras Street (highlighted in red) with extensive glazing damage. The Superdome is at the left of the figure. (estimated wind speed: 105 mph. New Orleans, Louisiana.)

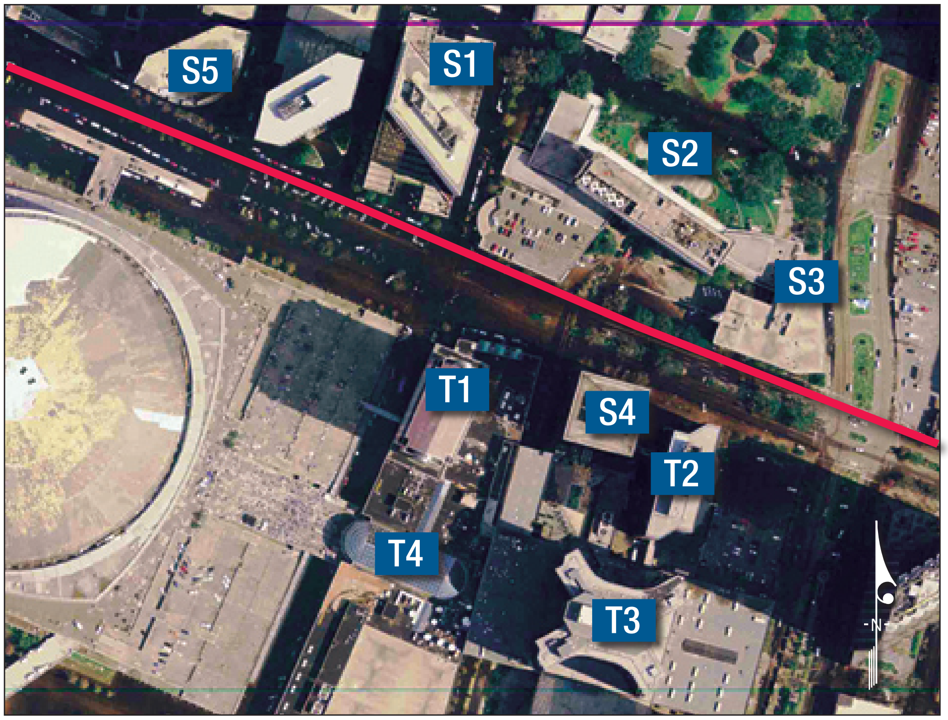


Figure 5-81.
Closeup of Cluster A (estimated wind speed: 105 mph. New Orleans, Louisiana).

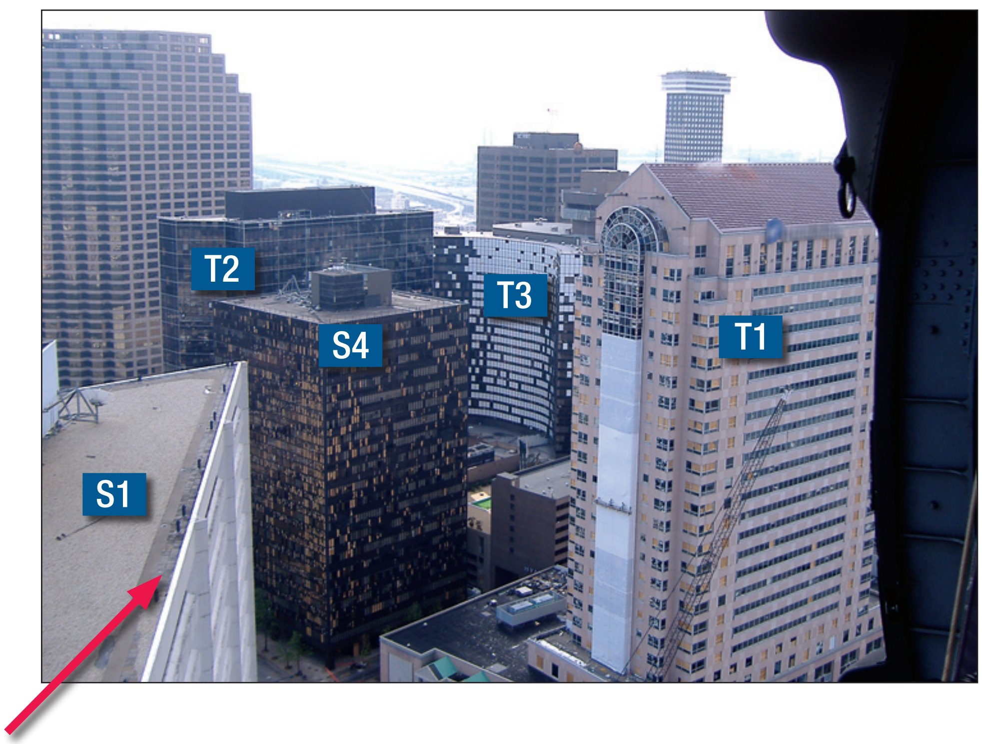
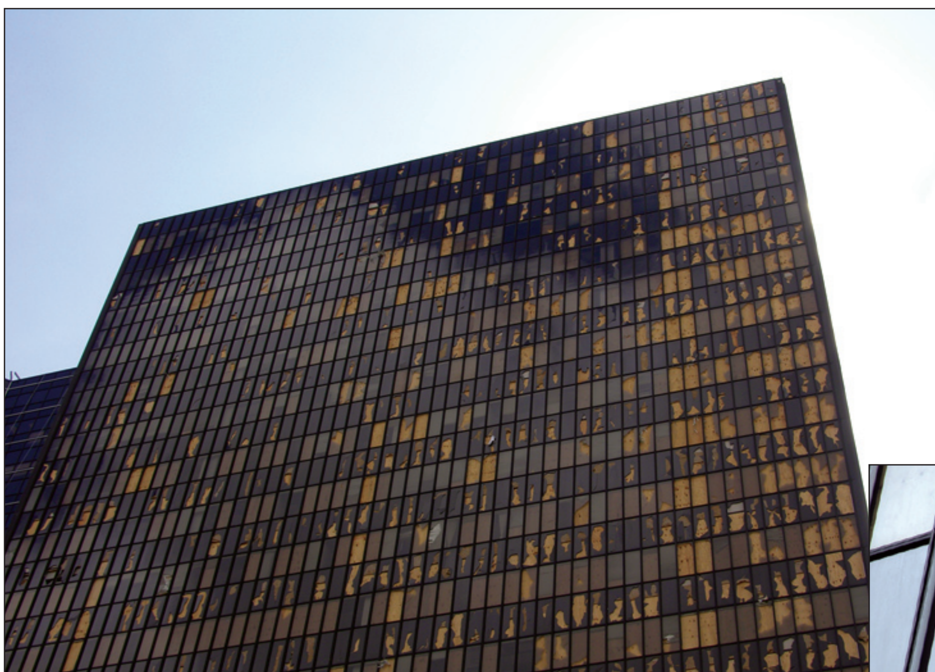


Figure 5-82.
View of glazing damage at T1 - T3 and S4. Building S1 had an aggregate ballasted roof membrane; aggregate from this roof was one of the likely sources of debris (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-83.
Closeup view of T1 (estimated wind speed: 105 mph. New Orleans, Louisiana).



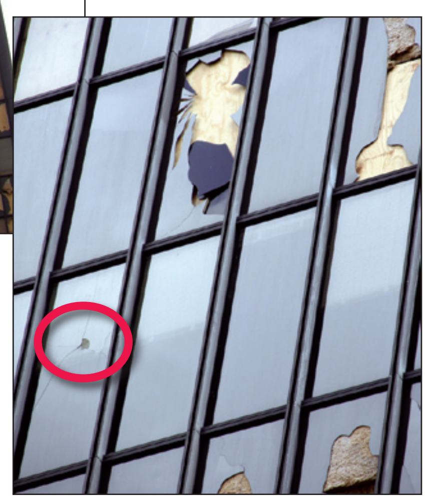


Figure 5-84.
Closeup view of the north façade of S4. The inset (west façade) shows broken windows and spandrel panels. The broken glass at the circle is indicative of impact by a large piece of aggregate (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-85.
Closeup view of the north and west façades of T2. S4 is to the right. Workers on scaffolds were in the process of removing the broken glass (estimated wind speed: 105 mph. New Orleans, Louisiana).

