4. Structural Systems Performance

The dominant causes of structural failure observed by the MAT included storm surge, waves, floodborne debris, and wind. Structural damage due to erosion was also common on the barrier islands. Damage occurred to residential buildings (single- and multi-family housing), commercial buildings, and critical and essential facilities.

Section 4.1 discusses flood impacts on single-family, manufactured housing, and low-rise multi-family residential buildings, low-rise commercial buildings, and high-rise buildings. Wind impacts are addressed in Section 4.2, including wind impacts on wood-framed buildings; concrete, steel, and masonry buildings; PEMBs; and manufactured housing.

4.1 Flood

Storm surge stillwater elevations varied from approximately 10 feet (at the eastern end of the study area, on Dauphin Island, Alabama), to over 20 feet in coastal Louisiana and Mississippi. Associated flood conditions (e.g., wave heights, floodborne debris, shoreline erosion, and localized scour) varied widely by location.

The performance of structural systems was closely tied to the severity and variability of the storm surge, erosion, and wave and debris impacts. In particular, there were significant differences in building performance between those areas where flood conditions were near or below the previously predicted design conditions, and regions where the flood conditions exceeded design flood levels. Structural damage was less in areas where flooding was near or below design conditions. As typically is the case, older, low-elevation buildings were the most likely to be flooded and more severely damaged.

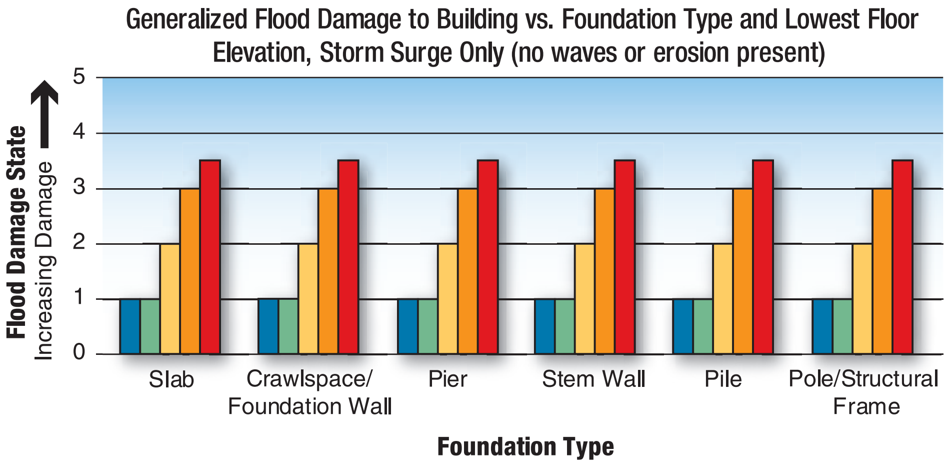
The MAT observed differences in building damage based on the structural system and foundation type employed. These observations have been generalized and are shown in Figures 4-1 (a-c). Flood damage states (ranging from 1 = no damage to 5 = destroyed) are plotted against floor elevation and foundation type for three different combinations of flood and erosion conditions. As defined herein, damage states 1 and 2 would be "successes" and damage states 3 and 4 would generally be classified as "survivors."

- Figure 4-1(a) shows observed damages for the case where inundation by storm surge occurred, but where waves and erosion were not present. In this case, damage tends to vary by floor elevation and be similar for all foundation types, as long as buildings are firmly attached to their foundations, buildings with the floor elevation far above the surge elevation tend to be undamaged and, as the floor elevation drops relative to the surge elevation, damage increases. This scenario is representative of much of the New Orleans area and in the areas of coastal Alabama and Mississippi where buildings are distant from the shoreline, and waves have dissipated.

- Figure 4-1(b) shows observed damages for the case where inundation by storm surge occurred and damaging waves were also present (erosion in these cases was non-existent or minor). A comparison with Figure 4-1(a) shows the effects of waves on buildings; as the wave crest rises to and above the floor level, building damage increases. Building damage does depend on foundation type in this case, with buildings supported on shallow foundations tending to sustain the greatest damage. The scenario depicted in Figure 4-1(b) was probably the most common situation observed by the MAT.

- Figure 4-1(c) shows observed damages for the case of inundation by storm surge with damaging waves and moderate erosion.[1] In this case, building damage is more closely associated with foundation type, even for situations where the floor level is far above the wave crest. Comparison of Figure 4-1(c) with Figure 4-1(b) shows that, when moderate erosion occurs to buildings with typical slab, crawlspace, foundation wall, pier, and stem wall foundations, severe building damage or destruction generally occurs, regardless of the floor elevation. Virtually all one-and two-family and other light-frame buildings will be destroyed when the floor level is far below the wave crest, with the possible exception of buildings with continuous structural frame systems; these buildings may survive, but will sustain severe damage.

[1] Moderate erosion is defined as up to a few feet of erosion, sufficient to undermine shallow foundations, but not enough to cause collapse of buildings supported on deep foundations.



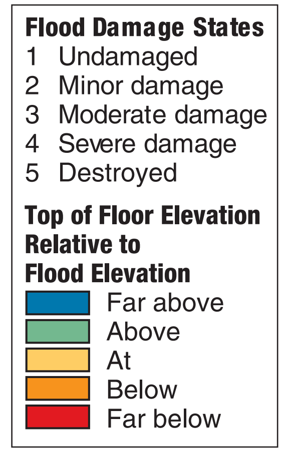


Figure 4-1 (a).
Flood damage vs. foundation type and floor elevation (no waves or erosion)

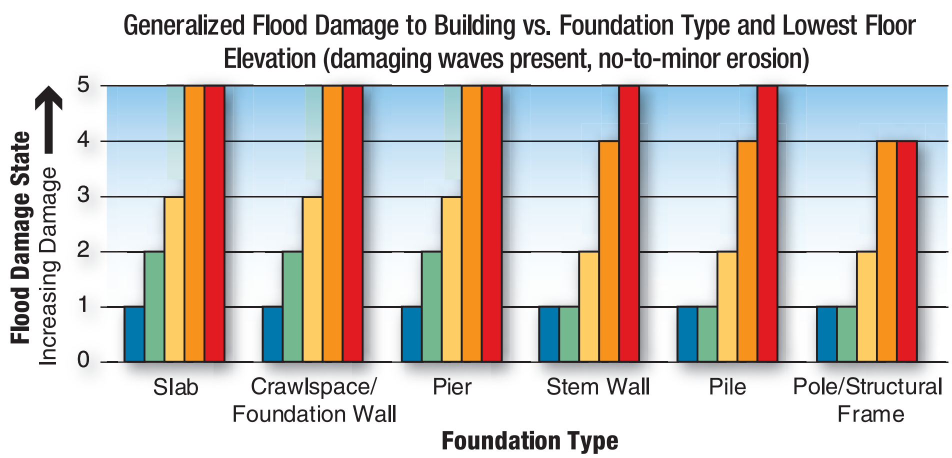


Figure 4-1 (b).
Flood damage vs. foundation type and floor elevation (waves present)

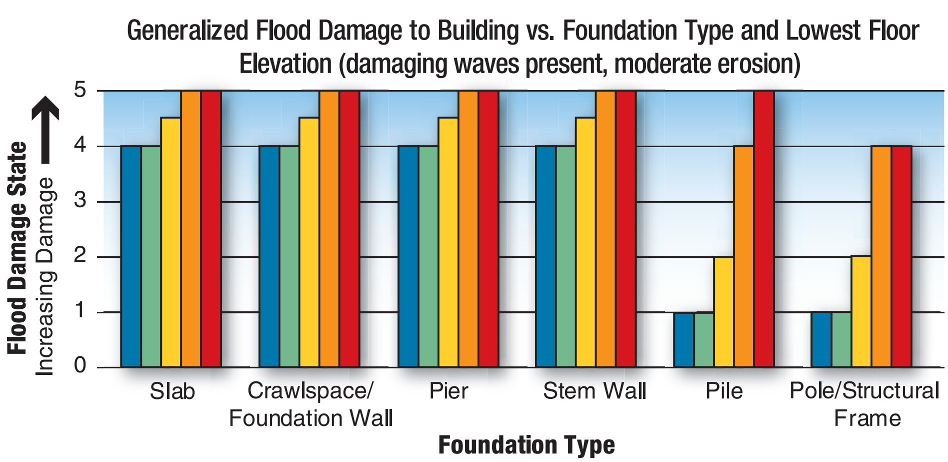


Figure 4-1 (c).
Flood damage vs. Foundation type and floor elevation (waves and moderate erosion present)

4.1.1 Single-Family Residential Buildings

Single-family and other light-frame buildings are generally incapable of resisting coastal flood loads and, therefore, are designed to *avoid* those flood loads through elevation above the design flood level (including wave effects), and by limiting flood loads to the building foundation. In coastal areas, foundations must be designed to resist wave forces, wave-induced erosion and localized scour, and floodborne debris, all of which can threaten the stability of the foundation (and the building). Thus, the foundation type makes a significant difference in the ability of the structure to resist a variety of flood conditions and flood loads. Where Hurricane Katrina's storm surge level exceeded the lowest floor level and waves were present, virtually all of the buildings were destroyed or heavily damaged, regardless of foundation type. However, some foundation types exhibited clear advantages during Katrina, such as those buildings constructed with foundations that are integral to the structural building frame.

4.1.1.1 Pile Foundations

Deep pile foundations are generally the most effective choice on barrier islands and open bay shorelines where waves, high velocity flow, and storm-induced erosion and scour are anticipated, provided the top of the pile foundation is at or above the wave elevation. Where Katrina's storm surge and waves exceeded the floor elevations of pile-supported buildings, building destruction or significant building damage usually occurred.

Where Katrina's storm surge and waves were below the building's first floor elevation, pile foundations consistently supported a wide range of small building designs. The slender cross-section of piles minimizes the wave force transferred to the elevated building until the wave crest reaches the floor beams and joists. The most commonly observed piles were wooden, but piles made of concrete and other materials were also observed. Piles consist of a continuous structural unit along the embedded and exposed length, which, unlike piers, does not contain splices or joints. Splices and joints were identified as common failure points for piers in areas subject to high flood levels, wave effects, and large floating debris loads. This indicates that better pier designs are needed in the region. In areas where the BFEs are approximately 6 feet above exterior grade (including erosion effects), homes supported by pile foundations can be elevated 3 to 5 feet above the BFE with only moderate cost increases. Elevating above the BFE is desirable because the freeboard created provides an added safety factor against flood damage. In areas where homes need to be elevated more than 10 feet above grade, pile foundations are still a viable method of providing reasonably-priced freeboard if longer piles are readily available in the area. The ability to deeply embed the pile makes it the most reliable support in areas subject to the deeper erosion commonly found on barrier island and ocean dune exposures.

To perform successfully, piles must be adequately embedded. Where piles were not adequately embedded, pile foundation failure occurred and resulted in destroyed or missing houses or racked piles and leaning buildings.

Erosion compounded the stress from the surge and caused pile foundations that were not adequately embedded to fail even when the surge did not exceed the first floor elevation. On Dauphin

Island, Alabama, more pile-supported houses were destroyed by Katrina (108) than by Hurricane Ivan (17). Two-thirds of the 150 houses on the far west side of the island were totally destroyed and many of the remaining houses were significantly damaged. Many of these homes were not flooded to the first floor level. The failure of the pile systems was likely due to erosion and loss of foundation support from successive storms (Hurricanes Ivan, Dennis, and Katrina) that made the buildings more susceptible to pile failure.

Isolated shoreline erosion and localized scour of a foot or two were widely observed throughout the Katrina impact area. Local geology dictates that there are few coastal dune systems where deeper erosion is commonly found. Erosion depths greater than 10 feet, which were recently noted in Hurricanes Ivan (2004) and Dennis (2005), were not observed following Katrina. The closest exception was the developed area on the west end of Dauphin Island, Alabama. USGS ground elevation comparisons based on light detection and ranging (LIDAR) surveys are shown in Figure 4-2. The figure compares erosion and accretion trends and building losses along part of Dauphin Island for the pre Ivan to post Ivan period, and for the post Ivan to post Katrina period. The dark red points in the figure indicate the footprints of destroyed houses. The pink area shows erosion, and the green areas show accretion.

