4

Structural Systems Performance

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

Flood impacts are discussed in Section 4.1. Subsections 4.1.1 and 4.1.2 discuss the flood impacts on single-family and multi-family residential buildings, respectively. Subsection 4.1.3 discusses flood impacts to miscellaneous structures associated with residential buildings, such as bulkheads, non-structural slabs, breakaway walls, and utilities. Section 4.1.4 discusses impacts of debris borne by floodwaters. Flood impacts on commercial buildings were similar to those on residential buildings; thus, commercial buildings are not discussed separately. Wind impacts are discussed in Section 4.2.

4.1 Flood

4.1.1 Single-Family Residential Buildings

Single-family buildings throughout the western sections of the Florida Panhandle and the coastal areas of Baldwin County, Alabama, incurred significant damage caused by high floodwaters with wave action and debris impacts. In general, the damage resulted less from foundation failures (although these were observed) than from the high flood elevations (which exceeded the BFEs) and from the impacts of wave action and debris. In coastal back bay areas designated as flood Zones AE, severe damage was caused by wave action and debris generated from docks and damaged buildings, including debris originating on the barrier islands that washed across the sounds and bays.

Many structures constructed on pile foundations performed well, especially those buildings built several feet above the minimum flood elevation standards. Structural failures resulting from flooding generally correlate with the first floor elevation of the building, although some failures also resulted from erosion and improper connections between structural components. In general, the lower the elevation of the first floor of a building, the more the building was damaged. In coastal areas where the lowest floor elevation was lower than the wave crest elevation, the building was not only inundated by flooding, but also extremely susceptible to additional lateral and impact loads from wave action, floodborne debris, and velocity flow.

4.1.1.1 Pile Foundations

Pile foundations were the most common foundation type for residential buildings on the barrier islands and were also common for newer construction on the bay and sound shorelines. Generally, buildings constructed on pile foundation systems performed well, especially those constructed with the lowest floor several feet above the BFE. Exceptions were buildings with shallow pile embedment on the barrier islands which experienced significant erosion and pile-supported buildings anywhere the wave crests exceeded the elevation of the lowest floor.

Barrier Islands

Figures 4-1 through 4-3 show barrier island houses that experienced destruction of enclosures below the houses. Structurally, these houses performed well, but the breakaway walls, non-structural parking slabs, and the contents below the lowest floor were generally destroyed. This type of damage is anticipated when floodwaters and waves rise above the parking slab and batter the breakaway walls forming a below BFE-enclosure. Figure 4-4 shows another problem observed by the MAT – survival of residential buildings on pile foundations, but damage or destruction of pile-supported decks. Deck failure was sometimes due to deck foundation failure (piles supporting decks often are smaller and shorter than the building foundation) and sometimes to wind failure (uplift). In some instances, loss of decks led to envelope or structural damage to the houses.

In instances where pile-elevated buildings had their lowest floor at or just below the wave crest elevation during Ivan, damage to the floor system was observed. Figure 4-5 shows a typical example, where the piles and shore-perpendicular floor beams performed as intended, but where the wave crests struck the shore-parallel floor joists. The lateral forces exceeded the capacity of the joist connections, and the joists were pushed landward. The collapse of the joists was usually accompanied by damage to the floor and the building interior.

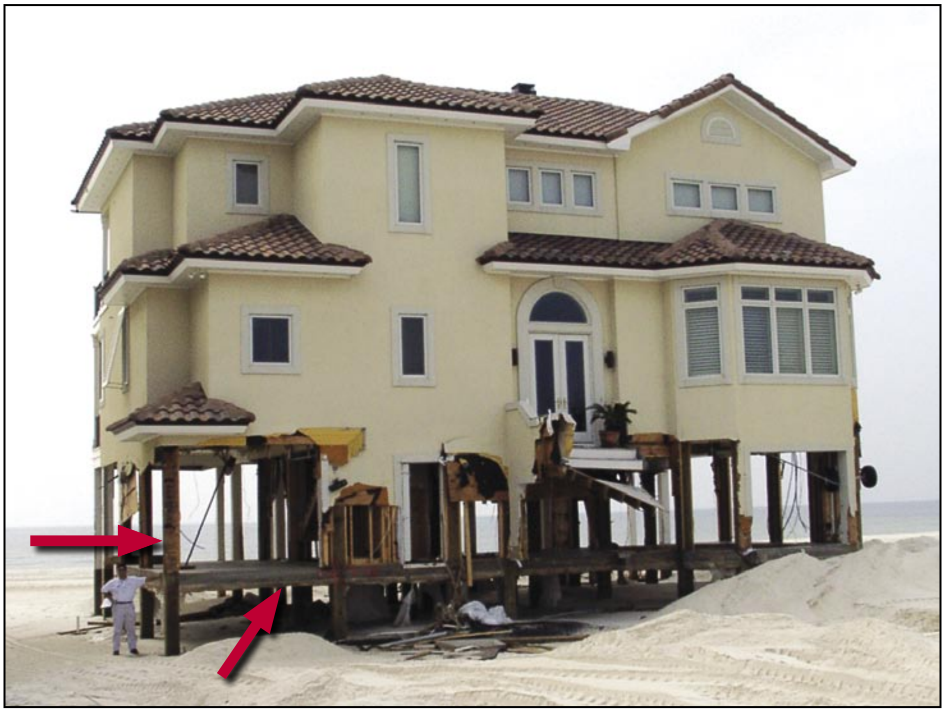

Figure 4-1.
House on a pile foundation that performed well. It experienced 5 feet of erosion that resulted in failure of a non-structural slab. Breakaway walls in lower level also failed as expected. (Gulf Shores)

Figure 4-2.
House on pile foundation, adjacent to breach in the barrier island, that experienced erosion and significant non-structural damage below the lowest floor (Gulf Shores).