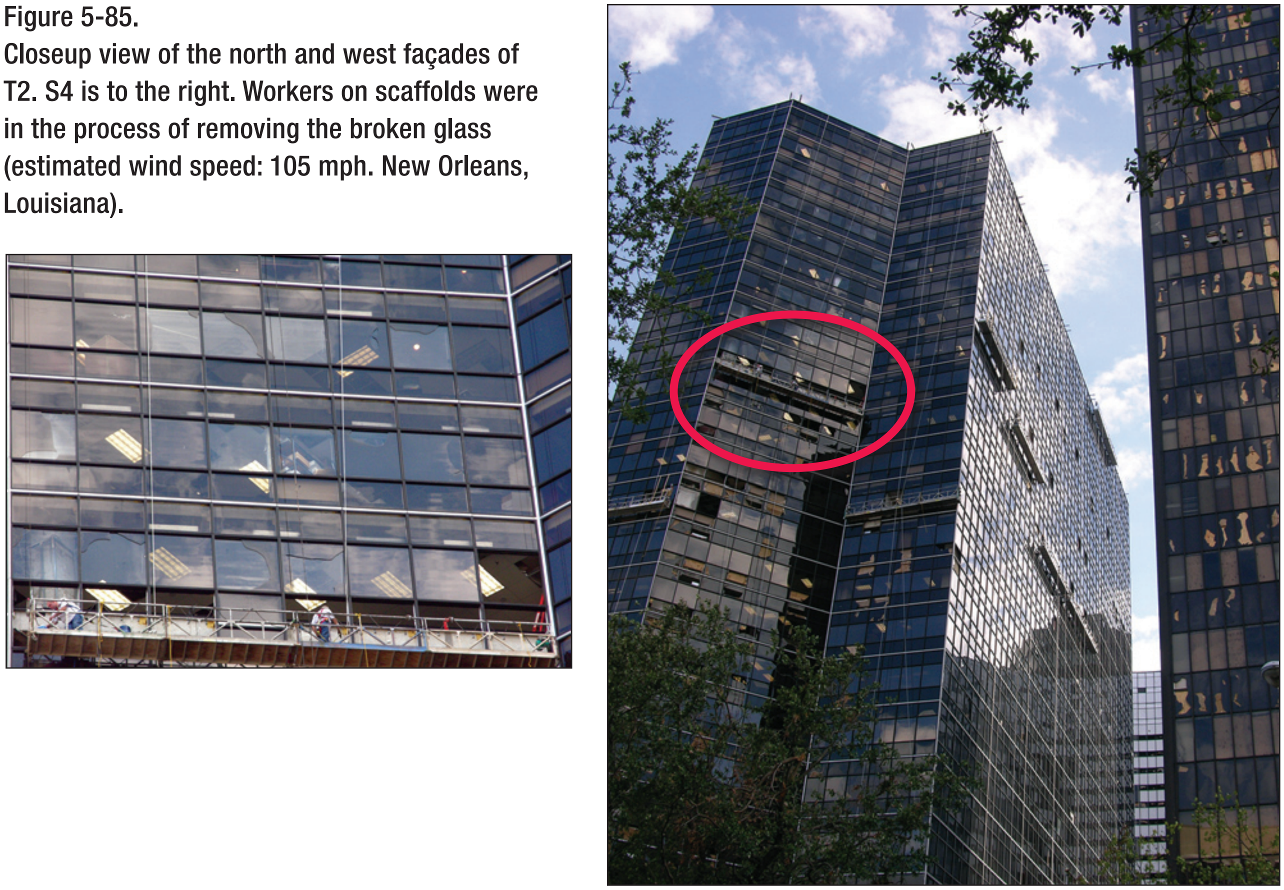


Figure 5-86.
View of skylight T4. The inset is a view from the direction of the red arrow. Large roof aggregate was found in the vicinity of the yellow arrow (estimated wind speed: 105 mph. New Orleans, Louisiana).

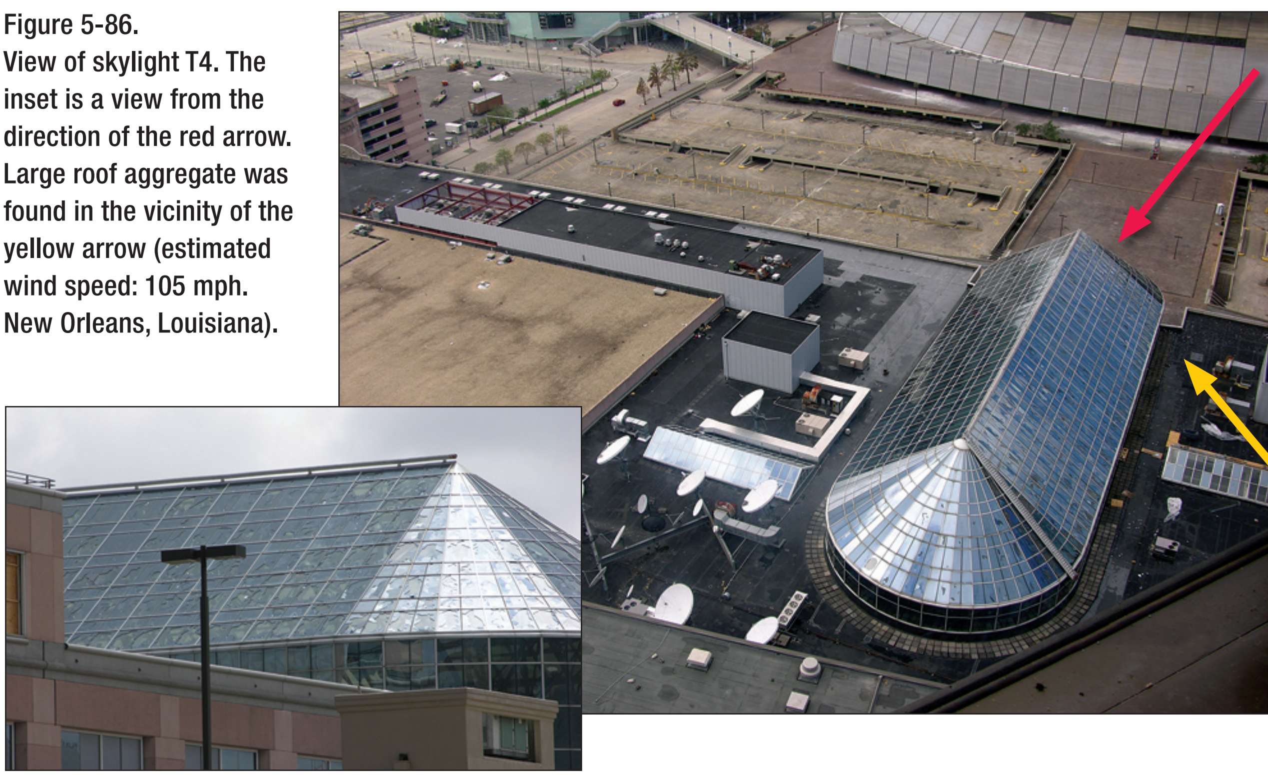


Figure 5-87. Scoured aggregate at Building T1 is shown by the blue arrows. Aggregate was ramped behind the parapet (yellow arrow). A gooseneck lifted from its curb but did not blow away (red arrow). The inset shows displaced pavers and concrete walkway at the windward corner (out of view at the bottom right of the figure) (estimated wind speed: 105 mph. New Orleans, Louisiana).

Potential Number of Aggregate Missiles

The potential number of aggregate missiles per square foot (psf) of roof area is as follows:

BUR: Aggregate surfaced BURs normally have a minimum of 4 pounds of aggregate per square foot. About 2 pounds of the aggregate per square foot is typically embedded in the flood coat; therefore, about 2 per square feet of loose aggregate are susceptible to blow-off. The standard for BUR aggregate (ASTM D 1863) includes three aggregate sizes. Depending upon the size of aggregate and gradation, the number of loose aggregates is likely in the range of 225 to 450 per square foot.

Ballasted systems using #4 aggregate: ANSI/SPRI RP-4 specifies a minimum of 10 pounds per square foot. Depending upon gradation, as a lower bound the number of loose aggregates is likely in the range of 80 per square foot.

ANSI/SPRI RP-4 provides aggregate ballast design tables for building heights up to 150 feet. Above that height, RP-4 states that "the roof design shall be based on an expert's design method and approved by the authority having jurisdiction." This building has 27 stories; therefore, it is well above the 150-foot height addressed in RP-4.

S1 is about 315 feet from T1, about 590 feet from T2, about 760 feet from T3, and about 400 feet from T4. S1 was a likely source of aggregate debris that impacted T1, T4, and S4 and aggregate from S1 may have impacted T2 and/or T3.

Building S2: This was an aggregate surfaced BUR with a parapet that appeared to be about 12 to 18 inches high. Aggregate from this roof was a likely source of debris that impacted T2 and S4, and aggregate from S2 may have impacted T3. S2 has 10 stories; therefore, it is unlikely that aggregate from this building struck above the upper half of T2, T3, and S4.

Building S3: This four-story building had an aggregate surfaced BUR with a parapet that appeared to be about 12 inches high. The roof was scoured and it appeared that a substantial amount of aggregate blew off. Because of the wind directions, some aggregate may have hit T2, but it is unlikely that other buildings in Cluster A were impacted.

Building S4: This was an aggregate surfaced BUR with a parapet that appeared to be about 18 to 24 inches high. This building is about the same height as the 27-story hotel (T3). Virtually all of the main roof was scoured and it appeared that a substantial amount of aggregate blew off. Aggregate was ramped along the south parapet (see Figure 5-88). The roof on the penthouse (red arrow in Figure 5-88) did not have a parapet. It appeared that all of the loose aggregate was blown from the penthouse roof. Equipment screen wall panels were blown toward the south (yellow arrow in Figure 5-88) and east. The north and east support structure for the screen walls collapsed. Two exhaust fan cowlings were also blown away.

T1 is at the top of Figure 5-88, T3 is to the left, and T2 is at the bottom (both T2 and T3 are out of view). Aggregate from S4 was a likely source of debris that impacted T2 and T3. Aggregate from S4 also likely impacted the east wall of this building.

Building S5: This was an aggregate surfaced BUR (see Figure 5-89). There was a parapet (which appeared to be about 2 feet high at the low point) around the main roof, but there was no parapet around the penthouse. This building is approximately the same height as S1. S5 is about 670 feet from T1 and about 840 feet from T4. Aggregate from S5 was a possible source of aggregate debris that impacted T1 and T4, and aggregate from S5 may have impacted some of the other buildings.

Buildings T1, T2, and T3: These buildings did not have aggregate roof surfacings.

Cluster B: The buildings in circle B in Figure 5-80 are shown in Figure 5-90. (Note: The buildings in cluster A are relatively close together, whereas the cluster B buildings are spread out over a few blocks.) Although not as extensively damaged as the cluster A buildings, office buildings T5 - T8 experienced notable glazing damage.

Figure 5-88.
View of the roof of S4. Note the glazing damage on the east side of S4 (bottom of figure). Equipment screen wall panels landed on a lower roof (yellow arrow). The penthouse roof (red arrow) did not have a parapet (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-89.
Aggregate was scoured on the main roof of Building S5 and blown from the penthouse (red arrow). The building to the left of S5 did not have an aggregate surfaced roof, nor did the lower roofs of the Superdome (estimated wind speed: 105 mph. New Orleans, Louisiana).

Building T5: Several windows on the west façade of this 11-story building were broken (see Figure 5-91). A few isolated breaks occurred on the north and east façades. BURs occurred in the vicinity, but a likely source of aggregate debris was not definitively determined.

Building T6: Several windows were broken on the north façade (see Figure 5-92). The likely sources of debris were the aggregate surfaced roofs on S6, which is directly across the street from T6 (see Figure 5-93). The narrow stair-stepped roofs (see Figure 5-94) appeared to be aggregate ballasted single-ply membranes. Metal roof panels were also blown from S6 and may have caused some of the glazing damage. At least 20 windows on the west façade of T6 were also broken (in most cases, only the outer pane broke). The debris source for the west façade was not determined.

Building T7: This high-rise building is shown in Figure 5-93. It had sloped glazing that was sloped to the east (see Figure 5-95). Several of the outer panes of the sloped glazing were broken. Inner panes may have also been broken where plywood was installed after the hurricane. Several of the vertical windows adjacent to the sloped glazing were broken as well as a few windows on the east façade of the tower. A few windows were also broken on the north and south façades. The main roof and one of the stair-stepped roofs had ballasted single-ply membranes. A stone-protection mat occurred between the aggregate and membrane. Some aggregate was ramped against a portion of the west parapet. A substantial amount of aggregate was scoured and blown from the main roof (see Figure 5-96). The parapet appeared to be about 3 feet high. Aggregate from the main roof was the likely source of debris that broke the sloped glazing and nearby windows.