The top figure shows erosion closest to the Gulf and accretion along the center of the island (where the road was buried by 2 to 3 feet of sand) during Ivan. Approximately 17 houses were lost in this region during Ivan. The middle figure shows that erosion occurred across the entire barrier island during Katrina (surveys showed that grade elevations on the island dropped 2 to 5 feet), with deposition in the sound. Approximately 108 houses were lost in this region during Katrina. The bottom figure shows a post Katrina aerial photo of the same area.

When pile foundations elevated single-family houses above the storm surge/waves and the piles were adequately embedded to tolerate the erosion, they performed well, as shown in Figures 4-3 and 4-4.

Flood maps identified the area seaward of the beach road as a V Zone with BFEs of +10 to +12 feet NGVD. Preliminary water level estimates indicate that the west end of Dauphin Island experienced storm surge and wave heights several feet above the predicted BFE. Many of the newer houses received minimal damage when constructed in the +14 to +20 NGVD range like those in Figures 4-3 and 4-4. However, many older buildings had shallower pile embedments and prior storm-induced erosion of the dunes had already lowered the ground elevations. The consequences of building too low or on too shallow a pile for Katrina's conditions were severe. Some of the surviving buildings were substantially damaged. The successes received little or no flood damage, but generally required new stairs and/or utility connections to return to normal use.

Damage and failures caused by inadequate pile embedment are shown in Figures 4-5 and 4-6. Wave damage to elevated buildings is shown in Figures 4-7 and 4-8. Once the storm surge and wave heights rose above the bottom of the floor beams and joists, either on stable foundations or when the foundation was undermined, the buildings were quickly destroyed by the waves, leaving little debris on the island.

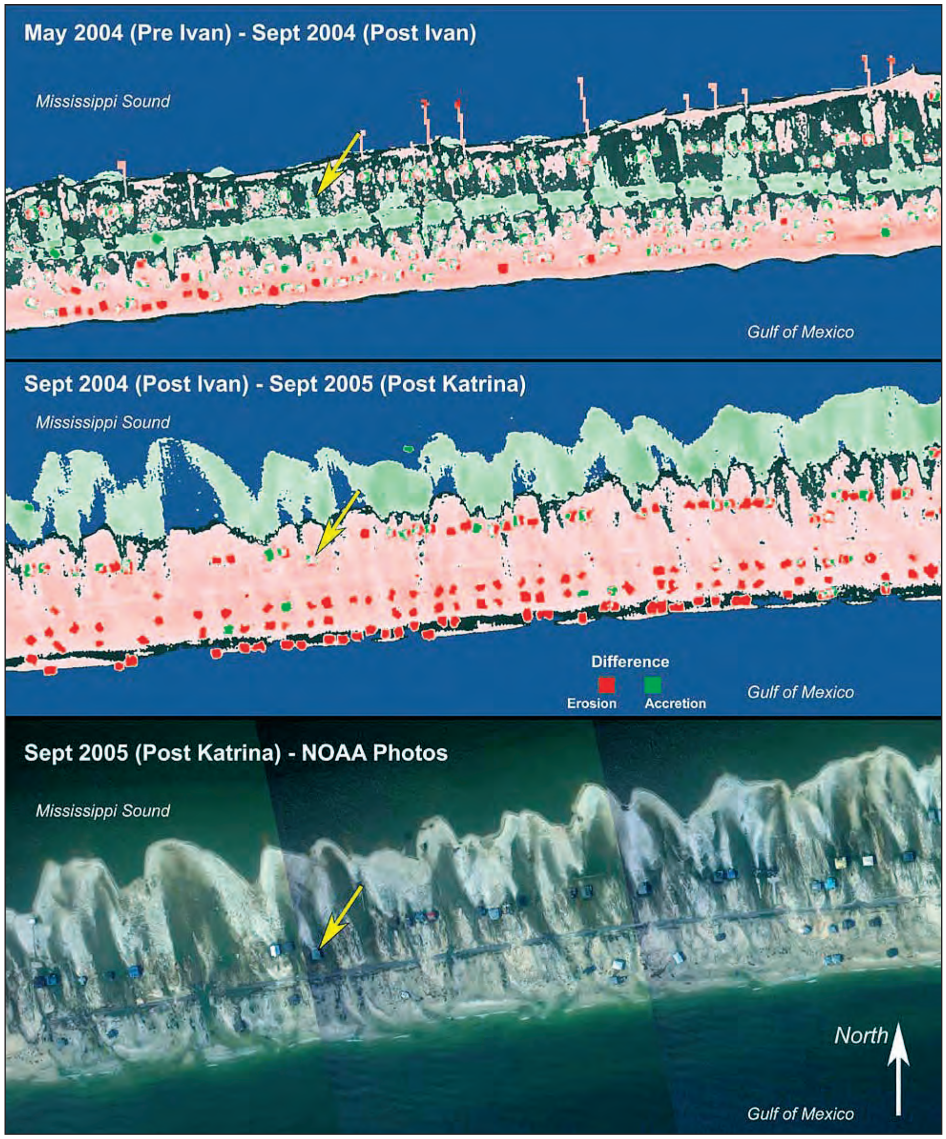


Figure 4-2. Comparison of erosion patterns and building losses on Dauphin Island, Alabama, due to Hurricanes Ivan (2004) and Katrina (2005)

SOURCE: USGS

In contrast to Dauphin Island, few other areas affected by Katrina experienced significant erosion losses around building foundations. Therefore, the lack of embedment and piling rotation was a rare cause of damage other than on Dauphin Island.

Storm surge and wave elevations were significantly higher than the BFEs shown on the FIRMs for much of the Mississippi Coast and sections of the Louisiana Delta. Successful, pile-elevated buildings that remained above Katrina's waves were observed in the fringes of the high storm surge areas, as shown in Figure 4-9.

Examples of survivor building designs were relatively rare along the Mississippi Coast and sections of the Louisiana Delta. When waves exceeded the floor elevations of the pile-supported buildings, many were destroyed, as shown near the Mississippi Gulf shoreline in Pass Christian (see Figure 4-10) and on the north-facing bay shoreline in Bay St. Louis (see Figure 4-11). In most cases, the waves destroyed the floor beams, joists and above, but left the piles in place where erosion was not a significant factor.

Figure 4-3.
Successful example of well-elevated and embedded pile foundation following Katrina (Dauphin Island, Alabama)

Figure 4-4.
Another successful example of well-elevated and embedded pile foundation following Katrina. Note adjacent building failures where foundations were not high enough or where pile embedment was inadequate (Dauphin Island, Alabama).

Figure 4-5.
Near failing house due to inadequate pile embedment (Dauphin Island, Alabama)

Figure 4-6.
Leaning piles indicate building failures due to shallow embedment (Dauphin Island, Alabama).

Figure 4-7.
Partial wave damage after wave heights exceeded the floor elevations (Dauphin Island, Alabama)

Figure 4-8.
Total wave damage after wave heights exceeded the floor elevations (Dauphin Island, Alabama)

Figure 4-9.
Successful house on high pile foundations, well above the local BFE (Shell Beach, Louisiana)

Figure 4-10.
Failure at connections between pile foundations and buildings (Pass Christian, Mississippi)

Figure 4-11.
Pile and connection failure (Bay St. Louis, Mississippi)

4.1.1.2 Foundations Integral with Structural Frames

Where Katrina's breaking waves rose above the foundation and impacted floor beams and walls, most houses quickly disintegrated into debris. Residential buildings that survived Katrina's worst storm surge and wave conditions typically had heavier than normal open foundations that were part of the building's structural frame. Examples of other surviving buildings that had foundations that are integral to the structural frames include steel-framed buildings in Mississippi that survived storm surge and wave action above the first floor level, wood-framed buildings along Mississippi's Jourdan River, and

> Pole construction is a type of construction where the pilings extend from the ground to the roof system. It differs from platform construction where the piles terminate at the lowest floor.

houses with reinforced concrete frames and walls in Long Beach, Mississippi. These houses, though heavily damaged, survived next to destroyed houses on slab, pier, or pile foundations that had first floor elevations below the wave elevation.

Figures 4-12 through Figure 4-14 show an example of a house with timber pole-type construction. Wave heights exceeded the elevated floor level by approximately 4 feet, lateral wave forces destroyed many of the exterior and interior walls, and wave uplift damaged the floor (Figure 4-14) and interior floors. However, the upper portion of the structure and the roof remained stable due to the nature of the foundation and structural frame.

Figure 4-12.
Aerial view based on USGS imagery of the surviving pole constructed house shown in Figures 4-13 and 4-14 (circle). Note the many slabs and foundation remnants of destroyed houses nearby (Waveland, Mississippi).

Figure 4-13.
Ground view of same building circled in Figure 4-12. Storm surge and waves reached at least 4 feet above the elevated floor (red line) (Waveland, Mississippi).

Figure 4-14.
Wave damage to floors and walls, but pole construction left a repairable, surviving building (Waveland, Mississippi)

Other examples of single-family buildings surviving Katrina surge and wave levels above the elevated floor are shown in Figures 4-15 through 4-21. In each case, the buildings were damaged by Katrina, but the buildings were not destroyed like most of the neighboring homes, which were on slab foundations, or elevated on piers or piles below the wave elevation. Figure 4-17 shows the devastation in the area where only two buildings survived.

Figure 4-15.
Steel-framed building on St. Louis Bay survived storm surge and wave action above the elevated floor level (Pass Christian, Mississippi)

Figure 4-16.
Wood-framed survivor exposed to storm surge and waves (Jourdan River shoreline of Bay St. Louis, Mississippi)

Figure 4-17.
Destruction of pile-and pier-supported homes (platform type construction) adjacent to the house shown in Figure 4-16. Only two homes out of approximately 100 survived in the neighborhood (Bay St. Louis, Mississippi).

Figure 4-18.
Surviving house constructed with a reinforced concrete frame and walls. Note storm shutters on upper level damaged by waves (Long Beach, Mississippi).

Figure 4-19.
Another surviving house constructed with a reinforced concrete frame. The wave elevation was approximately 2 to 3 feet above the elevated floor (Long Beach, Mississippi).