Figure 4-3.
These pile-elevated houses in an area mapped as Zone VE at Pensacola Beach successfully resisted flood forces. Loss of breakaway enclosures and garage doors below the lowest floors occurred, as expected. (FL DEP Photo)

Figure 4-4.
Row of newer houses on pile foundations that experienced significant damages below the lowest floor, but overall the pile foundation systems performed well. Improper pile embedment for decks remains a concern as shown in the two houses in the center; one house shows the deck is sagging, and the other deck was destroyed. (Gulf Shores)

Figure 4-5.
Floor joists were pushed landward when the wave crest elevation was above the floor beam. (Gulf Shores)

Erosion can have a significant impact on the performance of pile foundations that are not embedded deeply enough in the soil. Many newer buildings with deep pile foundations performed well; however, there were numerous older buildings that lacked sufficient pile embedment to account for the loss of soil due to erosion and scour. In these instances, permanent deformation or failure of the foundation resulted. Figures 4-6 through 4-9 show several examples of failure of the pile foundations – either under buildings or under decks – that lacked sufficient embedment depth and structural capacity to resist Ivan's flood and wind forces.

Figure 4-6.
Significant erosion caused the non-structural parking slab to fail, and insufficient pile embedment caused the structure to lean. The high storm surge and waves caused destruction of the enclosure below the lowest floor. (Orange Beach)

Figure 4-7.
Erosion contributed to loss of the porch, failure of the retaining wall and non-structural parking slab, and destruction of the enclosure below the first floor. The main structure remained standing, but appears to have sustained some envelope damage when the porch failed. (Orange Beach)

Figure 4-8.
The pile foundations in the foreground failed. These houses were washed away (see Figures 3-2 and 4-9).

Figure 4-9.
These houses floated off their pile foundations (shown in Figures 4-8 and 3-2), probably a result of inadequate pile embedment.

Bay and Sound Shorelines

Pile-foundation performance along inland bays and sounds varied depending on the flood level, the pile diameter, and pile-to-beam connections. Most of the pile-elevated houses observed by the MAT along bay and sound shorelines were probably constructed in Zones A, B, or C; V Zones mapped along the bay and sound shorelines were relatively narrow, and relatively few houses were actually constructed in V Zones. However, many of the areas mapped as Zone A sustained V-Zone conditions during Ivan, and those areas mapped as Zone V usually sustained flood conditions far worse than those indicated by the FIRM. Where floor elevations were below the wave crest elevation, buildings were damaged or destroyed; where small diameter piles were struck by waves and large debris, they failed; where connections at the tops of the piles were inadequate, they failed.

As with the barrier islands, most of the pile foundations along bay and sound shorelines performed well where the lowest floor was elevated several feet above the BFE. In other cases, where pile-elevated houses were at or near the BFE, they often were heavily damaged by waves and debris (see Figures 4-10 and 4-11), sometimes torn completely from the pile foundations (see Figures 4-12 and 4-13).

Figure 4-10.
House constructed on a pile foundation in a V Zone along Escambia Bay. The house was apparently built in compliance with V-Zone requirements (BFE of 12 feet NGVD), but still experienced wave impacts on the elevated first floor of the building. (Floridatown)

Figure 4-11.
Damage to pile-supported house on a bay shoreline, when flooding and waves exceeded the lowest floor elevation (Gulf Breeze, Pensacola Bay)

Figure 4-12.
House at left (circle) was torn from its pile foundation. New houses under construction (arrows, see Figure 4-31 also) survived Ivan (Big Lagoon).

The destroyed house on the left side of Figure 4-12 was in the Grande Lagoon neighborhood, approximately ¾ mile across Big Lagoon from the barrier island, Perdido Key. Perdido Key was completely overwashed by Ivan, and stillwater flood levels in the vicinity of Grande Lagoon were approximately 13 to 14 ft NGVD (see Figure 1-11), with wave crest elevations higher. Flood hazard zones and BFEs shown on the FIRMs for this area ranged from VE, elevation 11 feet NGVD, to AE, elevation 9 feet NGVD. Figure 4-13 shows the same house (circled) with several nearby, pile-elevated houses that were also destroyed. It should be noted that some older but intact houses in the neighborhood were observed to have poor connections between the floor beams and the elevated houses. Wind might also have contributed to the structural failures seen in Figures 4-12 and 4-13.

Figure 4-13.
Same destroyed house as in Figure 4-12 (circled). Note adjacent pile-elevated houses near shoreline, also destroyed (Big Lagoon).

Another nearby neighborhood also illustrates the value of a sound pile foundation along bay and sound shorelines. Figure 4-14 shows an older pile-elevated house near the east end of Seaglade Drive, approximately one mile east of the Grande Lagoon neighborhood and exposed to similar flood conditions during Ivan. This house is in an area mapped as Zone AE, elevation 9 feet NGVD. The enclosure at ground level was destroyed, but, otherwise, the house sustained little flood damage.

Figure 4-14.
House constructed on piles several feet higher than the BFE. Floodwater, waves, and debris caused damages to the ground level enclosed area of the house, but not to the elevated portion.
(Big Lagoon)

Figure 4-15 shows the region just to the west of the house in Figure 4-14. Older unreinforced masonry houses on slab foundations (arrows) were destroyed, but other houses elevated on piles above the BFE (circled) survived. MAT team members observed many debris scars 5-to-7 feet above the base of trees in the area, giving an indication of flood depths during Ivan. Debris scars were also evident on the underside of the joist sheathing of the house circled on the right side of Figure 4-15. The house was elevated one full story to allow for under-house parking. The dashed line in Figure 4-15 shows the landward limit of floodborne debris in the area; Figure 4-16 shows some of the debris.

Figure 4-15.
Area just to the west of the house shown in Figure 4-14. Pile-elevated houses above the BFE (circled) survived, while older houses on slab foundations were destroyed. Dashed line indicates landward limit of debris that washed through the area.

Figure 4-16.
Ground view of some of the debris shown in Figure 4-15.