Building T8: Several windows were broken on the north façade (see Figure 5-97). The debris source was not determined. One window was broken on the west façade and a few were broken on the east façade. The roof of this building was not aggregate surfaced.

The cost associated with the damaged glazing was enormous. In addition to the cost of repairing the damaged glazing and the wetted and wind-swept building interiors, the cost of business interruption was significant. Also, the potential for falling glass presented a significant life-safety threat to workers removing the broken glass. Pedestrians were also at risk.

This was the most significant glazing damage in an urban area since Hurricane Alicia struck Houston in 1983. Several high-rise buildings experienced extensive glazing damage during that

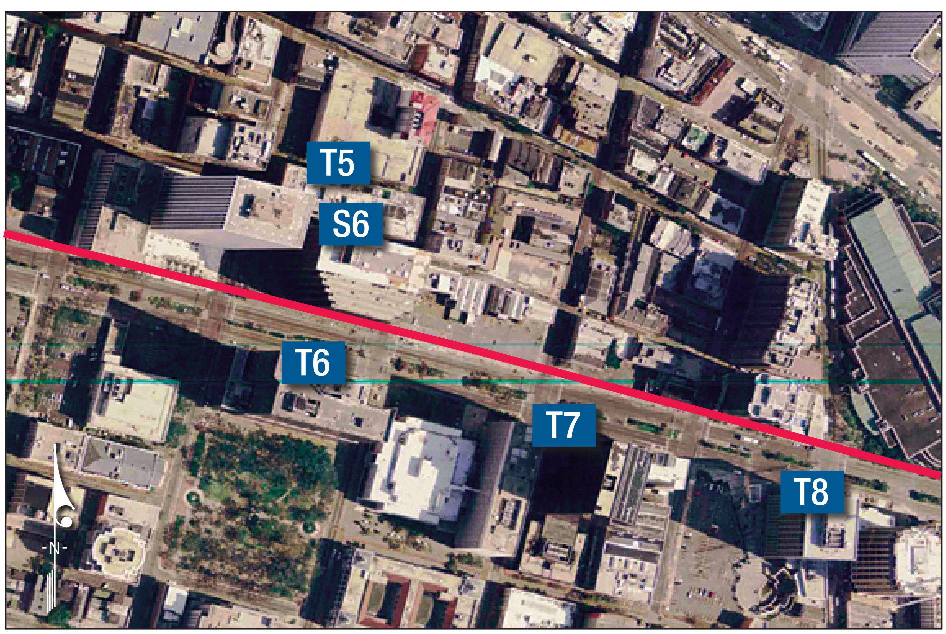


Figure 5-90. Closeup of Cluster B (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-91.
View of the west façade of T5. The tallest building in New Orleans is at the right (estimated wind speed: 105 mph. New Orleans, Louisiana).

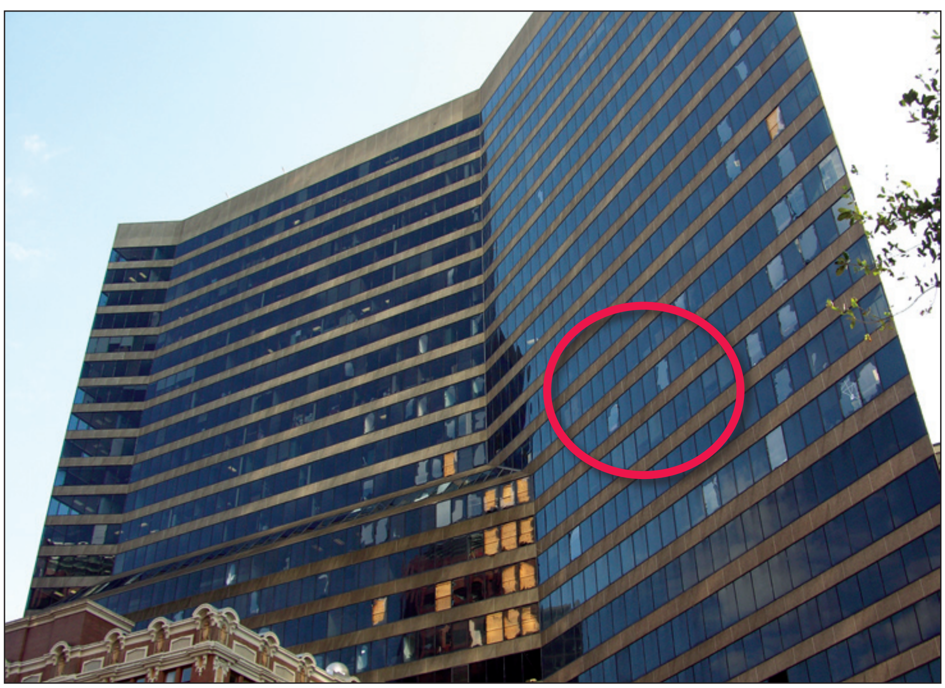


Figure 5-92.
General view of T6. Plywood had been placed where the inner and outer panes had been broken. At most of the broken windows, only the outer pane broke (red circle). The building at the lower left did not have an aggregate roof surface (estimated wind speed: 105 mph. New Orleans, Louisiana).

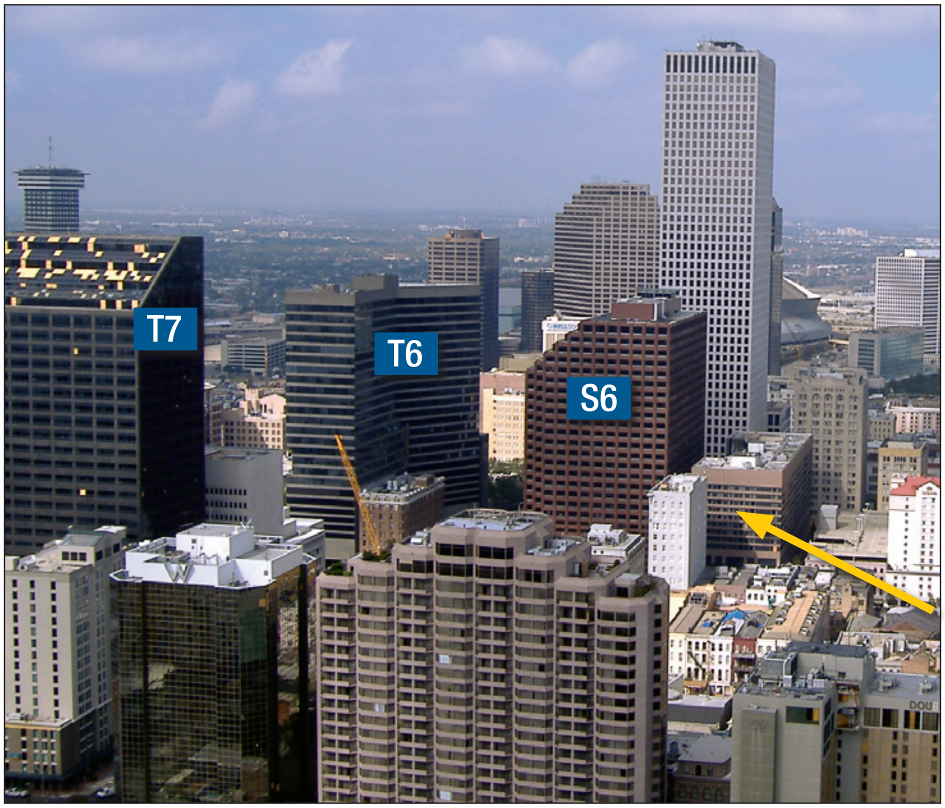


Figure 5-93.
General view of S6, T6, and T7. The east façade of T5 is shown by the arrow (estimated wind speed: 105 mph. New Orleans, Louisiana).

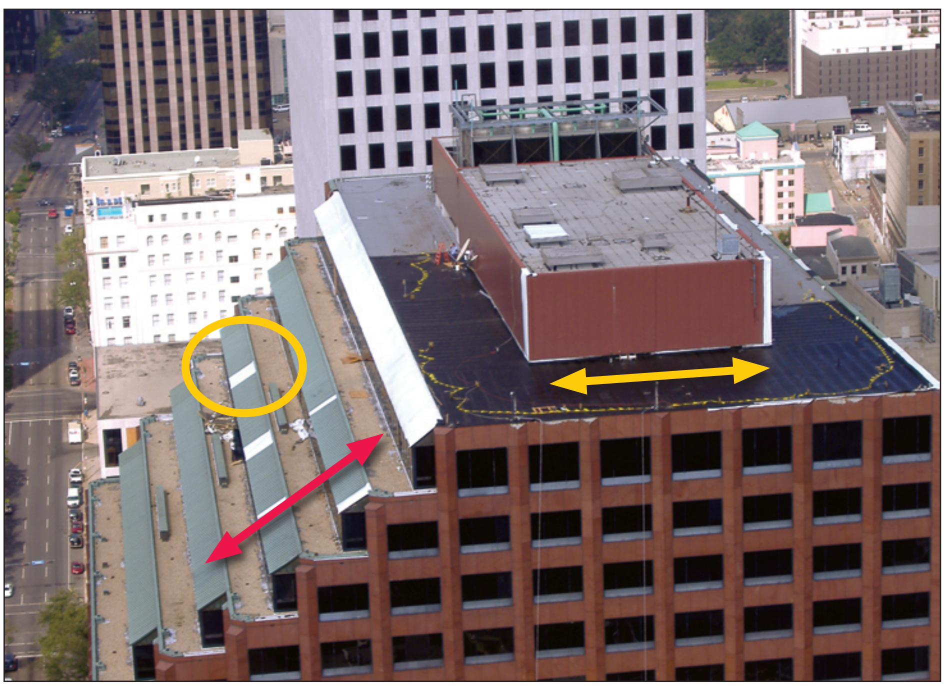


Figure 5-94.
The stair-stepped roofs of S6 (red arrow) were aggregate surfaced. Some of the metal roof panels had also blown away (yellow circle). The black area (yellow arrow) is a roof membrane installed after the hurricane (estimated wind speed: 105 mph. New Orleans, Louisiana).