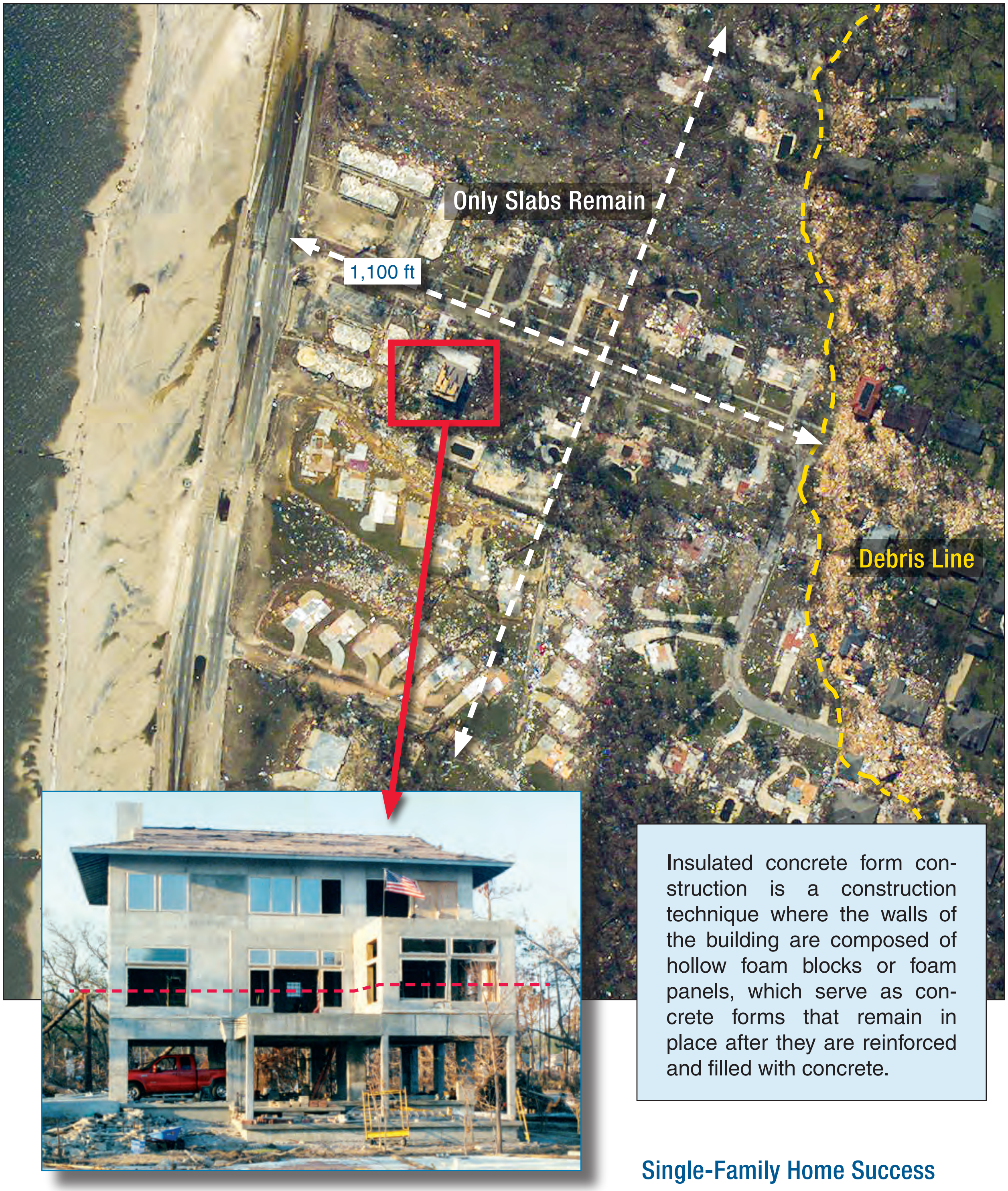


Figure 4-20.
Success amidst dozens of destroyed homes; the house was constructed with a reinforced concrete frame and insulated concrete form walls. Waves during Katrina washed through the elevated portion of the house (white dashed lines on aerial indicate total destruction of all houses except the one in the insert; red line on house indicates flood level) (Pass Christian, Mississippi).

Figure 4-21. Successful pole construction home (background) near Old Fort Bayou. The top photo was taken approximately 3 weeks after Hurricane Katrina. The lower photo was taken during Katrina (the water level had dropped approximately 6 feet from its peak when the photo was taken) (Ocean Springs, Mississippi).

SOURCE: OCEAN SPRINGS FIRE CHIEF

4.1.1.3 Masonry Pier Foundations

Masonry piers were the most common foundation type used to elevate small buildings above grade in Louisiana and Mississippi. Materials and designs varied widely, but most were concrete-filled masonry units or cast-in-place, reinforced concrete. Piers were used to elevate floors from a couple feet to more than 10 feet above grade. Most piers appeared to have been supported on shallow concrete footings or slabs. Discussions with local contractors indicate that pier foundations constructed on reinforced concrete beams are also common. The footings on grade beam foundations are interconnected to create an integral mat that is structurally superior to discrete pad footings.

When properly designed and constructed, piers were effective foundations as long as storm surge and waves remained below the floor beam and floor system components, and erosion and scour did not undermine the foundations. In Mandeville, Louisiana (see Figures 4-22 and 4-23), on the north shoreline of Lake Pontchartrain, storm surge in the lake was close to the predicted BFEs. Many buildings along the lakefront experienced storm surge and waves ranging from 2 to 6 feet above existing grade; however, buildings were adequately set back from the shoreline such that erosion was not a threat around most building locations.

Figure 4-22. Pier-supported house with minimal flood damage (Mandeville, Louisiana)

Figure 4-23. This 100-year-old building is on the National Register of Historic Places. It sustained minimal flood damage due to elevation on taller piers (an architectural choice, not a requirement when the building was constructed in 1905). Note the estimated flood depth in relation to the first floor (red line) (Mandeville, Louisiana).

Piers have been used to support buildings in the United States for centuries. In 1905, long before BFEs became a requirement, the builder of a house in Mandeville (see Figure 4-23) made the architectural choice to elevate on brick piers approximately 9 feet above grade. The foundation contained arches that provided some fixity and resistance to lateral forces. The building had damage to a few recently added under-house, breakaway walls, and minor damage to several columns, but was otherwise undamaged compared to older, lower houses.

As with pile foundations, when Katrina's storm surge and even small waves exceeded the pier foundation height and impacted the elevated building, damage was severe. Total building loss is shown in Figures 4-24 and 4-25. Such losses of houses elevated on piers 9 to 12 feet above grade were widespread across coastal Louisiana and Mississippi near the Gulf and around larger bays.

Compared to piles, traditional pier foundations have several disadvantages in storm surge and wave conditions. Some can be overcome with conservative design, but others are inherent in their construction. Piers constructed on shallow discrete footings are the most vulnerable and can be undermined by shallow erosion or localized scour, or the pier and footing can fail as a unit and rotate when exposed to lateral forces from flood and wind loads as shown in Figure 4-26. For similar support capacities, piers must generally have larger cross-sections and, therefore, are subject to higher wave forces as compared to piles.[2] In Figure 4-27, the porch roof supports have failed and the building piers have rotated landward due to lateral wave and wind forces.

Figure 4-24. Typical building failures when surge and waves exceeded pier foundation height (Long Beach, Mississippi)

[2] Piers are commonly constructed on shallow footings for one or more of the following reasons: 1) pier construction on shallow footings can be accomplished with labor and hand tools (no large equipment needed); 2) codes typically require footing depths based on frost considerations, and the designer/contractor has either underestimated erosion and scour, or has "determined" that erosion and scour will not be a problem; and 3) designers and contractors have traditionally used piers on shallow footings.

Figure 4-25.
Another typical example of building failures when surge and waves exceeded pier foundation height (Long Beach, Mississippi)

Figure 4-26.
Failure of masonry piers on shallow footings (Pass Christian, Mississippi)

Figure 4-27.
Tops of piers have been pushed landward, probably due to wave effects on the foundation and lateral wind loads on the building. Note reinforcing bars hanging from the porch roof overhang (circle). These bars were placed through wood columns and attached to the foundation, apparently as a way of providing wind uplift resistance for the wide overhang (Belle Fontaine Point, Jackson County, Mississippi).

Piers with discrete footings are much more prone to failure than piers constructed with continuous grade beams. Grade beams allow the foundation to respond as an integral system. While discrete footings can rotate and fail with relatively low lateral loads, properly designed foundations using grade beams can withstand much higher lateral loads since the entire grade beam matrix must rotate as an entity. Although grade beam foundations can resist much greater lateral loads than foundations using discrete footings, they are just as vulnerable to erosion- and scour-induced failures as foundations with discrete footings.

Compared to continuous piles that are manufactured off site, most piers are constructed on site, where the quality of construction is more difficult to control. Since piers typically consist of numerous individual components and steps in construction, there are many opportunities for error, assuming the pier is designed properly. Common pier failures observed by the MAT were due to a combination of factors, such as insufficient reinforcement (size or number or placement of bars) or inadequate splicing, shallow footings, or poor connections between the pier and the footing. Failures usually took the form of pier breakage or pier separation from the footing (see Figures 4-28 through 4-30).

Figure 4-28.
Pier connection failure (Belle Fontaine Point, Jackson County, Mississippi)

Figure 4-29.
Pier breakage (Long Beach, Mississippi)

Figure 4-30.
Failure from a poorly detailed pier to beam connection (Long Beach, Mississippi)

The MAT also observed instances where lateral flood and wind forces acting on a building caused failure in the connections between the piers and the building before the foundation itself failed (see Figure 4-31). The result was foundations standing after the storm with no buildings atop the foundations.

Pier performance was best in stillwater flood conditions where erosion was minimal and waves were small. However, when the stillwater elevation exceeded the floor elevation, buoyant forces acted on the buildings, in conjunction with lack of adequate uplift anchoring in floor framing, causing some to float off their pier foundations. For example, 19 of 32 new houses in a Pass Christian subdivision (approximately 1 mile from the Gulf shoreline) floated off their pier foundations due to flood heights approximately 10 feet above the BFE and poor connections between the building and the floor beams or the floor beams and the piers (see Figures 4-32 and 4-33)[3]. Floated buildings experienced a variety of structural damage when the water receded, and appeared to be total losses. Buildings that remained attached were flooded to approximately 8-9 feet above the floor elevations, but received minimal structural damage and appeared repairable.

Each of the failures noted points out the importance of a continuous load path, from the top of the building, through the foundation, and into the ground. A continuous load path would have reduced flood damage to many buildings subject to storm surge only (no damaging waves), such as those shown in Figure 4-32, and would have had a mitigating effect on some of the buildings subject to wave forces (turning some failures into survivors).

[3] A better connection to resist flotation and lateral loads can be made using heavy beam seats, such as those shown in Figure 4-34.

Figure 4-31.
Failure of pier-to-beam connections due to wave and flood forces acting on the elevated building (Long Beach, Mississippi)

Figure 4-32.
Buildings floated off of pier foundations (Pass Christian, Mississippi)

Figure 4-33.
Poor pier-to beam connection. Although this particular connection did not fail (because the wall and floor-to-beam connections failed first), this connection is poor. Note use of light gauge metal straps and nailing of strap at a joint in the beam (Pass Christian, Mississippi).

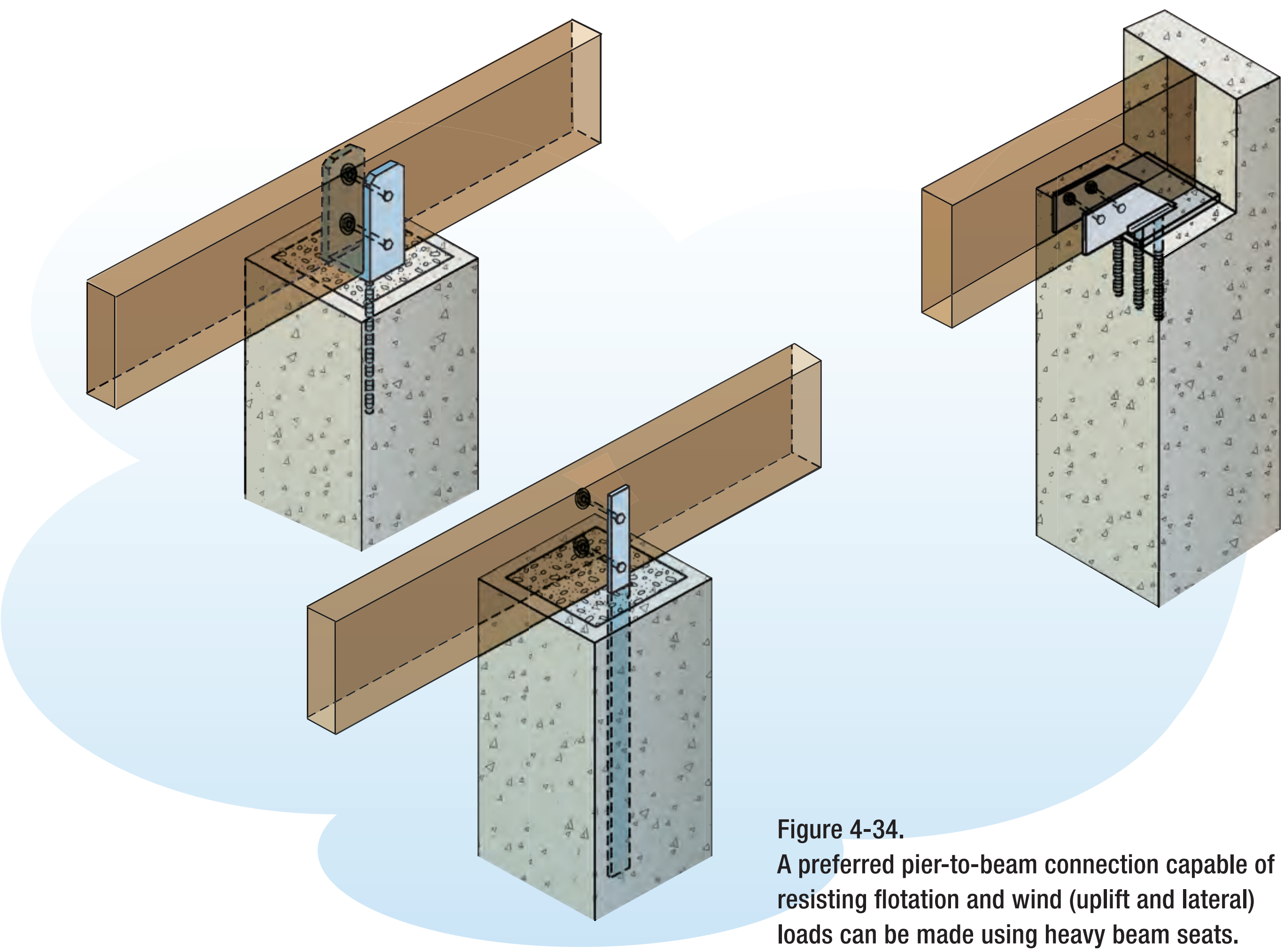


Figure 4-34.
A preferred pier-to-beam connection capable of resisting flotation and wind (uplift and lateral) loads can be made using heavy beam seats.