Another location visited by the MAT along the north shoreline of Big Lagoon, was the Sinton Drive area, approximately 1.5 miles east of Seaglade Drive. Flood damages in the Sinton Drive area were consistent with those observed at Grande Lagoon and Seaglade Drive: survival of pile-elevated houses several feet above the BFE (see Figure 4-17), damage to houses elevated at or near the BFE (see Figure 4-18), and destruction of older houses at or near grade. The flood hazard zone and BFE for the house in Figure 4-17 are AE, elevation 8 feet NGVD, but this area experienced V-Zone conditions, i.e., water levels close to 14 feet NGVD with waves and floodborne debris.

Figure 4-17.
This house located near Sinton Drive successfully resisted flood forces since it was elevated higher than the BFE on piles (note the wind damage: loss of vinyl siding, soffit and roof covering). Lower, adjacent houses (see Figure 4-18) were destroyed.
(Big Lagoon)

Figure 4-18.
This photo shows the destroyed building adjacent to the house in Figure 4-17. It was destroyed (knocked off the masonry pier foundation) by some combination of storm surge, wave and debris impacts, and wind.
(Big Lagoon)

4.1.1.2 Slab on Grade

Buildings constructed with slab-on-grade foundations were widely observed throughout the affected area, and generally fell into two classes: 1) pre-FIRM houses inside and outside the SFHA, and 2) post-FIRM houses outside the SFHA. Many of these buildings sustained significant damage or were destroyed. In numerous cases, the high level of damage was associated with water levels several feet above the slab, accompanied by waves and floodborne debris (see Figures 4-19 through 4-22). Inundation-only damage was observed in flooded houses far from the shoreline (see Figure 4-23). Slab failure due to erosion was frequently evident on the barrier islands, but less so on the bay and sound shorelines.

Figure 4-19.
The pre-FIRM building constructed on a slab foundation (foreground) was completely destroyed, yet the adjacent building constructed on piles at a higher elevation remained intact and suffered relatively little damage. (Big Lagoon)

Figure 4-20.
Destruction of slab-on-grade house (circled) in the Grande Lagoon neighborhood. Adjacent houses elevated on piles above the BFE sustained destruction of ground level enclosures and some wind damage, but survived. (Big Lagoon)

Figure 4-21.
The unreinforced masonry pre-FIRM building in the foreground was swept off its slab foundation during Ivan. On the adjacent building, the lowest floor was gutted and the walls ripped out by wave and debris impacts. (Oriole Beach)

Figure 4-22.
This slab-on-grade building located on the back side of the barrier island but directly on the sound was heavily damaged by wave action. (Pensacola Beach)

Figure 4-23.
The slab-on-grade building located near the back side of the barrier island was protected from wave action by other houses, but had 4 to 5 feet of water inside. (Pensacola Beach)

4.1.1.3 Stem Walls

Overall, the MAT observed that stem wall foundations performed well against the storm surge, and wave and debris impacts near bay and sound shorelines. However, the MAT observed several buildings where the stem wall foundations survived, but the buildings atop the foundations were destroyed (see Figure 3-8) or heavily damaged (see Figures 4-24 and 4-25). In one instance, a stem wall foundation was used to elevate a house (under construction) above the BFE, and damage to the unfinished house was relatively minor – porch columns and one exterior wall were damaged, apparently by waves or debris slightly exceeding the top of the foundation (see Figure 4-26).

In all cases observed by the MAT, scour around the stem wall foundations was limited, and foundation failures did not occur; however, this type of foundation would be expected to be vulnerable to scour and erosion on barrier islands or on higher relief, sloping bay shorelines.

Figure 4-24.
House constructed in a Zone AE on a stem wall foundation, which survived, although high floodwaters with debris and wave action caused major damage (Big Lagoon)

Figure 4-25.
Stem wall foundation where floodwater exceeded required flood elevation by approximately 4 feet (Garcon Point, Escambia Bay)

Figure 4-26.
This stem foundation elevated the house above the BFE and performed well. The house, which was under construction at the time of Ivan, sustained minor flood damage to the walls and the columns under the porch. (Tiger Point, Santa Rosa Sound)

4.1.1.4 Piers

Many pier foundations were observed to perform poorly, although many of these foundations were used for older, pre-FIRM structures and were minimally reinforced or unreinforced. Figures 4-27 and 4-28 show examples of pier foundation failures at older structures. Figure 3-3 shows a newly constructed house on piers that was severely damaged by waves and debris that exceeded the height of the lowest floor although the piers themselves remained intact.

Pier foundations are typically constructed on shallow footings, which are prone to failure due to erosion and scour. Tall pier foundations are also prone to failure from overturning when flood loads are applied to the building. Pile foundations generally perform better than pier foundations, especially when constructed in sandy material, which is vulnerable to erosion and scour (see Figure 4-29). Pile foundations provide much more flexibility and cost efficiencies to account for increases in elevation of the finished floor of the structure and for additional embedment to allow for any erosion and scour that will likely occur on sandy beaches.

Figure 4-27.
Unreinforced pier foundations failed due to scour at the footing and flood levels exceeding the floor elevation (Oriole Beach).

Figure 4-28.
Center pier failed causing the elevated floor to collapse. Other adjacent buildings were elevated on pilings and solid foundation walls; the piers performed better than the solid walls, but not as well as the pilings (Santa Rosa Sound)

Figure 4-29.
Tall, lightly reinforced masonry piers failed due to lateral loads from surge and wave action. The pile supported houses under construction in the background are the same ones indicated (by arrows) in Figure 4-12. (Big Lagoon)

Manufactured houses placed on unreinforced, dry-stacked block piers were observed to shift in some cases due to the storm surge and wave action effects. Figures 4-30 through 4-32 provide several examples of piers shifting under manufactured houses. These types of piers are not suitable for coastal areas.