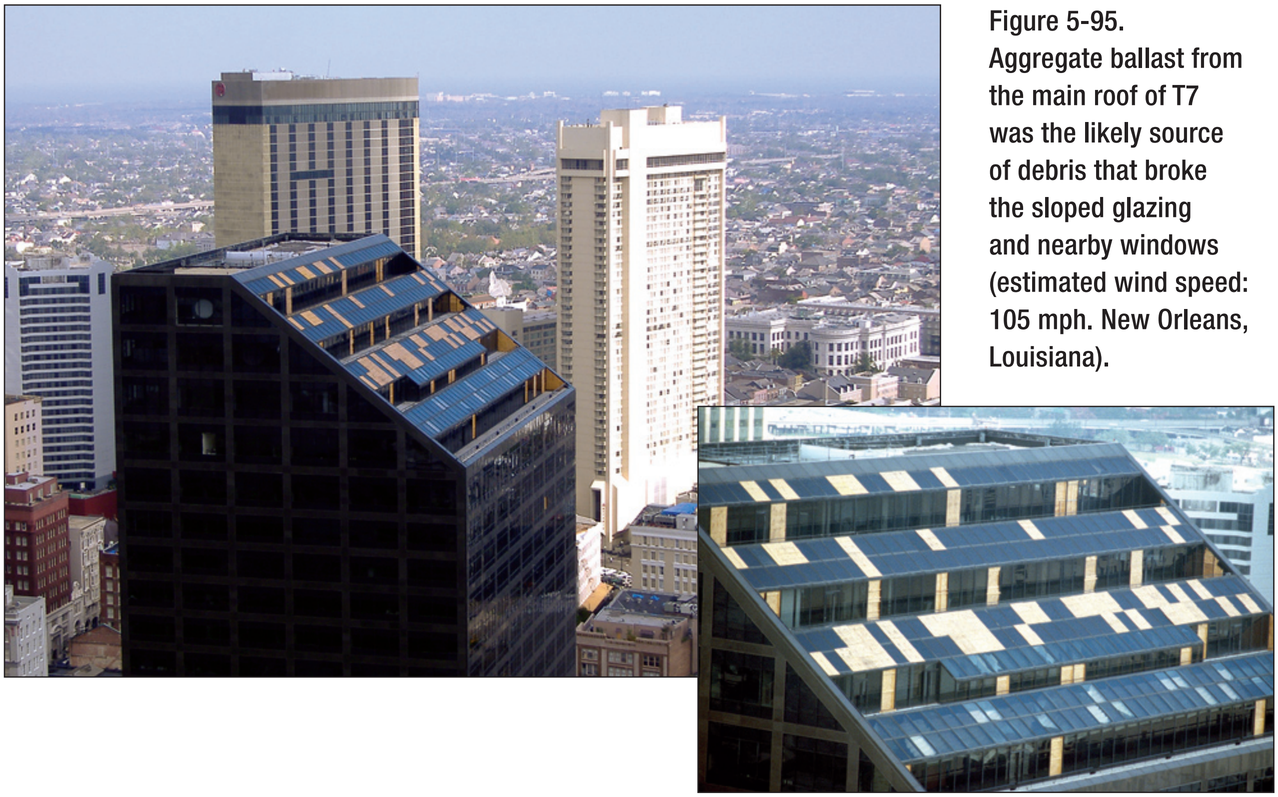


Figure 5-95.
Aggregate ballast from the main roof of T7 was the likely source of debris that broke the sloped glazing and nearby windows (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-96.
Aggregate ballast was scoured and blown from a large portion of the T7 roof. Aggregate also occurred at one, but not all of the stair-stepped roofs (yellow arrow) (estimated wind speed: 105 mph. New Orleans, Louisiana).

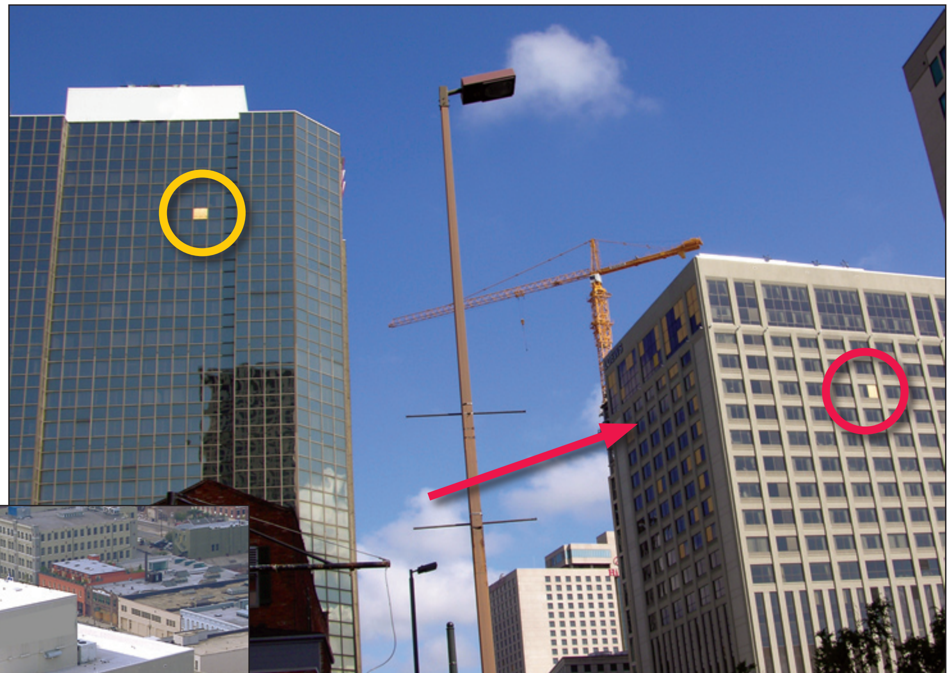


Figure 5-97.
Several windows in the north façade of T8 (red arrow) were broken. One window was broken on the west façade (red circle). One window in the building across the street was broken (yellow circle) (estimated wind speed: 105 mph. New Orleans, Louisiana).

hurricane. *Hurricane Alicia, Galveston and Houston, Texas, August 17 – 18, 1983* (published in 1984 by the Committee on Natural Disasters, National Research Council) attributed the majority of the damage to windborne aggregate from BURs and subsequent cascading.[5] The phenomenon of glass breakage caused by windborne roof aggregate has been documented at least as far back as 1970 when Hurricane Celia struck the Corpus Christi area. For further information on this issue, Minor, Joseph E., "Lessons Learned from Failures of the Building Envelope in Windstorms," *Journal of Architectural Engineering*, March 2005, pp. 10 – 13.

5.5.2 Protected Glazing

The MAT observed shutters on a few residential, commercial, and critical and essential buildings. However, shuttering was not as prevalent as in the areas impacted by Hurricanes Charley, Frances, and Ivan in 2004. The greater use of shutters in Florida versus Alabama, Louisiana, and Mississippi was likely due to Florida's building code requirement for protected glazing and greater public awareness of the benefits provided by shutters.

[5] If debris breaks a window, as pieces of the broken glass fall they in turn can become windborne debris. This glass debris may then strike other windows and generate additional debris. Some of the Hurricane Katrina glazing damage was also likely due to cascading.

A variety of shutters were observed. They were made of wood sheathing, metal panels, polycarbonate, or plastic panels of various designs. Figure 5-98 shows the use of inexpensive pre-cut OSB shutters to protect storefront glazing. Because wood sheathing shutters are not pre-engineered, it is important that they be adequately anchored to avoid blow-off. Prescriptive anchoring requirements are provided in the IBC. Other examples of shutters are shown in Chapter 9.

Figure 5-98.
Pre-cut OSB shutters (estimated wind speed: 115 mph. Slidell, Louisiana)

A few shutter problems were observed. At the house shown in Figure 5-99, several of the roll-up shutter slats disengaged from their tracks. Because the shutter was not labeled, it was not possible to determine if the shutter had been tested in accordance with the standard referenced in ASCE 7. At the house shown in Figure 5-100, the shutter did not completely cover the glazing. One of the windows the shutter was protecting was broken. This illustrates the importance of completely protecting the glazing. Other potential problems are illustrated at the new house shown in Figure 5-101. Although the main entry doors and some of the lower-level windows were shuttered, not all of the glazing was protected. In addition, the swinging shutters were very susceptible to being blown open due to use of very weak latches.

The MAT observed a few cases where shutters were impacted by debris and were effective in preventing glass breakage (see Figure 9-19).

5.5.2.1 Laminated Glass

The MAT observed some laminated glass that had been impacted by debris. Except for the window shown in Figure 5-102, this glazing occurred in skylights as discussed in Section 5.5.5. 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, costly interior water and wind damage is avoided.

Figure 5-99.
Shutter slats detached from their tracks (estimated wind speed: 110 mph. Meraux, Louisiana)

Figure 5-100.
This plastic shutter did not completely cover the window. The lower window was broken (estimated wind speed: 105 mph. Pascagoula, Mississippi).

Figure 5-101.
Metal shutters were over the main doors, and swinging wood shutters were over the larger first floor windows. However, several windows were unprotected (yellow arrows). The shutter latch (inset) was susceptible to unlatching. Note the wood sheathing debris (yellow circle) (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 5-102.
The laminated glass broke, but remained in the frame and continued to provide wind and water protection (estimated wind speed: 105 mph. New Orleans, Louisiana).

5.5.2.2 Tempered Glass

Tempered glass is somewhat more resistant to windborne debris than common glazing. However, tempered glass does not meet the debris testing requirements in ASCE 7. Tempered glass is not considered to be windborne debris-resistant because it can easily be broken by small debris such as aggregate from built-up roofs (Figure 5-78). When tempered glass breaks, it shatters into small pieces and falls out of the frame. Wind-driven rain could then be driven into the building and substantially increase the internal pressure. The MAT observed broken tempered glass at several buildings.

5.5.3 Over-Pressurization

Glazing damage is normally caused by windborne debris impact; however, windows can also be broken by over-pressurization via either high negative or positive wind loads. Glazing in older doors and windows is more susceptible to wind load damage because older glazing is often weakened by scratches. In addition, many older windows and glazed doors were installed when little attention was given to wind resistance. Surprisingly, at new residences under construction in Louisiana and Mississippi, the MAT found very few windows with wind pressure rating labels (see Figure 5-103). The windows typically only had labels pertaining to energy performance. This contrasts sharply to the Hurricane Charley and Ivan MAT observations, wherein all of the windows in houses under construction had pressure rating labels. Unless window and glazed doors assemblies are tested and labeled, the units' resistance to wind pressure is unknown.