4.1.1.4 Slab-on-Grade Foundations

Slab-on-grade foundations were very common in coastal Louisiana and Mississippi, especially for pre-FIRM buildings and buildings outside the SFHA where the ground elevation was above the BFE. During Katrina, as long as flood heights and wave runup remained below the adjacent ground elevation, there was little flood damage to buildings supported by slab foundations. Unlike most coastal storms, Katrina was not accompanied by widespread erosion, which could have undermined slab foundations just above the flood level. Buildings constructed with slab-on-grade designs were severely damaged when floodwaters and waves reached above the slab (see Figure 4-35). Where storm surge exceeded the slab elevation by more than about 3 feet and where breaking wave heights are believed to have exceeded 1.5 feet, wave damage to load-bearing walls resulted in severe building damage (see Figure 4-36) or total loss (see Figure 4-37). Total building loss, leaving nothing but the floor slab, was common in areas experiencing wave crest elevations several feet above the slab elevation. Figure 4-38 shows the wide zone of destruction of buildings supported on slab-on-grade foundations and subject to high waves and deep flooding in Pass Christian, Mississippi. All that remains of houses in the zone closest to the shore are the slab foundations. As buildings were destroyed, the resulting floating debris moved progressively farther inland. The debris zone represents the separation between total losses and deep, stillwater flooding, with little structural damage shown at the top of the photo.

Figure 4-35. Slab-on-grade undermining (Ocean Springs, Mississippi)

Figure 4-36.
Wave and surge damage to a house supported by load-bearing wood-frame walls atop a slab foundation. The house was approximately 1/4 mile from the Gulf, in mapped flood Zone C (1992 FIRM), and was probably exposed to Coastal A Zone conditions (3-4 feet stillwater depth and small waves) during Katrina (Pointe Aux Chenes area, Jackson County, Mississippi).

Figure 4-37.
Waves, surge, and floating debris destroyed many single-family homes on slab foundations. Note debris from houses washed landward into other buildings (Biloxi, Mississippi).

Figure 4-38. Typical zones of damage to homes supported on slab-on-grade foundations (Pass Christian, Mississippi)

4.1.1.5 Stem Wall Foundations

Stem walls typically use a masonry wall to contain and elevate compacted fill, which, in turn, supports a slab. The higher elevation above surrounding grade makes the foundation preferable to a slab-on-grade, and adds a safety factor against local stormwater flooding. Stem wall foundations are frequently used to meet the elevation requirements when the BFE is several feet above grade. The earth-filled wall also provides more initial wave capacity than typical crawl space perimeter walls. However, as with other shallow foundations, stem wall foundations are susceptible to undermining due to erosion or localized scour. If undermined, the contained fill can be lost, removing support for the slab floor, as shown in Figure 4-39. Similar to buildings with slab-on-grade foundations, buildings with stem wall foundations experienced severe damage when flood levels and wave heights far exceeded the top of the slab (see Figure 4-40).

Figure 4-39.
Shallow foundation failure due to localized scour and damage to walls by surge and wave impacts (Ocean Springs, Mississippi)

Figure 4-40.
Stem wall foundation survived intact, but waves and surge above the floor destroyed the house, sweeping it off the foundation (Waveland, Mississippi).

4.1.2 Manufactured Housing

Most of the damage to manufactured housing observed by the MAT was from flooding.[4] Many of the manufactured homes that experienced damage were separated from their foundations or the foundations shifted (see Figures 4-41 through 4-48 for examples of damage to manufactured homes). In all cases, however, homes were likely substantially damaged wherever the floodwaters rose above the floor of the homes.[5]

In other words, once flood levels rose above the floor, the MAT would classify no manufactured homes as "successes" and relatively few manufactured homes as "survivors," even if the foundation remained intact and the home remained attached to the foundation. The manner by which manufactured homes are constructed makes their repair difficult, if not impossible, once the floor is flooded. Thus, a successful manufactured home installation will require: 1) elevation of the floor system above the actual flood level, 2) attachment of the home to the foundation, and 3) anchorage of the home and foundation to the ground, capable of resisting wind loads experienced by the home.

Foundation type tended to affect whether or not manufactured homes were displaced from their foundations. Manufactured homes placed on, and secured to, poured concrete foundations generally remained intact (although with flood damage from inundation). Homes placed on dry-stacked (unmortared) piers and secured with helical ground anchors were often pushed off of their foundations and destroyed.

Wind provisions for manufactured homes are included in Section 305 of the Manufactured Home Construction and Safety Standard promulgated by HUD's Manufactured Housing Consensus Committee (MHCC).

There are three wind classifications of U.S. Department of Housing and Urban Development (HUD) homes: Zone I, Zone II, and Zone III. Each classification has specific requirements for wind resistance. HUD Zone I homes are not designed to a listed wind speed, but rather are required to resist specified horizontal loads and net roof uplift loads. HUD Zone II homes are designed for 100 mph (fastest mile) wind speeds (approximately 115 mph 3-second gust wind speed). HUD Zone III homes are designed for 110 mph (fastest mile) (approximately 125 mph 3-second gust wind speed).

The MHCC HUD Zone II and Zone III homes are required to be constructed to resist the wind pressures listed in CFR 24 Part 3285. The requirements extend to the "anchorage equipment" provided with the home, but the foundations that manufactured homes are placed on are not specified in the MHCC standard.

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4 Readers should note that flood damage to manufactured homes was common, both inside and outside the SFHA.

5 Manufactured homes are particularly vulnerable to flood damage when the flood level rises above the floor. FEMA depth-damage functions generated by flood insurance claims data show that manufactured homes in areas not affected by waves are likely to be substantially damaged by between 1 and 2 feet of stillwater flooding above the floor. If high velocity flow or waves are present, substantial damage can result from flooding at or below the top of the floor. These damage patterns are in contrast with conventional site-built homes, where the entire structure must be inundated by stillwater flooding before substantial damage is likely or, in the case of waves and high velocity flow, where flood levels must reach above the top of the floor before substantial damage is likely to occur.

HUD homes in all Mississippi counties along the Gulf Coast and many of the parishes in Louisiana that the MAT visited are in HUD Zone II. Other Louisiana parishes (e.g., Jefferson, St. Bernard, Plaquemines, La Fouche, and Terrebone) are in the higher HUD Zone III.

The new HUD standards, which have not yet been released, do include provisions for local floods.

Where nameplates could be viewed, all of the newer HUD style homes investigated were identified as HUD Zone II homes. Most were installed on dry-stacked masonry piers and were secured

Figure 4-41.
Collapse of manufactured home due to loss of anchorage and pier settlement (indicative of soil saturation under flooded conditions) (Pass Christian, Mississippi).

Figure 4-42.
Dry-stacked pier under home rotated 20 degrees from vertical (Pass Christian, Mississippi).

with ground anchors. Ground anchors in many structures were spaced at approximately 8-foot centers, but ground anchor spacing could not be determined on all homes. Ground anchor spacing requirements are not contained in the MHCC, but must be included in the manufacturer's installation instructions. Other homes were placed on more substantial foundations like cast-in-place concrete strip footings.

Figure 4-43. Manufactured home placed on and secured to poured concrete strip footing had floodwaters 6 feet above its floor, but was not moved from its foundation. Although this indicates good foundation performance, the cost of repairing may exceed the value of the residence because of the significant inundation damage (Ocean Springs, Mississippi).

Figure 4-44. Interior photo of manufactured home shown in Figure 4-43 (Ocean Springs, Mississippi)

Figure 4-45.
A manufactured home near the home shown in Figure 4-43, but placed using a "standard set" installation of ground anchors and dry-stacked masonry piers (Ocean Springs, Mississippi).

Figure 4-46.
Foundation of manufactured home in Figure 4-45. Although the home did not collapse, the ground anchors were partially pulled out of the ground (probably by flotation and lateral flood forces on the home under saturated soil conditions) and it shifted laterally on its piers (Ocean Springs, Mississippi).

Figure 4-47. Flood-damaged manufactured home (St. Bernard Parish, Louisiana)

Figure 4-48. Foundation of home shown in Figure 4-47. The flood level rose above the floor, the ground anchors were apparently pulled up from the saturated soil, and the piers were displaced (St. Bernard Parish, Louisiana).

4.1.3 Low-Rise, Multi-Family Residential Buildings

Low-rise, multi-family residential buildings were constructed on the same types of foundations used for single-family houses. Performance of these buildings during flooding was similar to that of single-family houses. With stillwater levels, storm surge, and wave elevations well above the BFEs, flood damage to affected multi-family structures was widespread and severe. The pile-supported Pascagoula condominium unit in Figures 4-49 and 4-50 lost bearing walls due to lateral wave forces, and elevated floors due to wave uplift. The unit was the only remaining one out of 20 (Figure 4-50).

The condominium in Figures 4-51 and 4-52 was supported on heavy reinforced concrete columns and beams, but progressively failed from lateral and uplift wave loads on the lower unit load-bearing walls and floors. Note that wind impacts to the building, apparent at the roof and upper stories, may have also contributed to building damage.

Katrina's high surge levels (and associated wave debris and wind conditions) completely destroyed apartment buildings constructed on slab foundations. Figure 4-53 shows multiple views of an apartment complex in Pass Christian. The red arrows on the aerial view indicate the point of view of the labeled closeups. The deepest flooding extended from the Gulf shoreline to the elevated railroad tracks at the top of the aerial image. The extent of the progressive failures moving inland from the Gulf is graphically identified by the upper limits of the debris field. The floating debris (a) consisted primarily of lumber from the destroyed buildings. All that remained of the seaward buildings were the slab foundations (b). The leading edge of the debris field combined with wave forces to progressively destroy the first- and second-story bearing walls

Figure 4-49. Severely damaged condominium unit was the only one remaining of 20 units (Pascagoula, Mississippi)

Figure 4-50.
Another view of the severely damaged condominium unit shown in Figure 4-49 (Pascagoula, Mississippi)

Figure 4-51.
Condominium on heavy concrete foundation severely damaged when wave elevations exceeded lower floor elevations (Gulfport, Mississippi)

Figure 4-52
Another view of the condominium shown in Figure 4-51 (Gulfport, Mississippi)

of the next remaining row of buildings (c). By the end of the storm, the floating debris field is thought to have grown so massive that it functioned as a breakwater, damping the waves from reaching the deeply flooded units, as shown by the watermark in (d), just landward of the debris field. Wind damage is apparent to the structures standing in (d), indicating that wind might have contributed to damage of the destroyed buildings seaward of the debris line.

Figure 4-53.
Multiple views of an apartment complex on slab foundations. The red arrows on the aerial image indicate the point of view of the labeled closeups (Pass Christian, Mississippi).