Figure 4-30.
Manufactured home park where houses experienced storm surge, scour, and foundation collapse (Orange Beach)

Figure 4-31.
Unreinforced, dry-stacked block piers slid off of footings. (Orange Beach)

Figure 4-32.
Dry-stacked pier failure (Orange Beach)

4.1.2 Multi-Family Residential Buildings

With a few exceptions, newer multi-family structures on the barrier islands generally withstood Ivan's flood and erosion effects quite well, with the exception of lower floors of some buildings that were heavily damaged when Ivan's waves exceeded local BFEs and when erosion undermined nonstructural slabs. Many multi-family buildings, however, sustained wind damage at less than design wind speeds (see Section 4.2).

One class of multi-family buildings sustained significant flood damage: those buildings constructed on shallow foundations on the barrier islands. Ivan caused up to eight feet or more of vertical sand loss in some beachfront areas, and several buildings not constructed with deep foundations collapsed. This was the first time that MAT members had seen catastrophic failures of multi-family buildings due to erosion. In some areas (e.g., Pensacola Beach, central Gulf Shores), undermining failures of some buildings on shallow foundations were probably prevented by recent beach nourishment projects.

The observed damages are discussed below by foundation types: shallow foundation and pile supported. Damages to bulkheads and pools are discussed in 4.1.3.1.

4.1.2.1 Shallow Foundations

Hurricane Ivan produced significant storm surge and high waves that caused widespread and severe erosion along the barrier islands of Baldwin County, Alabama, and the northwestern Florida Panhandle. In general, sand loss up to 8-10 feet high was observed, and 100 feet or more of dune loss was observed in some areas. Due to the severe sand loss, buildings constructed on shallow foundations experienced significant failure and collapse. Many of these buildings were constructed in flood Zones B or C, in which the NFIP has no specific foundation requirements. However, the FBC requires buildings constructed seaward of the CCCL to be constructed on pile foundations. In Alabama, where coastal construction requirements are not as strict as Florida's CCCL, severe building damage occurred as a result of erosion to soils supporting shallow foundations and surrounding shallowly embedded pile foundations. Figures 4-33 and 4-34 show a post-1997 building that was constructed on a shallow foundation in a Zone B. This building experienced total collapse during Hurricane Ivan. Figure 4-35 shows a similar collapsed building and the success of the adjacent buildings constructed on piles and columns.

Figure 4-33.
Total collapse of 5-story building on a shallow foundation (Orange Beach)

Figure 4-34.
Close-up of building shown in Figure 4-33 (Orange Beach)

Figure 4-35.
Shallow foundation failure. Note success of pile support structures in the background. (Orange Beach - Perdido Key)

Figure 4-36 shows before and after Hurricane Ivan photos of a 5-story building that was constructed on a shallow foundation in flood Zone C in the late 1990s. The lowest floor elevation was 19 feet NGVD, several feet above the highest BFE shown nearby on the 1992 FIRM in effect when the building was constructed. However, the supporting soil was undermined during Ivan and the seaward two-thirds of the building collapsed. Review of the permitting file shows initial calculations indicated erosion would occur beneath the seaward edge of the foundation during a base flood event. Sand was added to the dune to compensate for the potential undermining, but it was obviously a poor decision to rely on a shallow foundation and a crude erosion calculation. Figure 4-37 shows another multi-family building on a shallow foundation damaged by Hurricane Ivan. In this case, the storm undermined just the front of the building, causing it to settle, and damaging all eight stories.

Figure 4-38 shows ground and aerial views of older buildings at Pensacola Beach, elevated on masonry walls and columns atop shallow footings. The seaward row of buildings survived Hurricane Opal in 1995 but did not survive Ivan in 2004, due in large part to the severity of Ivan. This scene will be repeated less and less in the future since new construction on Pensacola Beach is restricted to pile foundations by the local unit of government, the Santa Rosa Island Authority (SRIA). SRIA has mandated V-Zone design and construction standards and required 1 to 3 feet of freeboard across the entire barrier island community (V Zones and A Zones) since before Hurricane Opal. After Ivan, SRIA is modifying their ordinance to require 3 feet of freeboard everywhere.

Figure 4-36.
Collapse of a 5-story building constructed on a shallow foundation. Arrows identify buildings before and after Ivan. (Orange Beach) Photo courtesy of USGS