At an older wing of a hospital in Gulfport, several window frames failed due to wind pressure (see Figure 5-104). Some of the glazing on the floors below were broken by pressure or debris. As discussed in Section 5.5.1, approximately 400 windows and spandrel panels were broken at this facility. This building was also damaged during Hurricane Camille.

Frame failure due to wind pressure caused the loss of several windows in the office building shown in Figure 5-105.

An unusual glazing failure is shown in Figure 5-106. This older brick building had been re-skinned with a curtain wall system. As part of the re-skinning, wood nailers had been attached

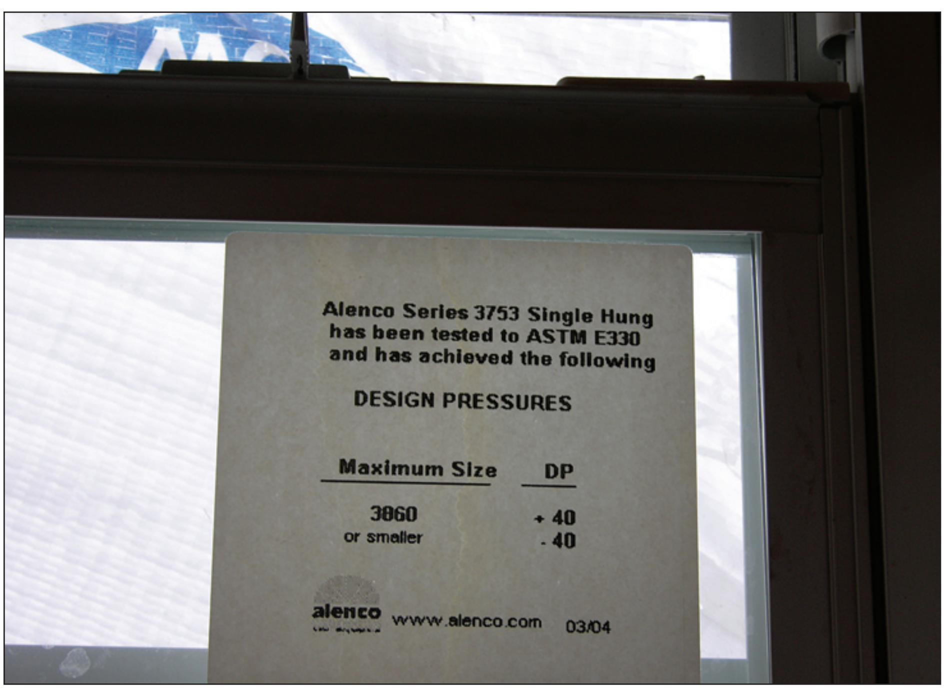


Figure 5-103. View of a wind pressure rating label at a house under construction. The windows on most of the houses observed did not have pressure labels (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

to the brick to provide anchorage for the curtain wall. A large number of spandrel panels were blown away. Several of the nailers had detached from the brick at the areas shown by the yellow circle and arrow. At the other missing spandrels, the panels had detached from the nailers.

At a relatively new school in Gulfport, Mississippi, a large window unit was blown into the corridor (Figure 3-58). The window failed because the head frame was not anchored to the structure.

Figure 5-104. The window frames on the upper floor failed (red arrow). Some of the windows on the lower level were broken by pressure or debris (estimated wind speed: 130 mph. Gulfport, Mississippi).

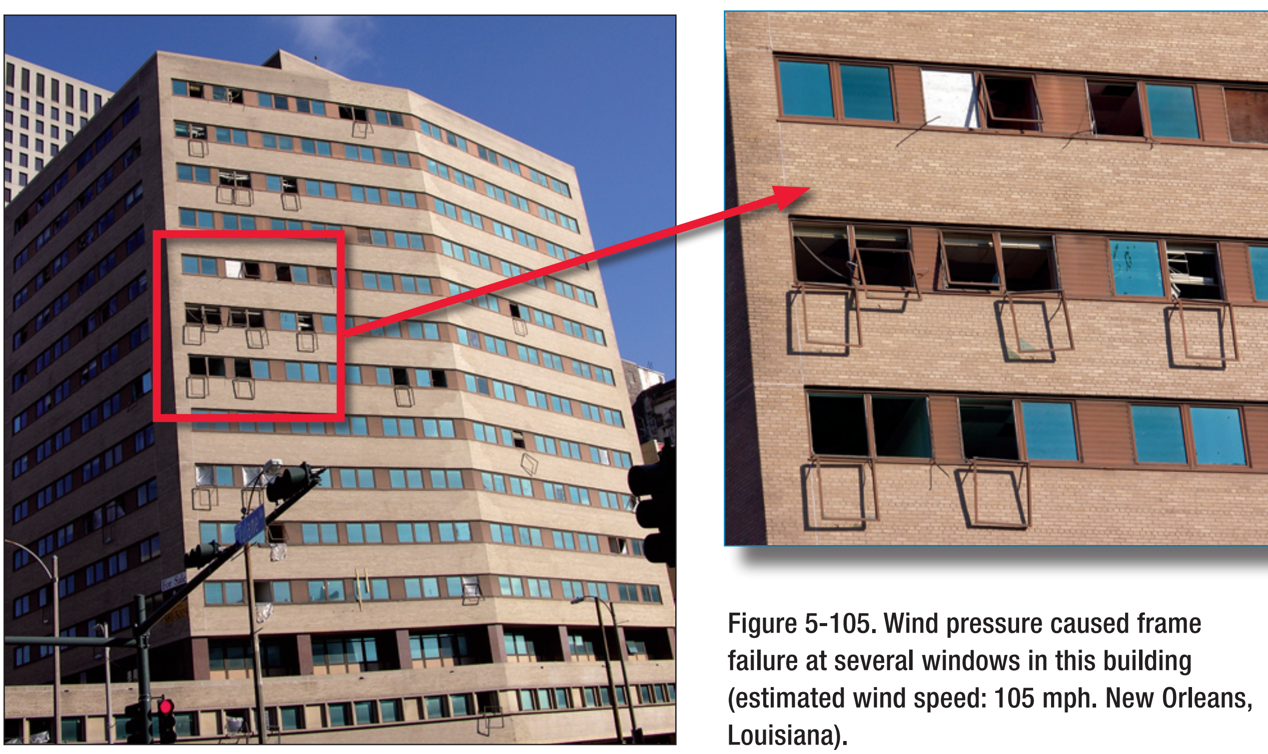
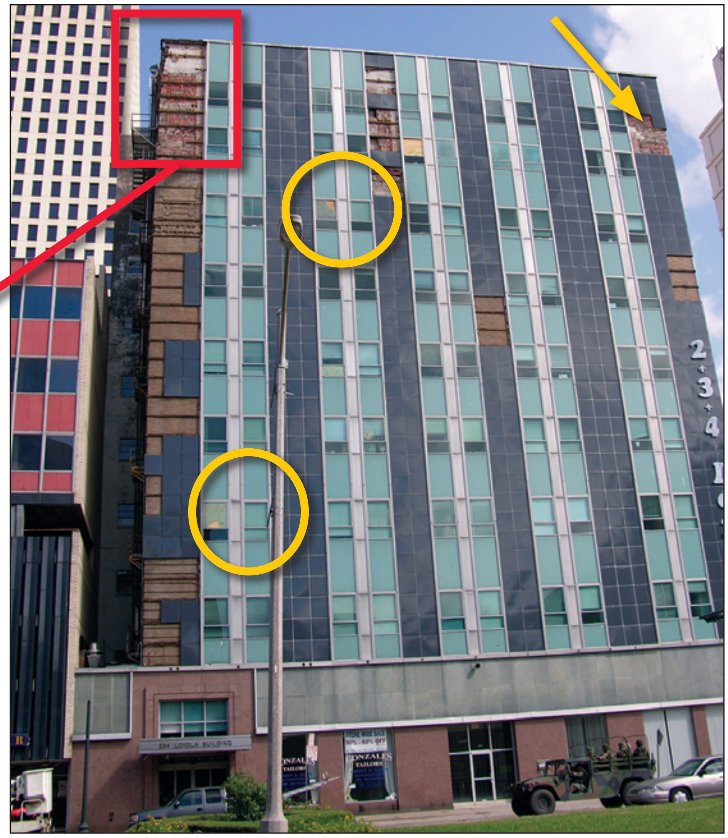


Figure 5-105. Wind pressure caused frame failure at several windows in this building (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-106.
Several spandrel panels detached from their wood nailers. In some areas, the nailers detached (red rectangle and arrow). The glazing at the yellow circles was likely broken by debris (estimated wind speed: 105 mph. New Orleans, Louisiana).



Although the jambs were anchored, those attachments were insufficient to resist the loads. A similar window unit at another corridor nearly collapsed. Its head was pushed inward about an inch. This failure was due to lack of attention to design and construction.

5.5.4 Installation

The MAT commonly observed window installation problems at houses under construction. The problems pertained to attachment and flashing. For example, at the house that had the windows with the pressure rating labels (see Figure 5-103), the manufacturer recommended attaching the nailing flange at 12 inches on center maximum. For one of the windows that was investigated, this would have required five nails at the head and sill, and six nails at each jamb. However, only two nails were installed at the head (siding prevented observation of the sill nailing) and only five were installed at the jambs. At another house, nails were spaced 21-1/2 inches apart at one area (a 12-inch spacing was likely the recommended maximum). At still another house, staples were used to attach the nailing flange even though the manufacturer recommends nails.

The window nailing flanges were not properly flashed to the housewrap at most of the observed windows. In several instances, self-adhering modified bitumen flashing tape was not installed. In other cases, the tape had been installed but improperly lapped. Flashing deficiencies do not directly affect wind performance, but they can have significant indirect influence. If water leaks past the window frame/housewrap interface, the studs and/or wood sheathing can be rotted. The window can be blown away during a storm if the framing is rotted.

5.5.5 Skylights

A few skylights with glass panes were observed, including the large skylight shown in Figure 5-86. These skylights were double-glazed. The outer panes were normal glass and the inner panes were laminated glass. Laminated glass is used for the inner panes in skylights to avoid occupant injury in the event the glazing breaks. Figure 5-107 shows a skylight in the vicinity of the skylight shown in Figure 5-86. At least six of the laminated panes were broken. Three other windows were broken, but these breaks appeared to be in the outer panes.