4.1.4 Low-Rise Commercial Buildings

A wide variety of commercial buildings experienced flooding and severe damage from the storm. These buildings included downtown storefronts in the older business districts, stand-alone food service/resort retail, motels, churches, seafood handling/processing facilities near the harbors, strip malls, and larger retailers. No type of commercial buildings constructed on slab foundations near the coastline escaped damage when the storm surge or wave elevations exceeded the floor levels. In denser development such as the downtown central business areas, those buildings farther from the shoreline experienced widespread stillwater flooding, but were protected by increasing ground elevations and the density of buildings closer to the Gulf. Most of the commercial buildings had light gauge metal stud exterior walls or masonry walls on slab foundations. As seen in other types of buildings (i.e., residential), the buildings closest to the shoreline that were exposed to waves lost load-bearing walls and were swept clean to the floor slab (see Figure 4-54). Steel-framed construction with in-fill masonry walls was more common in larger retail buildings and some churches. When exposed to waves, the heavier steel frame continued to support the roofs, but walls and contents were destroyed (see Figures 4-55 through 4-58).

A very unusual commercial structure investigated by the MAT was the Biloxi Harbor Master Administration Building (see Figure 4-59). The building structure was a hybrid. Its lower level consisted of a reinforced concrete frame; the upper levels and roof were constructed with heavy steel structural columns and joists. The building was constructed in a designated V Zone, and the first floor walls of glass behaved like breakaway walls and were sacrificed with the storm surge.

Figure 4-54. Commercial building destruction along the Mississippi coast

SOURCE: USGS

Figure 4-55.
Steel-framed strip mall construction with exterior and interior wave damage (Gulfport, Mississippi)

Figure 4-56.
Interior of steel-framed strip mall construction shown in Figure 4-55 (Gulfport, Mississippi)

Figure 4-57.
Steel-framed church that was gutted by waves, but the roof remained in place (Biloxi, Mississippi)

Figure 4-58.
Large retail store that was gutted by waves, but most of the roof remained in place (Pass Christian, Mississippi)

Figure 4-59.
Biloxi Harbor Master Administration Building with a hybrid structural system, concrete and steel (Biloxi, Mississippi)

4.1.5 High-Rise Buildings

High-rise buildings subject to stillwater flooding in Katrina included downtown office buildings and hospitals that were located more distant from the shoreline. Structural damage from the flooding was rare, but water damage to equipment and contents was severe in some cases. High-rise buildings close to the shoreline experienced some of the worst storm surge depths and wave heights. Shoreline erosion was rare compared to most recent storms (FEMA 489, 2005 [Ivan]). The foundation stability of the large buildings was not affected; most were cast-in-place, reinforced concrete. A few were steel-framed construction. Although sited near the shoreline and experiencing the worst flood conditions, the high-rises were some of the better examples of successes.

A concrete-framed building in downtown Gulfport (see Figure 4-60) sustained surge damage to its first floor and glazing damage from flying debris, but remained structurally sound and easily repairable.

An unusual failure of a concrete structure was the multi-family complex located outside of Pass Christian (see Figure 4-61). The project was under construction when Katrina hit. The structure consisted of concrete columns with post-tensioned slabs and integral drop pan beams. Like many post-tensioned concrete structures, the beams and slabs were likely cambered (intentionally curved upward) to counteract the natural downward deflection that occurs after a building is constructed and fully loaded.

Post-tensioned slabs are strong under gravity loading, but can be weak when exposed to uplift. The MAT believes failure resulted when the unloaded and post-tensioned cambered slab and

Figure 4-60.
Concrete-framed building sustained non-structural damage to lower portions from storm surge (Gulfport, Mississippi)

Figure 4-61.
Multi-family property on Beach Boulevard with failed post-tensioned slabs and columns. Note the post-tensioning tendons (circles) (Pass Christian, Mississippi).

beams were lifted and further cambered when surge and waves struck the bottom of the floor slab and beams. This lifting appeared to produce failure in portions of the slab and in some of the beams and resulted in localized collapse.

Most of the affected floating casinos located along the Gulf and bay shorelines were associated with high-rise hotels on adjacent land. It was common practice to elevate main entrances one or two stories above the low, adjacent ground elevations (see Figure 4-62). Lower level parking decks supported (see Figure 4-63) or were adjacent to the hotels. In some cases, the floor elevations were high enough to avoid flood and wave damage, or at least limit damage to the lowest finished-entrance floor level. The higher foundation elevations allowed several hotels on exposed shorelines to return to operation sooner than more sheltered lodging farther inland and outside the flood area.

Other post-storm inspection groups noted that the construction techniques used for the parking decks made a significant difference in the performance (MCEER, 2005). Cast-in-place concrete designs performed the best. Pre-stressed parking deck designs frequently experienced wave damage to horizontal structural members and the floor panels of the first elevated level. The designs frequently relied on gravity connections that failed when exposed to lateral and uplift wave forces, as shown in Figures 4-64 and 4-65. Cast-in-place designs integrated better component connections and performed better when exposed to waves. The performance of parking decks under and around the casino hotels indicated that the large buildings could be designed for Katrina's similar conditions if appropriate wave forces were considered.

Although the flood resistance of the casino hotels was better than many other building classes, the performance of floating casino barges was poor. Along the Gulf and exposed bay shorelines, the storm surge and waves either sank the barges at their docks or separated the barges from their moorings to become massive floating debris. An example of barge damage to a hotel parking deck in Biloxi is shown in Figure 4-66. The consequences of other barge impacts is described in Chapters 3 and 6.

Figure 4-62.
Elevated entrance driveway in casino hotel (Biloxi, Mississippi)

Figure 4-63.
Elevated lower level parking deck in casino hotel (Biloxi, Mississippi)

Figure 4-64.
Collapse of first elevated level of pre-stressed parking decks due to poor column-to-beam gravity connections that failed when exposed to lateral and uplift wave forces (see Figure 4-65) (Biloxi, Mississippi)

Figure 4-65.
Another view of the collapse of first elevated level of pre-stressed parking decks shown in Figure 4-64 (Biloxi, Mississippi)

Figure 4-66.
Parking deck collapse due to impact by casino barge, on left (Biloxi, Mississippi)

The MAT observed generally good structural performance of high-rise buildings located near the Gulf shoreline. The buildings observed included casinos/hotels, office buildings, and condominiums. High-rise foundation systems were generally not impacted by storm surge and wave impacts due to their location on high ground and building elevations. As an example, a high-rise building in Gulfport was sited on higher ground with a lower level office floor at elevation 20 feet NGVD (see Figures 4-67 and 4-68). One building was almost complete and the second tower was nearing completion. The cast-in-place concrete shear walls, aligned perpendicular to the shoreline, allowed waves to pass through the lower level, damaging only the office and other non-structural walls on the ground floor. The higher floors were undamaged.

Figure 4-67.
High-rise building along Beach Boulevard received non-structural flood damage to lower floors, but no apparent flood or wind damage to higher residential floors (Gulfport, Mississippi)

Figure 4-68.
Another view of the high-rise building along Beach Boulevard shown in Figure 4-67 (Gulfport, Mississippi)

4.2 Wind

While damages from Hurricane Katrina's storm surge devastated the Gulf Coast, Hurricane Katrina's winds also caused damage throughout the impacted area. Some of the damage was in areas that experienced wind speeds that approached current design wind speeds. However, much of the damage was in areas where the wind speeds were well below the design levels specified in the latest codes and standards.

In discussing wind damage, it is important to differentiate between structural damage and building envelope damage. Many buildings experienced little or no structural damage, but may be total losses due to water entry that resulted from building envelope failure. It is also important to differentiate between the design wind speeds and their resulting design pressures specified by the latest code and the design wind speeds/pressures specified by the older codes that were in effect when many of the buildings the MAT investigated were constructed. In many areas, the design wind pressures specified in current codes are higher than those specified in older codes.

Most of the damage was to building envelopes (discussed in Chapter 5), but structural damages occurred as well. Common types of structural damage included roof decking blow-off; gable end wall failures; collapse of unreinforced, load-bearing masonry walls, and purlin and moment frame failure of older (pre-1980) PEMBs. These damages were observed on all types of buildings with older residential and commercial buildings generally affected the worst.

4.2.1 Wood-Framed Buildings

Most of the wood-framed buildings observed by the MAT were residential buildings (both single-family and low-rise apartment buildings). The predominant wind related damage to these types of buildings was structural failure of wall and roof elements.

The construction type for these structures is known as light framed with superstructures supported by load-bearing, wood-framed walls. Building floors and roofs are supported by wood joists, rafters or trusses, and plywood or oriented-strand board (OSB) decks. Typical framing members are nominal 2-inch-thick lumber with widths ranging from nominal 4 inches to 12 inches, depending upon the member's use. Members are typically spaced at 12 inches, 16 inches, and 24 inches in order to accommodate building loads and 4x8-foot sheet material (i.e., gypsum board, plywood, and paneling).

Wood is a favored material of residential building contractors for its economy, architectural flexibility, and aesthetics. Small work crews can handle most wood members without special lifting equipment, cutting and fastening can be accomplished on site with hand-held or portable power tools, and the skills needed for wood construction are easily learned. The ease and flexibility of wood construction also leads to one of the major problems it has as a system (i.e., it can be assembled or modified in so many different ways).

Structural framing systems must be designed to transfer all gravity, uplift, and lateral loads to the foundation, as shown in Figure 4-69. The integrity of the overall building depends not only on the strength of these components, but also on the adequacy of the connections between them to properly transfer the forces. Critical connections occur in the following locations where the roof systems are supported by the top plate of the wall, there are openings and headers in the walls that collect forces, floors connect to each other, and the base of the wall connects to the foundation system. In buildings with trusses or rafters for roof framing, the roof sheathing typically works with the framing to create a roof diaphragm. The roof diaphragm in turn transfers lateral loads to the foundation through the building's shear walls.

Observations of hurricane damage during the past few decades have revealed that a common failure point was wood-framed gable end walls. These were commonly under designed, improperly constructed, and unbraced. Often, a typical roof truss is the only support element behind the wall covering of the gable, as shown in Figure 4-70. Properly designed, fabricated, and installed trusses are usually designed to carry gravity loads across their strong axis. However, when a truss is used alone as the wall framing for the gable end wall, the truss members must resist the wall's wind forces along its weak axis. In many cases, the gable end may be as tall as a story high and, even if wall studs are added to the truss, the truss may still be inadequate to carry the shear and bending forces produced by the lateral wind load. Lateral bracing must also be considered in buildings using scissor trusses. Scissor trusses have sloped bottom chords that create vaulted ceilings. If the wall framing below the gable assembly is not continuous, a hinge can form and the wall framing can fail under lateral loads. The MAT observed new construction where inadequate wall framing was being provided (see Figure 4-71).

In cases where adequate wall stud framing is present in the gables, the problem is typically the absence of adequate bracing of the gable end wall, which sits on top of the wall below, as shown in Figure 4-72. Without adequate bracing, a hinge is produced between the bottom of the truss and the top of the wall, as seen in Figure 4-73. In most cases, the only bracing is the roof diaphragm, and when removed by the wind, total collapse of the roof and wall occurs as shown in Figure 4-74.