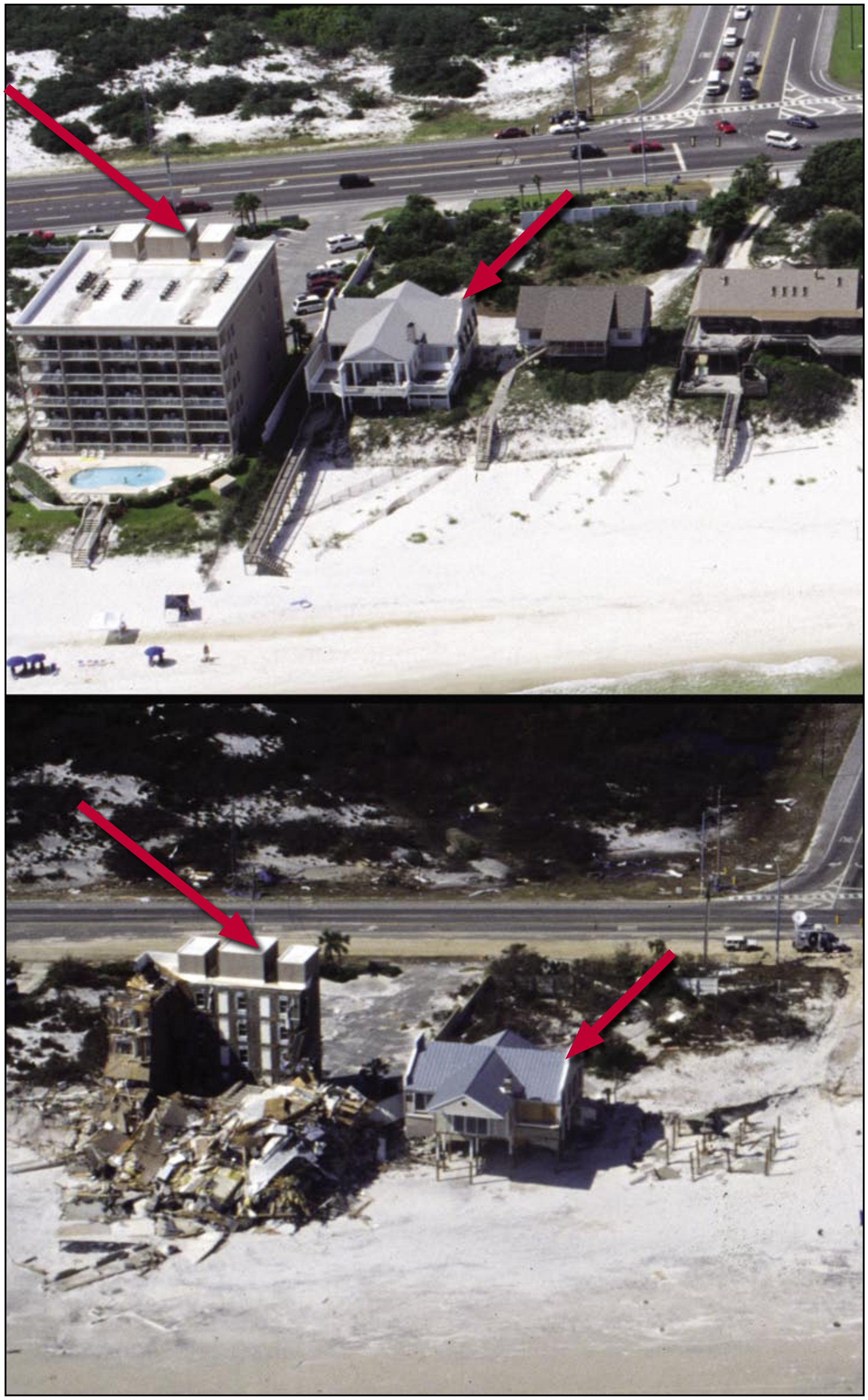


Figure 4-37.
Collapse of the seaward portion of a high-rise building supported by a shallow foundation (Perdido Key)


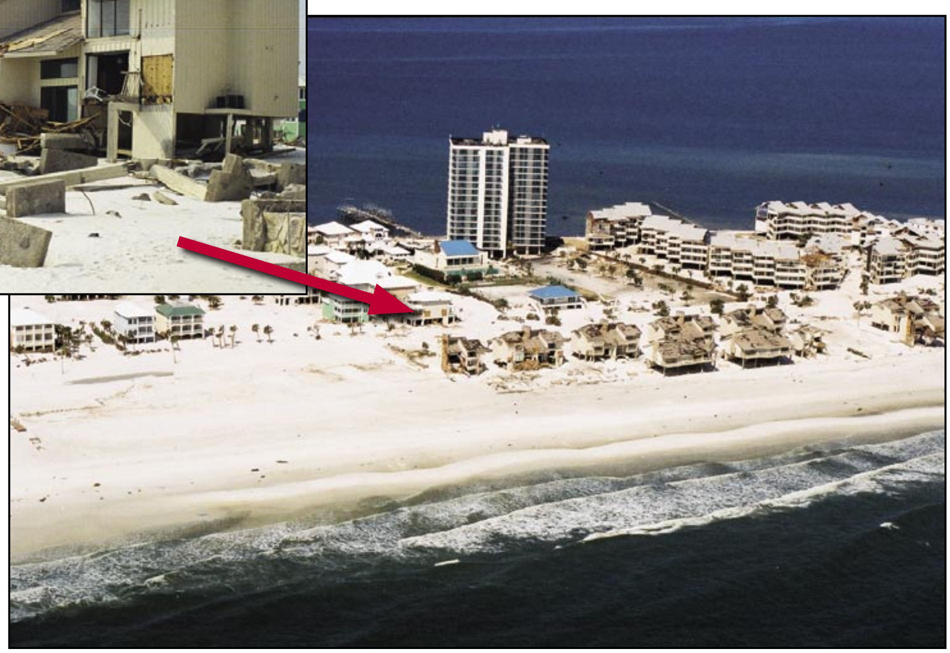

Figure 4-38.
Older buildings constructed on masonry columns and walls atop shallow footings (Pensacola Beach).

Although many multi-family structures were not affected by erosion during Ivan, many were affected by high winds, storm surge, waves, and floating debris. Figure 4-39 shows a building located on the north side of Pensacola Beach, near the Santa Rosa Sound shoreline. NFIP records indicate flood claims have been paid for units in the building on four occasions: September 1998 (Hurricane Georges), October 1995 (Hurricane Opal), August 1995 (Hurricane Erin), and September 1979 (Hurricane Frederic).

Figure 4-39.
This building has been flooded by Hurricane Ivan and four prior storms. (Pensacola Beach)

Figures 4-40 and 4-41 show another pre-FIRM multi-family building on a slab foundation that was heavily damaged by storm surge, waves, and debris, this one on the north side of Santa Rosa Sound.

Figure 4-40.
Multi-family building on a bay shoreline, heavily damaged by surge, waves, and floating debris (Oriole Beach, Santa Rosa Sound)

Figure 4-41.
Aerial view of building in Figure 4-40 (circled)

4.1.2.2 Pile Foundations

Pile foundations in multi-family structures generally performed very well, although the high storm surge elevations caused considerable damage to ground level enclosures and to some lowest floor living units, especially to those Orange Beach buildings constructed in flood hazard Zones B, C, or X, where BFEs had not been established. The use of pile foundations for multi-family buildings avoided the severe damage and collapse observed at buildings with shallow foundations but, by itself, was not sufficient to prevent loss of lowest floor living units. Full compliance with VE-Zone construction standards (e.g., use of a structural floor system and elevation of the lowest horizontal structural member above the wave crest elevation) was also necessary to prevent damage to those living units (see Figures 4-42 through 4-44). In some instances, buildings were sited far enough from the shoreline that erosion was not an issue, but Ivan's surge and wave action was still sufficient to damage the lower story.