As discussed in Section 5.5.2, although the inner and outer panes were broken, the laminated glass avoided costly interior water and wind damage. However, unless the outer panes are also laminated, if the outer panes are broken, the shards become windblown debris (see Figure 5-108).

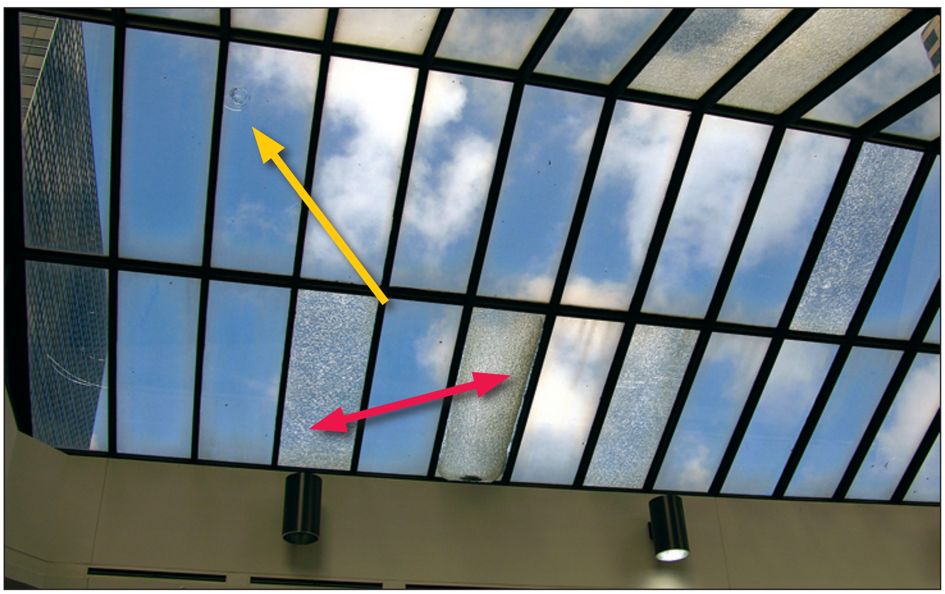


Figure 5-107.
Six of the inner laminated panes were broken (two of them are shown by the red arrow). Three other breaks appeared to be at the outer panes (one of these is shown by the yellow arrow) (estimated wind speed: 105 mph. New Orleans, Louisiana).

Figure 5-108.
Skylight on a new eight-story Federal courthouse. Two of the outer panes were broken. Windborne shards can cause injury and damage buildings and vehicles (estimated wind speed: 130 mph. Gulfport, Mississippi).

Performance problems were also observed with plastic-domed skylights. In some instances, the plastic dome was broken by windborne debris and in other instances skylight frames were blown from their curbs. Unlike the laminated skylights, the plastic dome skylight failures resulted in significant rainwater entry.

5.6 Exterior-Mounted Mechanical, Electrical, and Communications Equipment

The MAT observed many damages to mechanical and electrical devices mounted on the exterior of buildings. 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 lightning protection systems (LPS) anchorage. Guidance for these design factors is provided in the Hurricane Katrina Recovery Advisories on rooftop equipment and lightning protection systems in Appendix E.

Commercial and critical and essential facilities typically have a wide variety of mechanical and electrical equipment attached to their rooftops and elsewhere. Residences also frequently have rooftop equipment. In addition, condensers are also frequently mounted at grade or on elevated platforms in floodprone areas. Equipment lost as a result of Hurricane Katrina included condensers, combustion air louvers (Figure 3-60) relief air hoods, ducts, fan units and HVAC units, electrical and communications equipment, and LPS. Several effects occur 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 momentum windborne debris in some cases. The equipment observed on critical and essential facilities was typically not anchored more effectively than the equipment on common commercial buildings.

5.6.1 Mechanical Equipment

5.6.1.1 Condensers

Condensers should be elevated in floodprone areas. Condensers at many residences observed by the MAT were supported on cantilevered platforms as shown in Figures 9-18 and 5-109. As discussed in Section 9.5.1, cantilevered platforms are preferable over knee-braced or pile-supported platforms. Several condensers were blown from their platforms because they were not anchored or had insufficient anchorage. Cantilevered platforms are preferred because they are less susceptible to damage from floodborne debris impacts than are pile or knee-braced supported platforms.

Outside of flood-prone areas, condensers are normally mounted at grade or on rooftops. Both grade- and roof-mounted condensers were typically not anchored or were insufficiently anchored as shown in Figures 5-110 and 5-111. Figure 5-112 shows one of the few buildings observed by the MAT where special attention had been given to condenser attachment. These condensers remained attached to the structural steel equipment support stands, thereby avoiding damage to the condensers and the roof membrane.

Figure 5-109.
One of the condensers was blown off this cantilevered platform (estimated wind speed: 120 mph. Shell Beach, Louisiana).

Figure 5-110.
Inadequately attached condenser at the police station shown in Figure 3-54 (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 5-111.
These displaced condensers had been placed on wood sleepers that rested on the roof membrane. Sleepers do not provide resistance to uplift or lateral wind loads (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 5-112.
The condensers on this new medical office building were anchored to structural steel equipment support stands (estimated wind speed: 130 mph. Gulfport, Mississippi).

5.6.1.2 Fan Units and HVAC Units

As frequently observed following previous hurricanes, many fan and HVAC units were damaged. In several cases, the units were blown off the curbs because too few fasteners were used to attach the units to the curbs. The blown-off exhaust fan on the school in Figure 5-113 had been attached with only two screws. Had the fan been attached in accordance with the guidance in the Hurricane Katrina Recovery Advisory, *Attachment of Rooftop Equipment in High-Wind Regions* (Appendix E), there would have been five screws per side. Although the opening through the roof was small, a substantial quantity of rainwater was able to enter the school. Because of Katrina's widespread damage, this opening remained unprotected for more than a month after the storm.

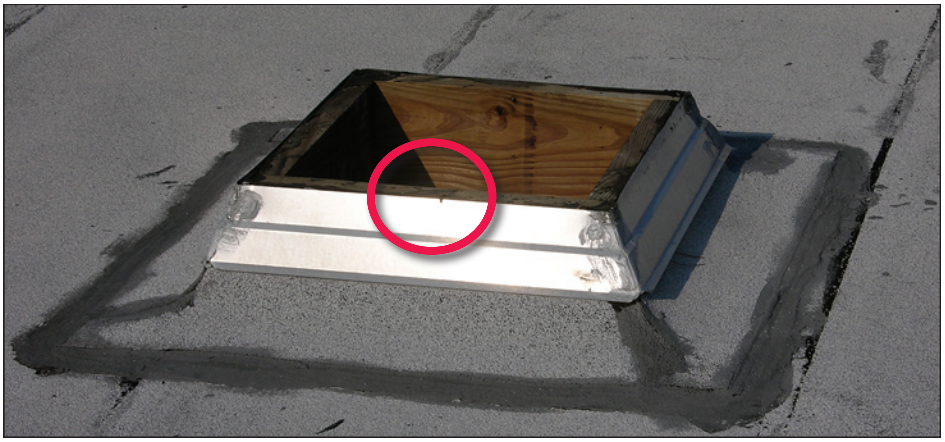


Figure 5-113.
The missing exhaust fan was attached with only two screws, one of which just grazed the top of the nailer (red circle). The screw that engaged the nailer was sheared off (estimated wind speed: 125 mph. Waveland, Mississippi).

In many other cases, the fans remained attached to their curbs, but the cowlings were blown away (see Figure 5-114). The Hurricane Katrina Recovery Advisory, *Attachment of Rooftop Equipment in High-Wind Regions* (Appendix E), provides guidance for jobsite strengthening of cowlings. Another fan near the one shown in Figure 5-114 was struck and damaged by windborne debris (see Figure 7-18). At least for critical and essential facilities, this illustrates the benefits of placing rooftop mechanical equipment in penthouses so that the equipment is protected from debris and remains operational.

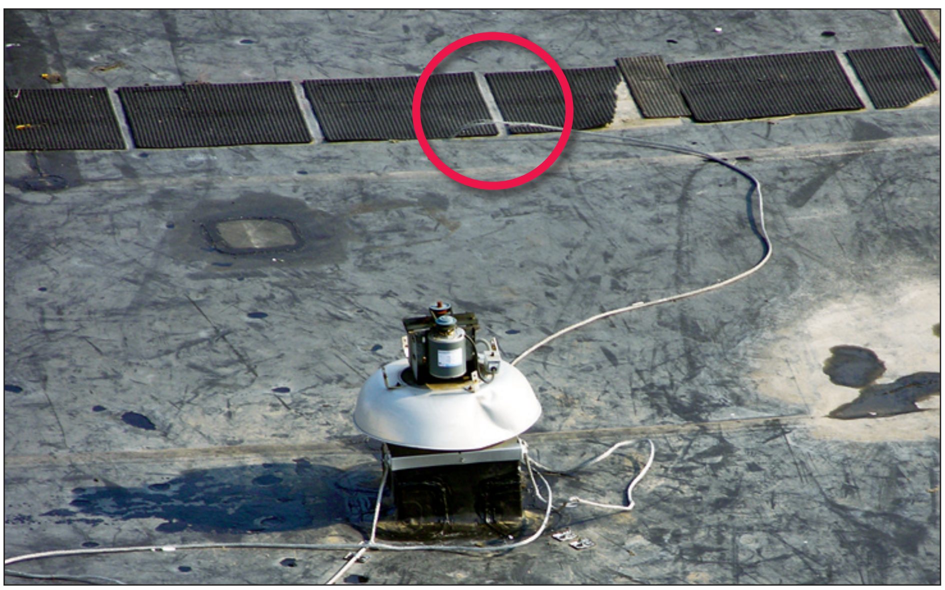


Figure 5-114.
At this hospital, the cowling was blown off the exhaust fan. Note also the loose LPS conductors (red circle, Figure 5-123) and missing walkway pads (estimated wind speed: 130 mph. Gulfport, Mississippi).

5.6.1.3 Ductwork

Rooftop-mounted ductwork was observed on a few buildings. At the building shown in Figure 5-79, portions of the ductwork were blown away as shown in Figure 5-115. The ducts rested on top of steel support channels. At the time of the MAT's observation, the openings through the roof had been unprotected for nearly a month after the storm.

At the recently constructed 13-story building shown in Figure 3-44, the main duct runs were not damaged during this hurricane (see Figure 5-116). However, ducting on either side of a fan was blown away (see Figure 5-117). The main duct support frames were spaced at 8 feet on center. The frames were made from 1-1/2 x 1-1/2 x 1/8-inch thick angles. The frames were bolted together. The top horizontal angle was about 7/8 inch above the ducts.