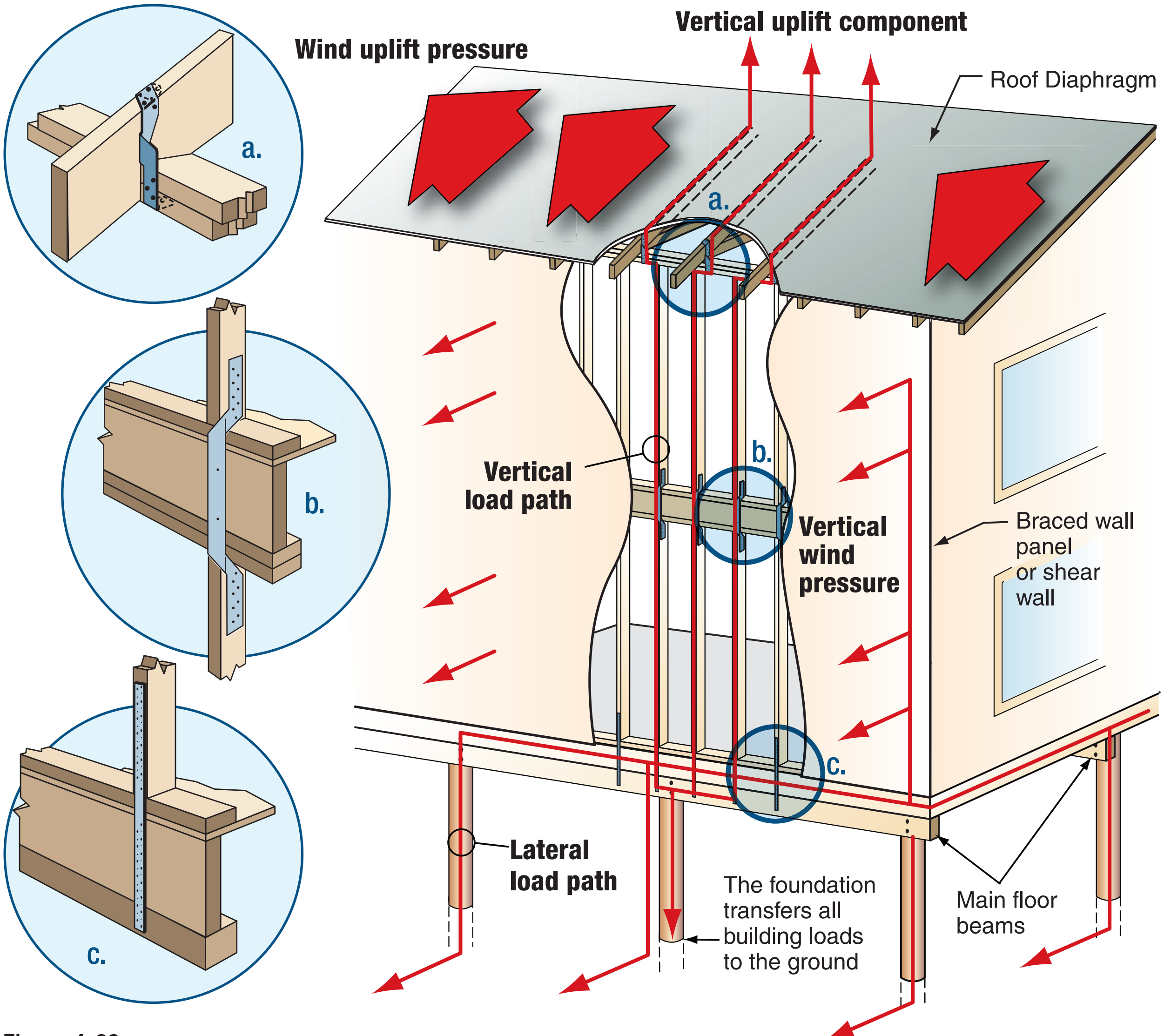

Figure 4-69.
Load path of a two-story building with a primary wood-framing system: walls, roof diaphragm, and floor diaphragm

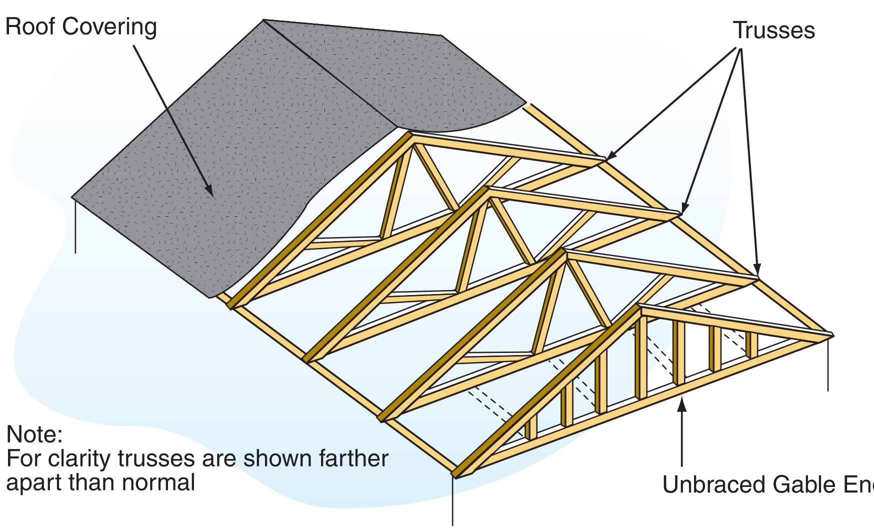

Figure 4-70.
Gable end wall framing diagram

Figure 4-71
Inadequately braced gable on a building under construction (the building was not in place during Katrina). The trusses have sloped bottom chords (scissor style trusses) to create a cathedral vaulted ceiling. While the gable truss has a flat bottom chord, the wall studs below the bottom of the gable assembly are interrupted, which creates a weak hinge that will not adequately brace the top of the wall or the bottom of the gable truss above (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 4-72.
Apartment with typical gable end wall truss with stud infill. Note the loss of gable sheathing and the lateral displacement of the bottom chord of the truss (circle) (estimated wind speed: 120 mph.[6] Ocean Springs, Mississippi).

[6] 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 130-mph Exposure C speed given for Figure 4-71 is equivalent to 110 mph in Exposure B.

Figure 4-73.
Hinge formed between gable end and top of wall (hinge circled) (estimated wind speed: 120 mph. Ocean Springs, Mississippi)

Figure 4-74.
Two-story apartment building that lost its roof diaphragm and load path connections (estimated wind speed: 120 mph. Ocean Springs, Mississippi)

The most common wind-related structural failures observed in light-framed construction were roof framing failures. Failures were observed in both new and old construction. Insufficient attachment of roof sheathing panels to the supporting framing was the most common problem. Before the 1982 SBC, the code did not account for higher uplift pressures that occur at roof perimeters and corners. Much closer nail spacing was required after implementation of the 1982 SBC criteria. Once the sheathing attachments fail, a variety of other failure modes can occur. Attics that have been breached can become pressurized and other structural elements may then become overstressed. This can lead to an "unzipping" effect of progressive failure where one failure leads to a series of subsequent failures, as seen in Figure 4-75.

Figure 4-75.
Failure of the gable end wall of this apartment building led to pressurization of the attic and the release of sheets of plywood sheathing. Note the plywood roof sheathing “unzipped” by wind pressures (arrows) (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

Zones of increased wind pressure occur at wall and roof corners, roof edges, roof ridges, hips, and overhangs. Failures of building structural and/or envelope components usually begin in these zones. Breaches of the building envelope (such as door or window failure) can result in increased internal pressure, which can damage interior partitions and ceilings and increase the wind load on structural and envelope components. Increased pressure can cause failure if the structure and envelope possess inadequate wind resistance. Figures 4-76 and 4-77 are illustrative of these zones of high pressure.

Figure 4-76.
Roof corners, edges, and ridges are zones of increased wind pressures (arrows), as seen in this apartment complex (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

Figure 4-77.
High pressures under overhangs often lead to progressive structural failures. Note the vinyl soffit material removed by high-wind pressures (arrows) (estimated wind speed: 130 mph. Pass Christian, Mississippi).

The MAT observed numerous examples of failures of building soffits that led to attic internal pressurization and subsequent loss of decking and roof framing members, as seen in Figure 4-78. Soffits supported by solid substrate, seen in Figure 4-79, often prevented significant air pressure from entering inside the building envelope.

Figure 4-78.
Pressurization of the second floor porch ceiling of this apartment led to soffit failure and loss of roof decking and other structural components (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

Figure 4-79.
Properly attached gypsum board substrate avoided attic pressurization and entrance of wind-driven rain when the finish soffit material was lost (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

4.2.1.1 Single-Family Homes

In the areas damaged by Hurricane Katrina, the MAT observed few houses new enough to have been built under the 2000 or 2003 IBC. Newer wood-framed houses generally performed well structurally. However, in most of the areas struck by Katrina, the actual wind pressures were below the code-prescribed pressures and Katrina could not be considered a true "code design-level test." [7] Therefore, it is difficult to evaluate the effectiveness of new codes because newer homes were not fully tested.

Efforts in the last 15 years to increase the quality of coastal construction using best practices and most current research, such as discussed and illustrated in the Standard Building Code (SBC) SSTD-10, *Hurricane Resistant Residential Construction Standard*, and FEMA 55, *Coastal Construction Manual*, have been successful. Many newer houses observed by the MAT had significant damage due to storm surge below their elevated floors and into first habitable floors, but remained structurally connected, as seen in Figures 4-80 and 4-81.

SSTD 10-99 is a high-wind standard first published by the Southern Building Code Congress International (SBCCI) in 1990. The standard references ASCE 7-88. ASCE 7 has been revised five times since 1988 and wind provisions have been significantly changed. To address those changes and other state-of-the-art research, the ICC will be releasing *Revised Standard for Hurricane Resistant Construction*.

[7] Hurricane Charley (2004) was a near code design-level test in some of the areas it impacted. For structural performance of new residential construction during that event, see *FEMA Mitigation Assessment Team Report: Hurricane Charley in Florida* (FEMA 488).

Figure 4-80.
Coastal home located in Exposure C received significant surge damage into the habitable level and, although it lost its porch and three porch columns, the basic load path remained connected. Red circle indicates location of Figure 4-81 (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

Figure 4-81.
Coastal home located in Exposure C that is well connected with beam-to-column lap joints and galvanized bolts and straps (estimated wind speed: 120 mph. Ocean Springs, Mississippi)

Good connections are essential in maintaining structural integrity of structures. For many years, metal framing connectors have been available for residential construction and are required by the various codes in coastal areas. If properly installed, the connectors, which have been engineered by industry, will transfer roof loads to foundations, thereby maintaining a continuous load path. The home shown in Figures 4-82 and 4-83 was still under construction and, although the first floor was completely inundated by floodwater, it remained fully connected.

Figure 4-82.
Home under construction subjected to flood and wind damage (estimated wind speed: 130 mph. Pass Christian, Mississippi)

Figure 4-83.
Home located in Exposure C with rafter-wall connectors and top plate-stud connectors. Note the rafter-top plate connector (arrow) is more effective to install on opposite side of wall, and the top plate stud connector (circle) (estimated wind speed: 130 mph. Pass Christian, Mississippi).

Frequently, the MAT found structures (including houses under construction) without proper connectors, or with inconsistently spaced, insufficient, or poorly attached connectors. Figures 4-84 and 4-85 illustrate floor-to-floor connectors that were adequately spaced, but improperly attached. They do not fully extend across the floor framing and several nails were missing from the connection. Furthermore, the sheathing was not installed in a fashion that best takes advantage of its potential to transfer lateral and vertical forces. As a best practices approach, sheathing should extend 2 feet above and below the floor level. When metal connectors are used, manufacturers usually recommend filling all holes with the proper-sized nails in order to maximize the strength of the fastener. Figure 4-86 shows a floor-to-floor strap that does not extend to the upper wall system. Figure 4-87 shows a plate-to-stud connector that is attached with the incorrect size of nail, which has been bent over to prevent pull-through.

Figure 4-84.
Two-story structure with floor-to-floor connectors (arrows) that are adequately spaced, but improperly attached (see Figure 4-83) (estimated wind speed: 120 mph. D'Iberville, Mississippi).