Figure 4-42. Multi-story buildings on piles, impacted by storm surge, waves, and erosion, which damaged many lower area walls and floors (Orange Beach)

Figure 4-43. Although the pile foundation and structural elements survived, damage to lowest floor exterior walls, interior partitions, and floor slabs occurred during Ivan. (Orange Beach)

Figure 4-44.
Pile foundations alone are not enough; elevation of the lowest floor is also critical. The building on the left shows minimal damage, while the building on the right with the lower-level living units experienced significant non-structural damage. (Orange Beach)

A separate study of Orange Beach multi-story structures was undertaken to determine the extent and characteristics of lowest floor living unit damages (see Appendix F). The study examined 41 multi-story structures, not including the collapsed structures. Thirty-nine of the 41 buildings had a total of 233 living units at the lowest floor level. The buildings were constructed over the years in flood hazard zones B, C, AE, and VE, using high-rise construction techniques typical for their respective zones.

Approximately 80 percent of the lowest floor living units were destroyed by flood and/or erosion effects. Although most of the tops of the lowest floors were at or above the highest BFEs appearing on any of the FIRMs in the past 20 years, much damage was still sustained by the buildings, due to lowest floor collapse and/or stillwater levels during Ivan that exceeded BFEs by up to 2 feet (see Table 1-2 and Figure 1-8), with wave crest elevations higher yet.

Figures 4-45 and 4-46 show a pile and column supported building at Pensacola Beach that sustained little flood damage, despite severe scour around its foundation, since use of the grade level area was limited to parking and building access.

Figure 4-45.
This condominium on a deep foundation is located on the back side of the barrier island, north of Ft. Pickens Road. This building was severely damaged by wind, along with some utility damage in the lower level, and severe scour around the concrete pile caps. Since it was constructed on deep foundations and there were limited enclosures below the first floor, damage caused by storm surge was limited. (Pensacola Beach)

Figure 4-46.
Aerial view of the building shown in Figure 4-45 (FL DEP photo) (Pensacola Beach)

Figures 4-47 through 4-49 show examples of other flood and erosion damages that affected multi-family buildings on the barrier islands. Figure 4-47 shows a Perdido Key lower floor living unit that was flooded and buried in sand; no structural damage occurred to the building as a result, but the lower unit walls, fixtures, and contents were destroyed. Figure 4-48 shows several Orange Beach multi-family structures whose bulkheads, pools, decks, and lower floor spaces were damaged or destroyed. Figure 4-49 again illustrates the relative damages associated with deep and shallow foundations during Ivan; the 5-story building in the center (shallow foundation) collapsed, while the buildings on either side (deep foundations) sustained flood damage to the ground level enclosures and parking areas only.

Figure 4-47. Building with flood and wave damage to the lowest floor living units. Some units had up to two feet of sand deposited inside. (Perdido Key)

Figure 4-48. Most of the first floor units in these buildings were severely damaged (see Figures 4-53 and 4-54). (Orange Beach)

Figure 4-49.
Pile-supported buildings performed much better than buildings constructed on shallow foundations as shown in the building in the center, which collapsed. (Orange Beach)

4.1.3 Miscellaneous Structures

This section discusses observed damages and successes for various elements related to single and multi-family residential structures, including bulkheads, non-structural slabs, breakaway walls, and utilities.

4.1.3.1 Bulkheads

Bulkheads were used around many single-family and multi-family structures along the open coast in Gulf Shores and Orange Beach, Alabama. These structures were not observed as frequently along beaches in Florida due to state-mandated restrictions on coastal armoring. Their general purpose is to retain soil and provide protection from erosion. They are often used to contain sand that supports pool decks and non-structural parking slabs beneath buildings. In most cases, these walls were observed to have been damaged or destroyed by Ivan.

High storm surge, waves, and erosion resulted in frequent damages to bulkheads, pools, and pool decks. Figure 4-50 shows a typical pool failure. Lightweight bulkheads (particularly those constructed of vinyl and timber) sustained significant damage during Ivan (see Figures 4-51 and 4-52). Some concrete bulkheads failed, but the more substantial ones remained intact. However, even intact concrete bulkheads were sometimes overtopped and suffered erosion on the landward side (see Figures 4-53 and 4-54).

Figure 4-50. Typical pool failure (Pensacola Beach)

Figure 4-51. Retaining wall failure (Gulf Shores)

Figure 4-52.
Failure of vinyl bulkhead with concrete cap (Orange Beach)