Other than the guidance provided in the Hurricane Katrina Recovery Advisory, *Attachment of Rooftop Equipment in High-Wind Regions* (Appendix E), very little wind design guidance is available for rooftop-mounted ductwork.

5.6.1.4 Vibration Isolators

A particular type of vibration isolator was observed on a few new buildings. The isolator's design provided lateral resistance, but no uplift resistance. Because of the lack of uplift resistance, the equipment shown in Figure 3-61 was lifted up and blown away. Rainwater was able to enter the building at the duct openings through the roof. This same vibration isolator design was used on a lower roof of the building shown in Figure 5-116. At the equipment shown in Figure 5-118, the equipment was not blown away, but it was lifted up and three of the four springs were blown away. When equipment is mounted on vibration isolators, the isolator design needs to provide both lateral and uplift resistance, or an alternative means to accommodate lateral and uplift loads needs to be provided.


Figure 5-115. Two large openings (red rectangle and inset) through the roof were left after the ductwork blew away (estimated wind speed: 130 mph. Gulfport, Mississippi).

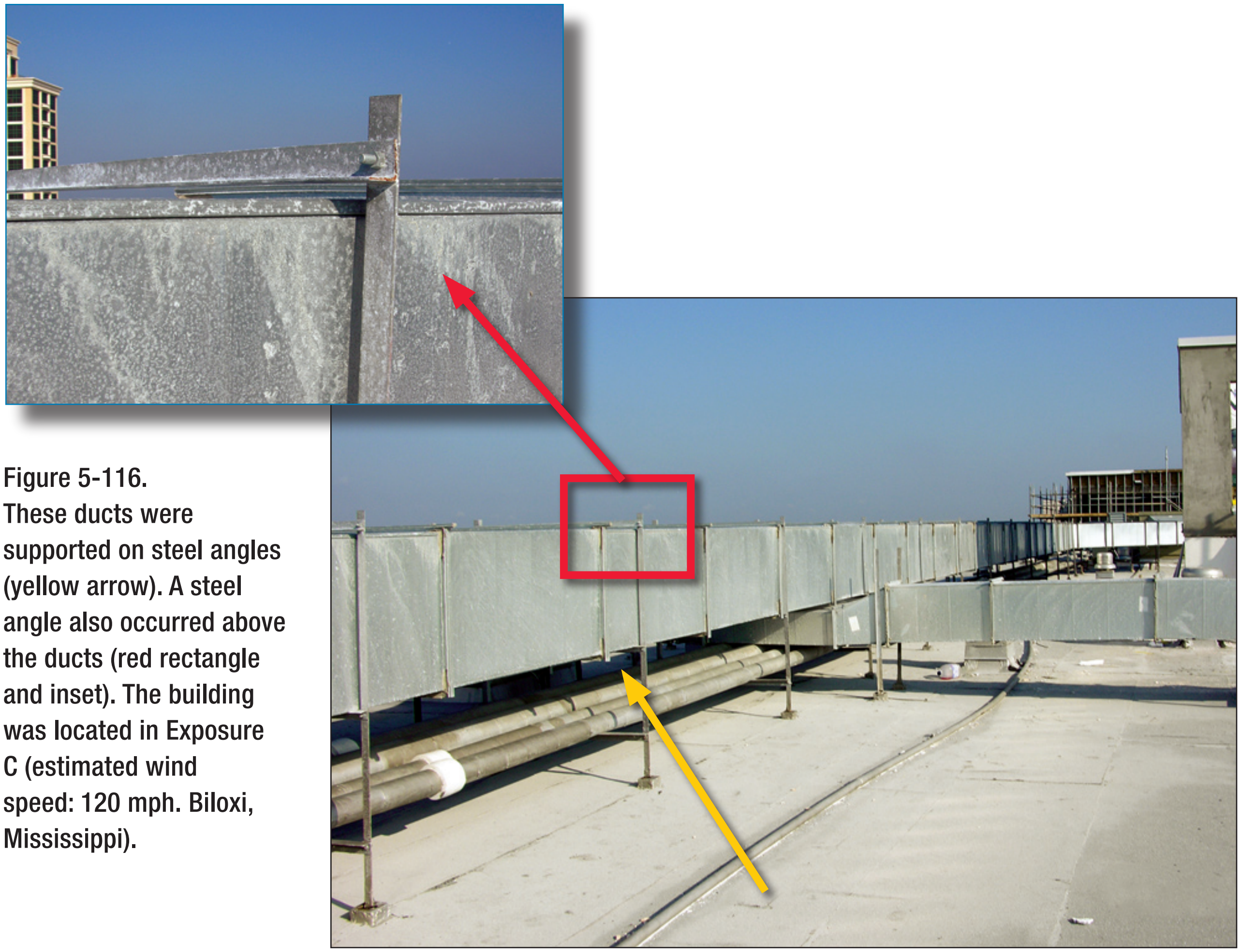


Figure 5-116.
These ducts were supported on steel angles (yellow arrow). A steel angle also occurred above the ducts (red rectangle and inset). The building was located in Exposure C (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 5-117.
Opposite view of Figure 5-116. The ducting on either side of the fan was blown away (red arrows) (estimated wind speed: 120 mph. Biloxi, Mississippi).

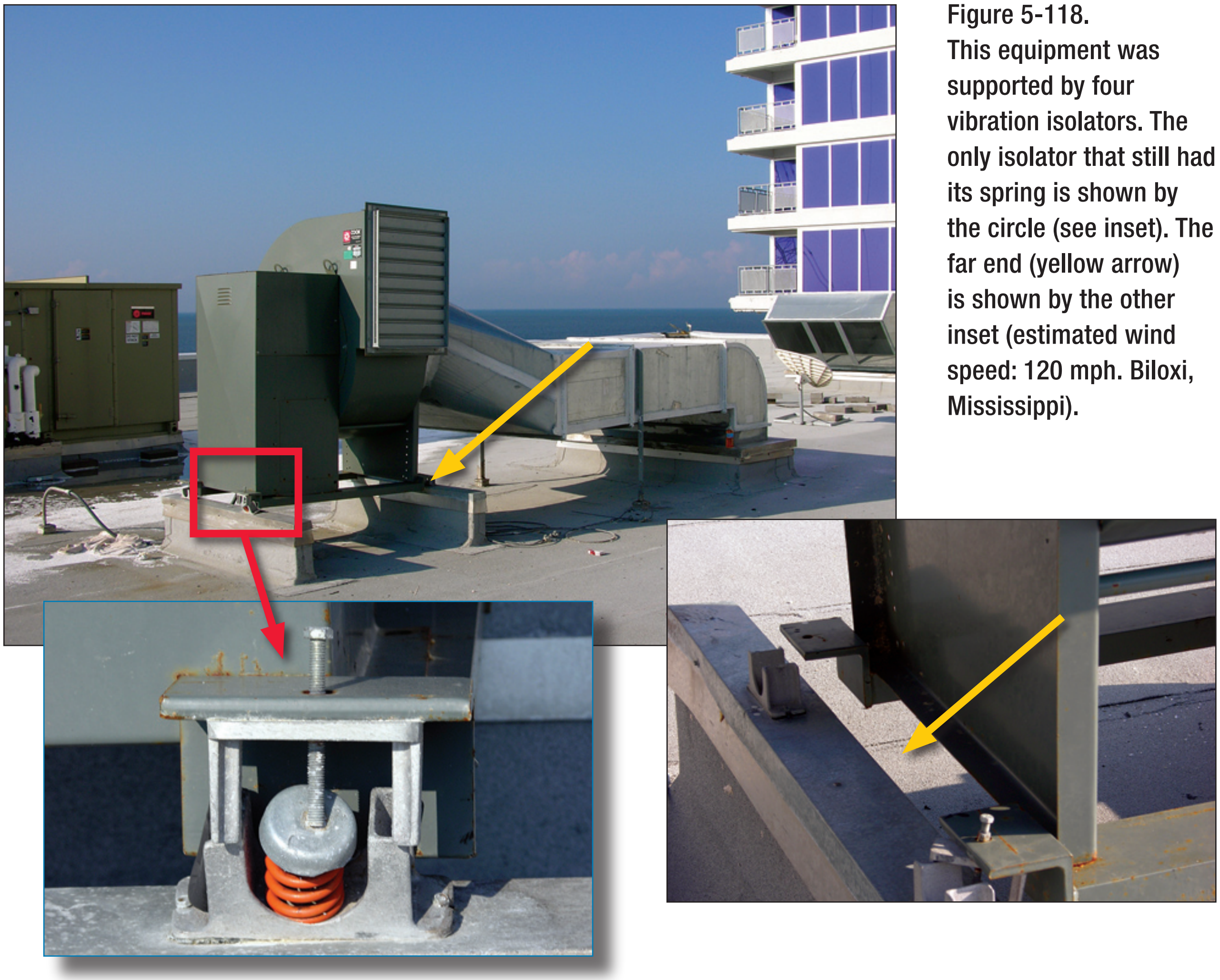


Figure 5-118.
This equipment was supported by four vibration isolators. The only isolator that still had its spring is shown by the circle (see inset). The far end (yellow arrow) is shown by the other inset (estimated wind speed: 120 mph. Biloxi, Mississippi).

5.6.2 Electrical and Communications Equipment

Rooftop electrical and communications equipment was also observed to be inadequately protected and anchored. Problems included flooded generators, antenna collapse, blown over satellite dishes and displacement of LPS. Collapsed parking lot light fixtures were also observed. Consequences of the damage included loss of electrical power and communications (both of which are significant losses for critical and essential facilities), damage to roof coverings, and loss of lightning protection. The loss of lightning protection is significant, considering the frequency of lightning storms along the Gulf Coast. Damage to electrical and communications equipment may cause additional damage to a facility, as well as severe loss of function.

5.6.2.1 Emergency Generators

Several generators at critical and essential facilities were inundated by flooding. In addition, some generators were mounted outdoors as shown in Figure 7-5 and discussed in Section 7.2.2. When mounted outdoors, generators are quite susceptible to damage from windborne debris. Other generators were located in enclosures that offered limited protection from tree-fall and windblown debris (see Figure 7-10).

5.6.2.2 Antennas

Collapse of both small and large antennas was quite common at emergency operations centers, fire and police stations and hospitals. In some cases the anchorage to the building failed as shown at Figure 7-2. However, more commonly, the antenna tower buckled (see Figure 5-119).