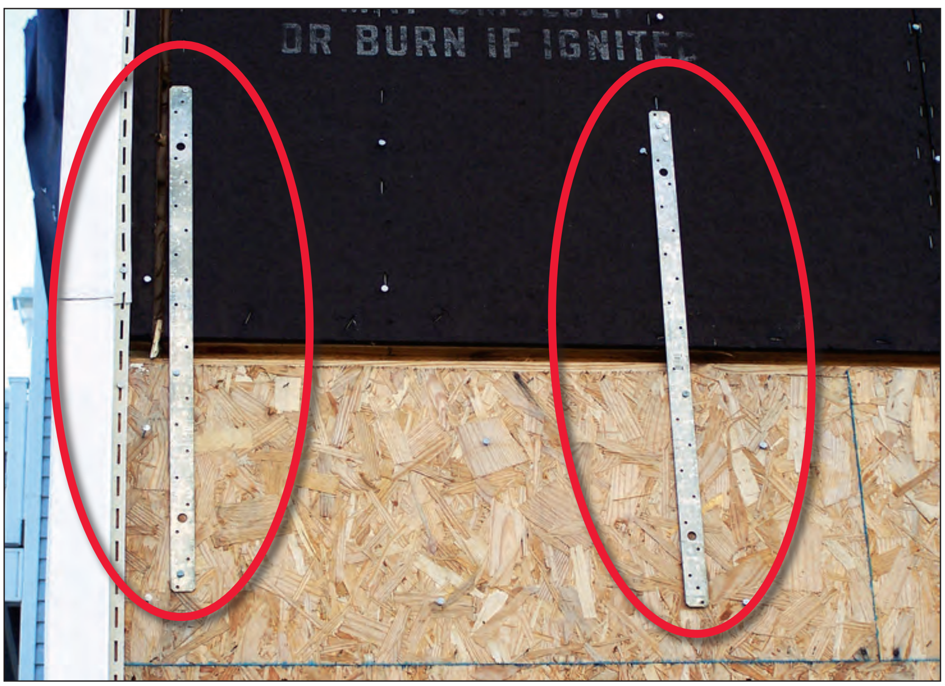

Figure 4-85.
Two-story structure with floor-to-floor connectors that were adequately spaced, but were too short to extend into the wall framing above and below the floor level and were missing several fasteners (circles) (estimated wind speed: 120 mph. D'Iberville, Mississippi).

Figure 4-86.
Floor-to-floor straps are intended to keep the load path connected (proper strap location in red). The strap installed in this Biloxi office condominium does not extend to the upper wall system and is insufficiently nailed (estimated wind speed: 120 mph. Biloxi, Mississippi).

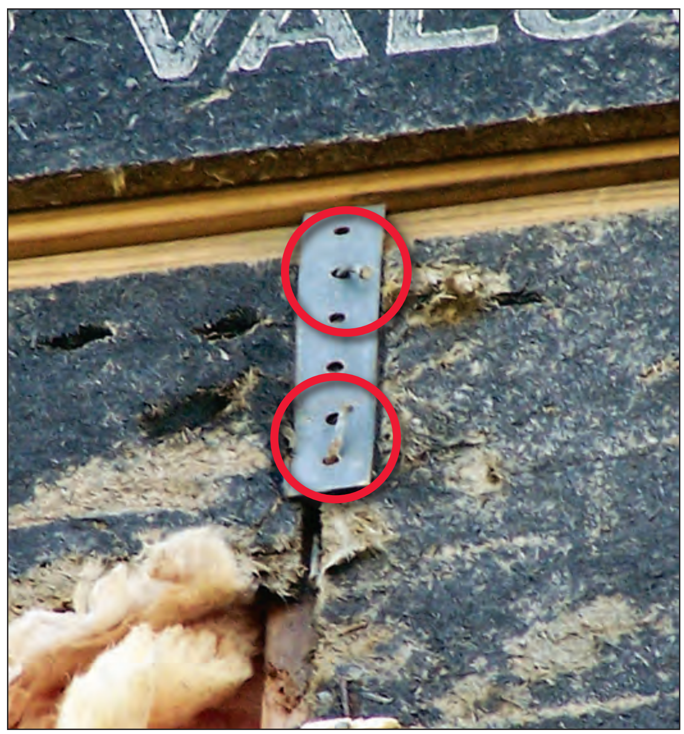

Figure 4-87.
Stud strap connected to top plate with improperly sized nails with bent heads (circles). The strap did not extend far enough down the stud and several fasteners were missing (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

Some homes under construction were severely damaged or destroyed by Katrina's winds even though wind speeds were well below current design levels. Figure 4-88 shows a home in St. Tammany Parish with failed shear walls and a collapsed garage. The complete destruction of the garage prevented the MAT from determining the mode of failure, but the failure of the home could be attributed to inadequate shear wall nailing. The home had shear walls that were only stapled and the staples were widely spaced. Several staples missed the wall framing.

Figure 4-88.
Home under construction whose garage collapsed and that racked laterally approximately 1 foot. Sheathing in the shear walls in the front of the home were found to be inadequately fastened to the wall framing (estimated wind speed: 120 mph. St. Tammany Parish, Louisiana).

Figure 4-89 shows another home under construction that experienced partial failure of the roof framing systems. The roof framing was fastened to the wall's top plate with framing anchors, but no fasteners were used to connect the top plate to the wall framing (see Figure 4-90).

Figures 4-91 (a) and 4-91 (b) show a home in St Bernard Parish, Louisiana, that did not experience significant damage during Katrina (it is possible that the home was constructed after Katrina), but was indicative of improper construction methods found in several new homes the MAT visited. Wall sheathing in the home was fastened to the bottom wall plate at 32 inches on center while prescriptive codes would require nailing at 6 to 8 inches. The presence of building wrap on the outside walls indicates that no additional nailing was to be installed.

Figure 4-89.
Home located in Exposure C that lost portions of its roof structure (estimated wind speed: 110 mph. Plaquemines Parish, Louisiana)

Figure 4-90.
Framing anchors were used to connect rafters to top plate, but no framing anchors connected top plate to wall framing at this house located in Exposure C (estimated wind speed: 110 mph. Plaquemines Parish, Louisiana).

Figure 4-91 (a) and 4-91 (b).
Wall framing was inadequately secured to the bottom plate with fasteners spaced over 32 inches on center. The presence of building wrap shows that no additional nailing was planned (estimated wind speed: 130 mph. St. Bernard Parish, Louisiana).

4.2.1.2 Multi-Family Residential Buildings

As reported in Chapter 3, the structural performance of multi-family dwellings varied with construction type. Reinforced concrete- and steel-framed structures performed well, while extensive damage was observed in many wood-framed, multi-family structures. The severity of wind damage did not vary significantly with foundation style. Structures with shallow foundations performed similarly to those with deeper foundations. Deeper foundations, like piers or pilings, were typically used in coastal sites where wind speeds were higher; thus those buildings had greater wind damages, but the difference in damages attributed to wind cannot and should not be attributed to foundation style.

Wood-framed, multi-family buildings fared the worst. Many buildings were severely damaged or destroyed. As stated in Chapter 3, breaching of the building envelope through soffits or other soft portions in the exterior contributed to failure. Weaknesses often involved inadequate roof sheathing attachment, inadequate connections between roof and wall framing, and other weaknesses in the vertical load path between roofs and foundations.

The MAT observed several damaged buildings where roof sheathing was tacked at corners with nails and fastened with staples in all other areas of the sheet (see Figures 4-92 and 4-93). Staple placement varied greatly and often one leg of the staples missed the roof framing. Where staples were squarely fastened to roof framing, some staples tore through the sheathing when the roof sheathing experienced pull-through failure, as shown in Figure 4-94. The 2003 IRC allows cellulosic fiberboard wall sheathing to be stapled along panel edges at 3-inch centers (on 6-inch centers within the panel), but specifies nails for fastening structural wall and roof panels.

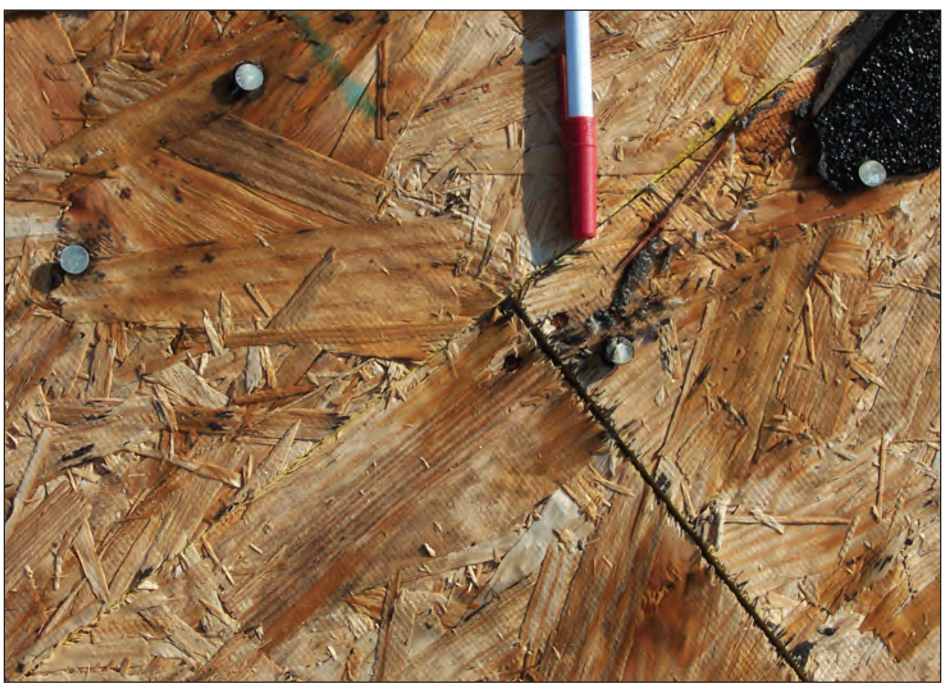

Figure 4-92.
Roof sheathing nailed only at corners, and stapled in other areas (estimated wind speed: 130 mph. Long Beach, Mississippi)

Figure 4-93.
Roof sheathing beneath the gable roof (that blew off) was tacked at corners with nails. No other fastening was used (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 4-94.
Roof sheathing attachment was inadequate. Several staples were missing, some staples missed framing, and inland the sheathing pulled over the staples (estimated wind speed: 130 mph. Long Beach, Mississippi).

Metal connectors were frequently left out, or were installed improperly. In a Long Beach apartment complex, connectors were used to anchor the main trusses to the bearing walls, but none were used on the gable trusses above the entrances and porches (see Figures 4-95 through 4-98). In those areas, the wide eaves and open breezeways were subjected to uplift forces on the trusses on several buildings in the complex. Connections failed and entire roof structures above the entrances and porches blew off of the buildings.

Gable end walls were often constructed with vinyl siding over rigid insulation sheathing, which is vulnerable to damage from wind and windborne debris. If the gable walls are penetrated, internal pressurization occurs and uplift forces on the trusses increase. Properly fastened plywood sheathing on the gable walls would have improved performance and may have prevented failure.

Figure 4-99 shows a similar apartment building whose gable end walls were OSB. The sheathing failed during Katrina. Resulting attic pressurization likely contributed to the loss of sheathing near the ridge. Vinyl siding was blown off, but the gable wall and the roof above remained intact.

Figure 4-95.
Metal connectors (arrow) were used on main trusses (estimated wind speed: 130 mph. inland Long Beach, Mississippi).

Figure 4-96.
Metal connectors were lacking on the gabled roofs over the porches and entrances. Several roof structures were blown off (estimated wind speed: 130 mph. Long Beach, Mississippi).

Figure 4-97.
Another example of metal connectors lacking on the gabled roof that once existed over the entrance (estimated wind speed: 130 mph. inland Long Beach, Mississippi)

Figure 4-98.
Apartment building's gable walls sheathed with insulation failed during Katrina (estimated wind speed: 130 mph. inland Long Beach, Mississippi)

Figure 4-99. Apartment building with gable end walls that were constructed with OSB sheathing under housewrap (estimated wind speed: 120 mph. D'Iberville, Mississippi)

4.2.1.3 Manufactured Housing

While most of the damage to manufactured housing was from flooding, wind damage was noted in both older and newer manufactured homes. Figure 4-100 shows an older manufactured home in St. Bernard Parish, Louisiana, that was rolled over and destroyed by wind forces. The home's frame was once secured with metal straps spaced approximately 13 feet on center. No wall ties for improved resistance to uplift were visible (see Figure 4-101). The strapping and lack of wall/vertical ties does not meet HUD Zone II requirements for newer homes. Even though the home was older and likely not constructed to current wind standards, proper anchorage may have prevented the home from being destroyed.

Figures 4-102 and 4-103 show damage to newer manufactured homes. The home in Figure 4-102 lost a gable roof over its entrance, asphalt shingles, and metal fascia along its eaves. Wind speeds were insufficient to displace the home from its foundation. Temporary roof repairs completed prior to the MAT's visit prevented full assessment of the extent of roof damage.