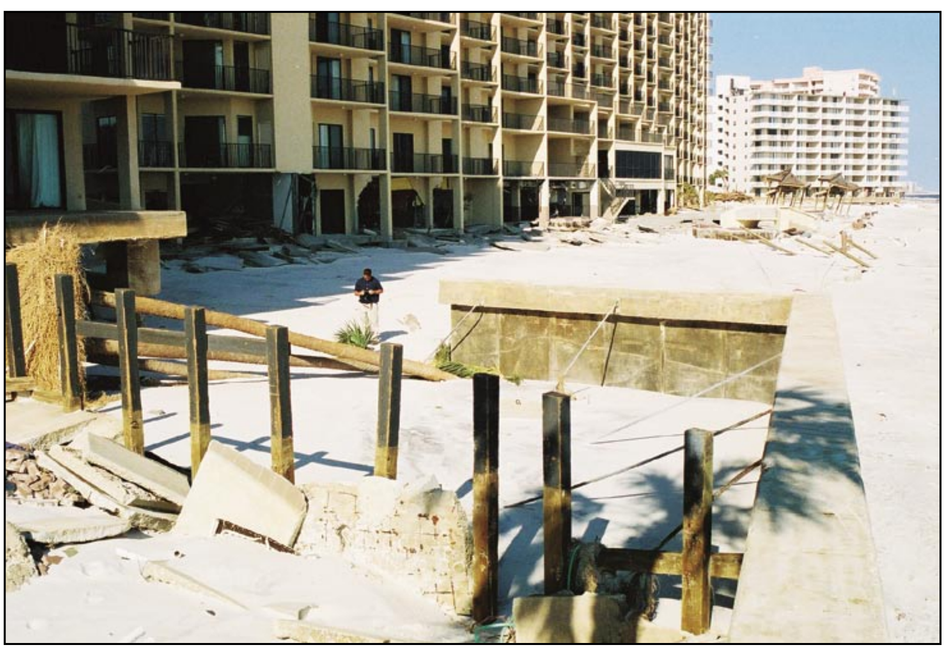

Figure 4-53.
Bulkhead remained intact, but short return wall allowed erosion behind the wall (Orange Beach)

Figure 4-54.
Bulkhead shown in Figure 4-53 remained in-place, but surge and wave overtopping, coupled with erosion at the short return wall, led to deck and retaining wall failure. (Orange Beach)

4.1.3.2 Non-Structural Slabs

Many pile-elevated single-family and multi-family buildings were constructed with non-structural parking slabs that relied on the underlying soil for support. When the underlying soil was washed away by Ivan, the slabs were undermined and almost always collapsed, as expected (some remained in place because they were tied to the pilings). Figures 4-55 through 4-58 show typical examples of the performance of these non-structural slabs.

Figure 4-55.
Sand below slab completely eroded away, causing the total failure of slab, but grade beams remained intact. (Gulf Shores)

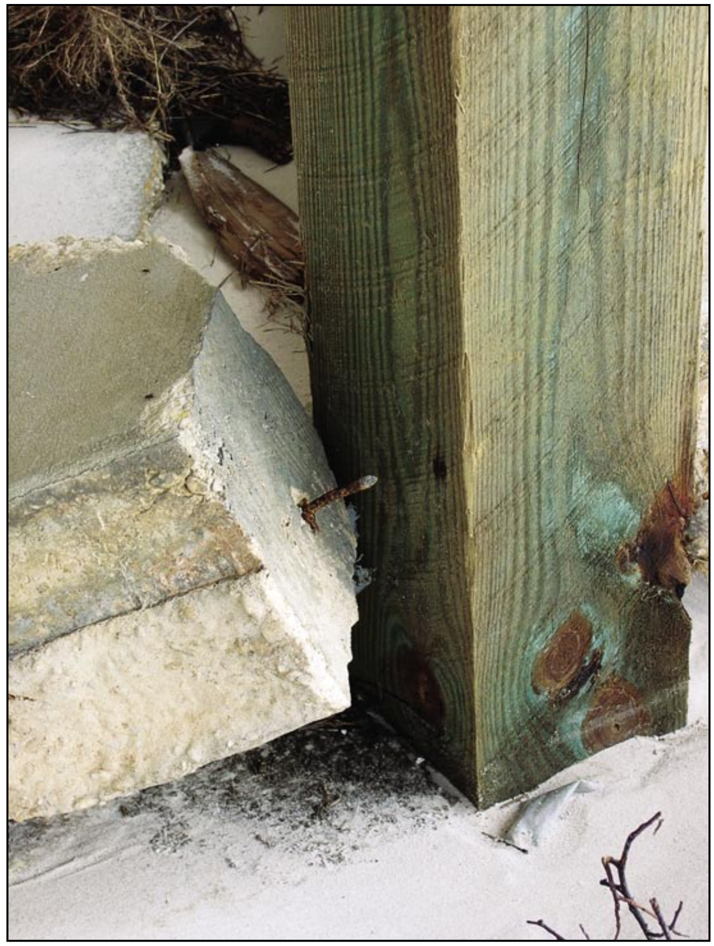

Figure 4-56.
Concrete slab partially separated from the pile even though it had been connected with a nail. These slabs should break free cleanly so they do not transfer flood loads to the foundation. (Gulf Shores)

Figure 4-57.
Typical non-structural concrete slab failure. Horizontal line indicates previous location of soil level and slab.
(Orange Beach)

Figure 4-58.
This slab failed but did not break into small pieces due to the reinforcing steel. The incomplete slab failure might have transferred flood forces to the foundation and contributed to the pile failure (piles in background were partially pulled out of the ground and are leaning). (Orange Beach)

4.1.3.3 Breakaway Walls

Walls used for enclosures below the BFE in areas designated as Zone VE must be designed to break away under the base flood. Breakaway walls are required in such instances so as to limit the transfer of wave and debris loads to the pile-elevated building foundation. The MAT observed the vast majority of breakaway walls functioned as intended (see Figure 4-59). However, in some instances the MAT observed some problems with breakaway wall design and construction. For example:

- Some breakaway walls did not break away cleanly, causing damage to wall finishes above the breakaway panels (see Figure 4-60).
- In some cases, utilities were connected to the walls, thereby preventing a clean wall failure (see Figure 4-61).
- In some cases, breakaway walls were installed across pilings instead of between pilings (see Figure 4-62).

Figure 4-59.
Failure of breakaway walls as designed (Gulf Shores)

Figure 4-60.
Poor detailing of the joint between the breakaway wall and the wall above contributed to loss of wall covering above the floor beam. (Pensacola Beach).