Figure 5-119.
The antenna tower at this fire station buckled (estimated wind speed: 120 mph. Diamondhead, Mississippi).

5.6.2.3 Satellite Dishes

The MAT observed several satellite dishes that were blown over. Failed satellite dishes did not have positive connections to the roof structure. Rather, the dish support simply rested on the roof and was weighted down with concrete pavers (see Figure 5-120). Blown over satellite dishes can puncture roof membranes, and if blown from the roof can damage other buildings or vehicles.

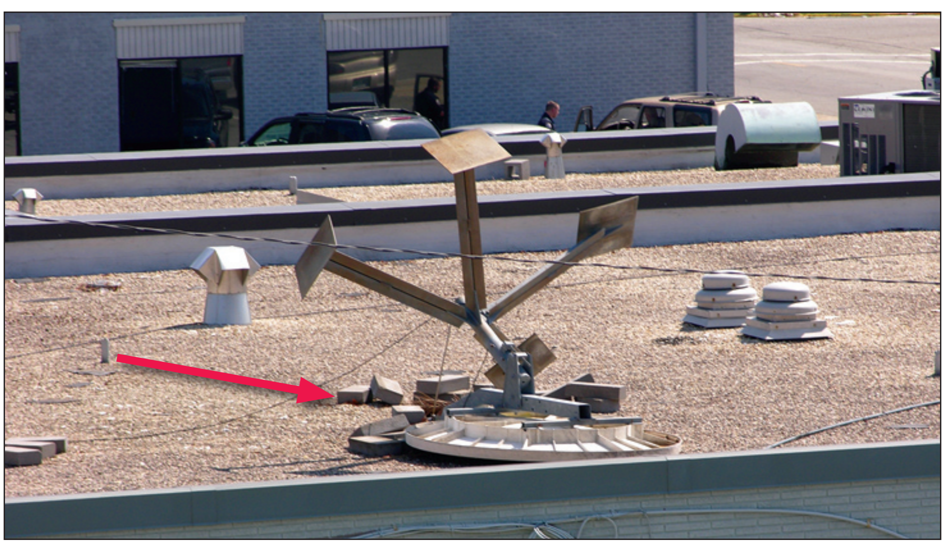


Figure 5-120.
This satellite dish was held down only with concrete pavers (estimated wind speed: 130 mph. Gulfport, Mississippi).

5.6.2.4 Lightning Protection Systems

LPS failures were typically the result of poorly anchored systems. Connectors often fail by opening up and releasing the conductor cable (see Figure 5-121) or they debond from the roof (see Figure 5-122). When conductors detach, the conductor ends can whip around and puncture and tear the roof membrane. At the hospital shown in Figures 5-122 and 5-123, several punctures had been patched after the hurricane. Some of the punctures were likely caused by loose conductors. At another hospital, a loose conductor whipped the exterior wall and punctured the EIFS in several locations (see Figure 5-124).

Two prudent practices were observed. At the hospital shown in Figure 5-122, bolted splice connectors were used (see Figure 5-125). Pronged splice connectors are approved for heights up to 75 feet. Above that height, bolted splice connectors are required. However, regardless of height, bolted connectors are prudent in hurricane-prone regions because they are less likely to pull apart if the conductor becomes detached. If detached conductors remain connected together, that minimizes the number of free ends whipping about.

The other prudent practice was the use of mechanically attached looped connectors to attach the conductor to the coping (see Figure 5-126). A looped connector does not have prongs; therefore, this is a reliable connector (provided sufficiently long screws are used).

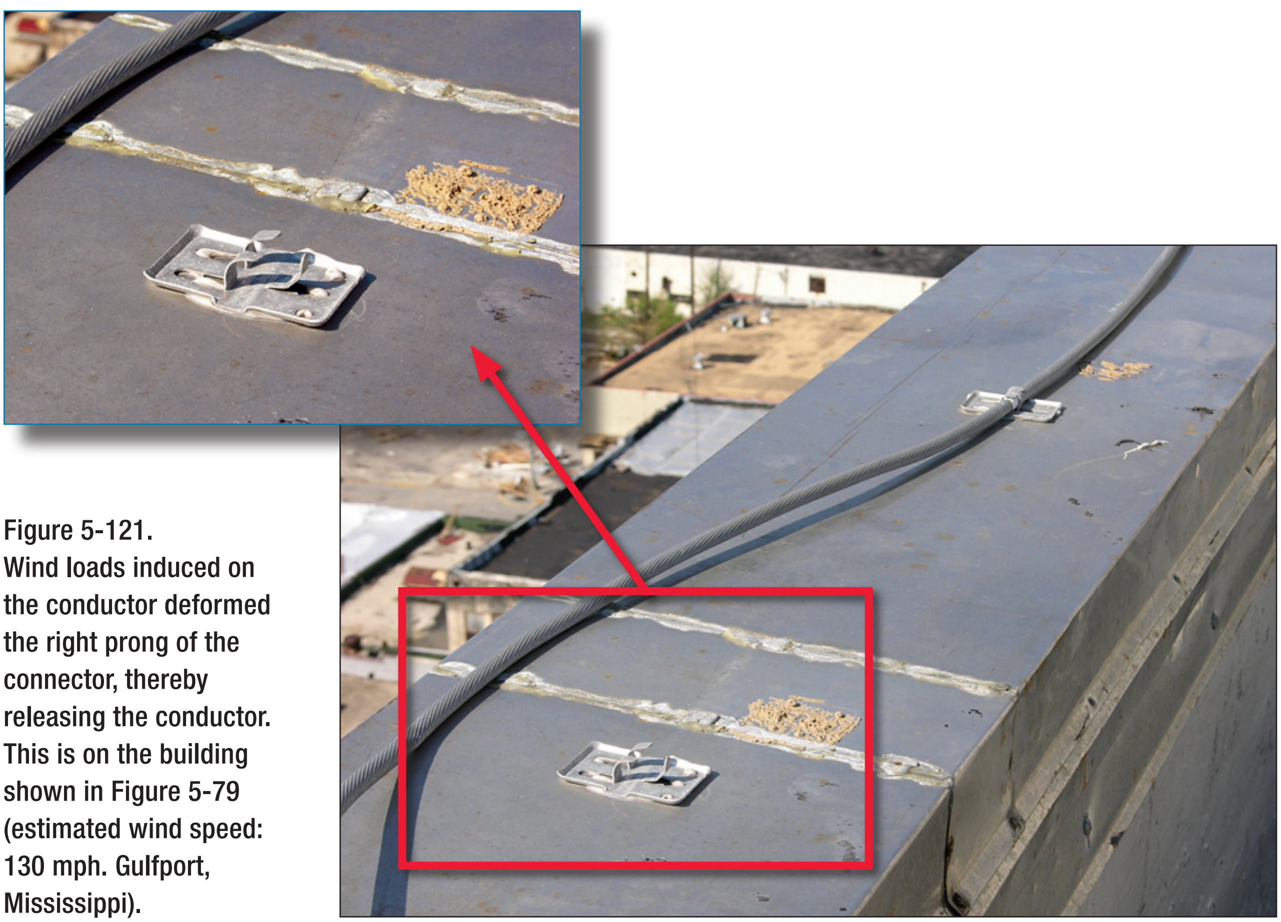


Figure 5-121.
Wind loads induced on the conductor deformed the right prong of the connector, thereby releasing the conductor. This is on the building shown in Figure 5-79 (estimated wind speed: 130 mph. Gulfport, Mississippi).

Figure 5-122.
At this hospital, in the area of the dashed line the conductor connectors debonded from the roof membrane. In the foreground, the connectors are attached to the roof, but the conductor pulled from the prongs (estimated wind speed: 130 mph. Gulfport, Mississippi).

Figure 5-123.
View of an abraded end of a conductor that became detached at the hospital shown in Figures 5-114 and 5-122 (estimated wind speed: 130 mph. Gulfport, Mississippi).

Figure 5-124.
A loose LPS conductor whipped the exterior wall and punctured the EIFS in several locations (estimated wind speed: 115 mph. Slidell, Louisiana).

Figure 5-125.
A bolted splice connector was used in lieu of a pronged splice connector (estimated wind speed: 130 mph. Gulfport, Mississippi).

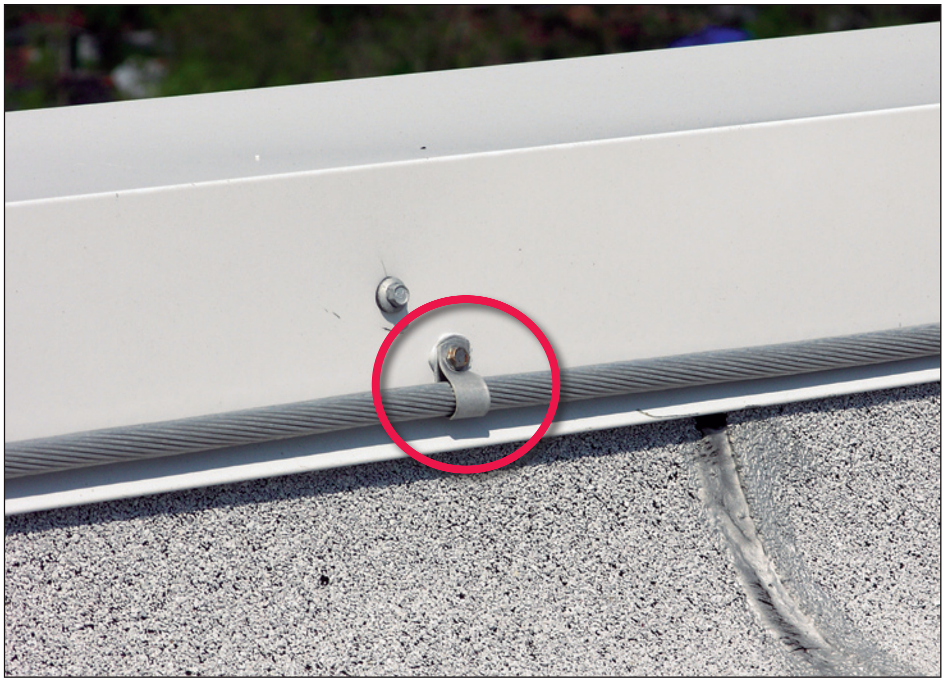


Figure 5-126.
Screw-attached looped connectors were used to anchor this conductor (estimated wind speed: 130 mph. Gulfport, Mississippi).