The styles of manufactured home installations impacted performance during Hurricane Katrina. When properly anchored, manufactured home damage under wind loads was less significant. Unanchored or improperly anchored homes or homes with damaged anchors were prone to wind-related damage. The home in Figure 4-104 was installed with ground anchors. The heads of the ground anchors extended several inches above the ground (see Figure 4-105). The straps that connect the ground anchors to the frame were loose and would allow the home to move several inches before the ground anchors would begin to resist wind loads.

Figure 4-100. Manufactured home rolled over by Hurricane Katrina's winds (estimated wind speed: 110 mph. Chalmette, Louisiana)

Figure 4-101. The metal straps were spaced approximately 13 feet on center on a manufactured home located in Exposure C (estimated wind speed: 110 mph. Chalmette, Louisiana).

Figure 4-102. Newer manufactured home located in Exposure C that lost the gable roof over its entrance (estimated wind speed: 110 mph. Plaquemines Parish, Louisiana)

Figure 4-103. Newer manufactured home located in Exposure C with roof covering damage (estimated wind speed: 110 mph. Plaquemines Parish, Louisiana)

Figure 4-104. Manufactured home located in Exposure C installed with ground anchors (estimated wind speed: 110 mph. Plaquemines Parish, Louisiana)

Figure 4-105. Ground anchors at manufactured home located in Exposure C (estimated wind speed: 110 mph. Plaquemines Parish, Louisiana)

Figure 4-106 shows an older manufactured home secured with straps that connect both the home's frame and its walls to the anchors set in the concrete slab. The older home was within 10 miles of the storm's path, but remained on its foundation piers and did not experience significant damage. Most of the straps were tight and there was no evidence of home movement.

4.2.1.4 Wood-Framed Non-Residential Buildings

Wood-framed commercial buildings failed similarly to wood-framed residential buildings. Roof structure uplift failures and gable wall end failures like the ones shown in Figures 4-107 through 4-109 were observed. In Figure 4-109, the bottom chords of the roof trusses appear to have buckled under uplift forces. Insufficient truss bracing is suspected.

Figure 4-106.
Manufactured home located in Exposure C secured to taut anchors in the concrete slab (estimated wind speed: 110 mph. Plaquemines Parish, Louisiana)

Figure 4-107.
Failure in a wood-framed commercial building. Trusses lost roof sheathing, allowing trusses to tip over (estimated wind speed: 120 mph. Ocean Springs, Mississippi).

Figure 4-108.
Roof uplift failure in wood-framed commercial building (estimated wind speed: 115 mph. Slidell, Louisiana)

Figure 4-109.
Three-story wood-framed commercial building lost roof sheathing and the exterior wall collapsed (estimated wind speed: 105 mph. New Orleans, Louisiana)

SOURCE: NIST

4.2.2 Engineered Buildings

Engineered buildings include buildings that are designed by registered architects and professional engineers. The amount of design professional involvement in engineered buildings can vary. In general, fully engineered buildings include schools, larger office buildings, hospitals, correctional institutions, and critical and essential facilities where great attention is given to compliance with building codes and standards. Fully engineered building types are typically designed with heavy structural elements such as concrete, steel, and masonry. In fully engineered buildings, design professionals are often involved with nearly all aspects of design and may be involved with construction to ensure that the designs are properly implemented.

Partially engineered buildings include those that receive limited engineering. Often, engineering involvement is limited to the minimum required by local building officials. Partially engineered (or sometimes called lightly engineered) buildings typically include fast food restaurants, strip malls, or large department stores.

While Katrina's winds caused widespread damage to engineered structures, most of the damage was to building envelopes. Structural damage was much less common.

4.2.2.1 Reinforced Concrete, Heavy Steel, and Masonry Buildings

Reinforced concrete is a favored method of construction for resistance to wind loads. In general, reinforced concrete and heavy steel buildings observed by the MAT performed well structurally. While the MAT noted little structural damage to most buildings constructed with reinforced concrete frames, extensive damage to unreinforced masonry buildings was observed. Most of the beach-front casino hotels were constructed of reinforced concrete and survived Katrina's winds, but were inundated with water and experienced envelope failures (see Figure 4-110). Though reinforced concrete buildings are normally quite expensive to construct, new methods have been developed to facilitate the ease of forming, reduce the sizes of members, and reduce the amount of labor required.

Probably the most successful concrete structures observed by the MAT were the buildings shown in Figures 4-110 through 4-112. At the building shown in Figure 4-111, reinforced concrete shear walls and post-tensioned concrete slabs constructed on "flying forms" were used on this luxury condominium complex. The folded concrete shell and circular plan of the Catholic church on Highway 90 in Biloxi (Figure 4-112), though subjected to storm surge, was resistant to Katrina's winds.

> A flying form is a large reusable form for pouring multiple floors in high-rise buildings. The form is used on one floor and then "flown" into place on a higher level with an on-site crane.
>
> Pre-stressing strengthens concrete by reducing potentially damaging tension stresses in concrete. Post-tensioning is a type of pre-stressing where tension is introduced after (or post) the concrete cures. Post-tensioning involves placing steel cables (tendons) in special ducts (or sheaths) before the concrete is placed. After the concrete is placed and cured, the tendons are tensioned to pre-stress and strengthen the concrete. The small dots at the ends of the floor slabs in Figure 4-111 are the ends of the pre-stressing tendons.

4.2.2.2 Unreinforced Masonry Buildings

Damage to unreinforced masonry buildings was typically initiated when wind forces exceeded the strength of connections between roof framing and bearing walls or exceeded the tensile strength of the top of the walls themselves. Overloading the connections allowed the roof structures to lift. Once the roof structures lifted, lateral support was lost for the top of the bearing walls, and the walls collapsed (see Figure 4-113). This mode of failure is often observed after wind events. Because the weight of many roof systems is less than the total uplift forces from wind, a structural failure takes place whenever the connections are not designed to resist the net uplift forces.

The MAT observed wind-related damage to many buildings with unreinforced masonry walls; however, the MAT did not concentrate their efforts in documenting collapsed unreinforced masonry walls because the failure mode is well understood, and improvements have been incorporated into the current codes. Therefore, only a few examples of these failures are included in this report.

Figure 4-110.
This casino located in Exposure C suffered water inundation and wind damage to wall finishes (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 4-111.
East tower located in Exposure C under construction with reinforced concrete and post-tensioned floor slabs. The east tower was water-inundated on the first floor and suffered only minor wind damage to the roof covering of the finished tower (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 4-112.
St. Michael's Catholic Church on Beach Boulevard (Highway 90), with its concrete shell roof and supporting concrete columns, was undamaged by Katrina's winds, but was severely damaged by the storm surge (estimated wind speed: 120 mph. Biloxi, Mississippi).

Figure 4-113.
Wind-induced damage to older unreinforced masonry building located in Exposure C (estimated wind speed: 130 mph. Gulfport, Mississippi)

Other failure modes were observed in unreinforced masonry construction. In Figure 4-114, the parapet failed and visibly rotated toward the center of the building. The parapet portion of the wall acts as a cantilever above the roof structure. In this structure, the roof side of the parapet was exposed to the relatively high eave zone wind pressures and to bending moments. With no reinforcing steel present, the parapet failed in bending. Like other failures in unreinforced masonry, this type of failure is well known and is easily avoided with better construction measures.

The MAT investigated numerous heavy masonry buildings, most 30 years old or older. The Hancock County Courthouse in Bay St. Louis, Mississippi (see Figure 4-115) received wind damage to its roof and most of its windows. The Hancock Bank Building in Pass Christian, Mississippi (see Figure 4-116), an early 20th century building, successfully survived Katrina, but suffered water inundation and wind damage to glazing, and loss of one suspended awning. The First Presbyterian Church of Gulfport, Mississippi (see Figures 4-117 and 4-118) was constructed of grouted multi-wythe brick masonry. Though the chapel lost its roof covering and decking, the heavy timber purlins and steel trusses remained firmly attached to the load-bearing masonry walls.

Figure 4-114. Unreinforced masonry parapet failure on a building located in Exposure C (estimated wind speed: 130 mph. Gulfport, Mississippi)

Figure 4-115. Hancock County Courthouse located in Exposure C with roof and windows damaged by wind and windborne debris (estimated wind speed: 125 mph. Bay St. Louis, Mississippi)

Figure 4-116.
Heavy masonry Hancock Bank Building located in Exposure C on Highway 49. Note the location of a missing awning (circle) and damaged windows (arrows) (estimated wind speed: 130 mph. Pass Christian, Mississippi).

Figure 4-117.
Gulfport First Presbyterian Church with wind damaged roofs. Note the wind damaged roof covering (circle) and the missing roof decking (arrow) (estimated wind speed: 130 mph. Gulfport, Mississippi).

Figure 4-118. Grouted multi-wythe masonry walls. Note loss of roof decking (estimated wind speed: 130 mph. Gulfport, Mississippi).

4.2.3 Pre-Engineered Metal Buildings

PEMBs are normally used for purposes such as warehouses, storage facilities, airplane hangars, and other similar open interior uses. Due to their relatively low cost and relatively short construction time, PEMBs are being used for other facilities like schools, retail, and low-rise commercial buildings. These buildings are easily recognized by their metal walls and roof coverings, tapered rigid frames, and long spans with open spaces. Secondary structural members consisting of girts and purlins are installed to support the metal siding and roofing panels.

Some components in PEMBs must perform more than one function (e.g., roof panels in PEMBs must function both as the roof deck and as the roof covering); in other styles of construction, two separate systems function as the roof deck and roof covering. This dual function reduces redundancy in a building and can increase its vulnerability to damage from wind, windborne debris, and water entry.

Like previous post wind event assessments, the MAT observed failures in several older buildings and PEMBs were no exception. Older PEMBs are generally those constructed before the mid-1980s when less attention was given to wind forces and less was known about wind effects on buildings. Although many older PEMBs were heavily damaged, newer ones performed much better.

Figures 4-119 through 4-121 show the relative performance of newer versus older PEMBs. In Figure 4-119, the PEMB on the left (built in 2001), was not damaged significantly by wind, but it was flooded; the building on the right (estimated to be 30 years old) lost its roof panels and was significantly damaged.

Figure 4-119.
Relative performance of older and newer PEMBs located in Exposure C. The 5-year old building on the left was not damaged by winds; the 30-year old building (estimated) on the right lost its roof (estimated wind speed: 130 mph. Pass Christian, Mississippi).

Figure 4-120.
Undamaged newer PEMB constructed in 2001 (estimated wind speed: 130 mph. Pass Christian, Mississippi)

Figure 4-121
Severely damaged PEMB estimated to be 30 years old (estimated wind speed: 130 mph. Pass Christian, Mississippi)

Most failures either involved connections between the metal roof panels and their supporting purlins, or between the purlins and the steel moment frames, as shown in Figures 4-122 through 4-125. Connection failures between the base of the moment frames and supporting footings were observed, but were much less common than connection failures higher up in the structure (Figure 4-124).

Though not a commercial-use structure, the airplane hangar with a second floor residence was constructed of a light steel pre-engineered frame (see Figure 4-126). This home/hangar, along with others in the Diamondhead, Mississippi, fly-in residential community, was devastated by wind and water.

Figure 4-122.
Failure of older (1974) pre-engineered metal building (estimated wind speed: 130 mph. Gulfport, Mississippi)

Figure 4-123.
Connection failures between roof panels and purlins and between purlins and rigid frames (estimated wind speed: 130 mph. Gulfport, Mississippi)

Figure 4-124.
Anchor bolt connection failure between steel base plate of the pre-engineered metal building frame and foundation (estimated wind speed: 130 mph. Gulfport, Mississippi)

Figure 4-125.
Wall and roof covering failure in pre-engineered metal building. Moment frames not visibly damaged (estimated wind speed: 125 mph. Stennis Airport, Hancock County, Mississippi).

SOURCE: NIST

Figure 4-126.
Residence/hangar constructed of a light-steel pre-engineered frame (estimated wind speed: 120 mph. Diamondhead, Mississippi)