Figure 4-61.
Failure of interior partition to break away cleanly due to the attachment of utilities (Gulf Shores)

Figure 4-62.
Breakaway walls were nailed over the piles and floor beam, preventing a clean break. (Gulf Shores)

4.1.3.4 Utilities

The MAT observed significant damages to utilities at residential structures. The damages occurred due to the locations of utility components, their support, and their attachment. Figures 4-63 through 4-71 illustrate typical utility performance concerns observed by the MAT, all of which are discussed in FEMA 348, *Protecting Building Utilities from Flood Damage* and FEMA 55, *Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas.*

Figure 4-63.
Loss of condenser platform support. A cantilevered condenser support is recommended (see Figure 8-3). (Pensacola Beach)

Figure 4-64.
Diagonal condenser platform members are susceptible to wave and waterborne debris damage. Cantilevered condenser platforms are preferable (see Figure 8-3). (Gulf Shores)

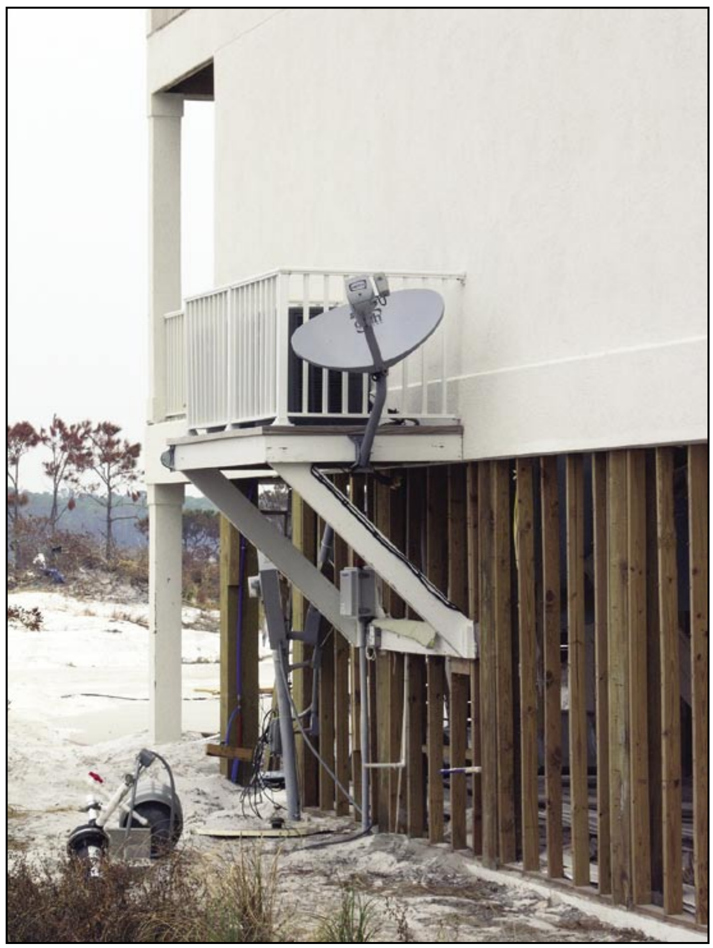

Figure 4-65.
Elevator system severely damaged by surge, waves, and debris (Gulf Shores)

Figure 4-66.
Loss of platform supports and air conditioning unit due to erosion and flood forces (Gulf Shores)

Figure 4-67.
House under construction at the time of Ivan (Big Lagoon). Note the condenser platform foundation survived the flood forces (masonry-column-supported house in the foreground was destroyed).

Figure 4-68.
Erosion and flood damage to multi-family electrical transformer and interior mechanical room (Perdido Key)

Figure 4-69.
Debris and sand in low-elevation mechanical room (Perdido Key)

Figure 4-70.
Damage to the electrical panel, but utility lines were located appropriately (beside an interior pile) (Pensacola Beach)

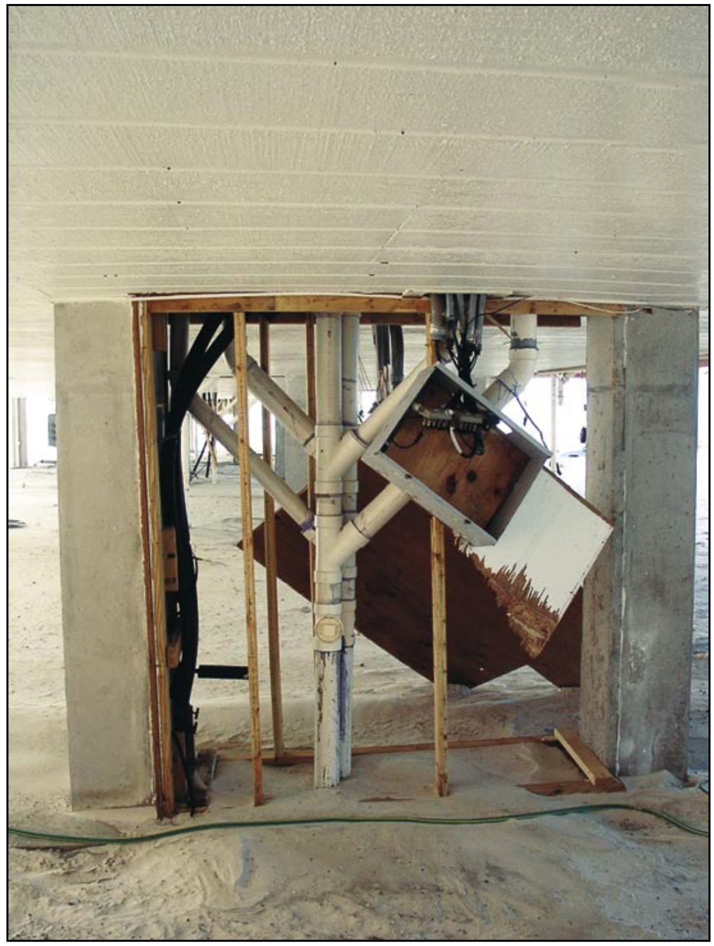

Figure 4-71.
Drain lines constructed between interior piles (which helped to protect them from flood forces), although electrical box was connected to plywood panel and was destroyed (Pensacola Beach)

4.1.3.5 Stairs

As coastal residences get more expensive and elaborate, the access stairs are getting larger and more substantial. In most cases, this does not present a problem; however, in some cases the stair structures could act as obstructions and could potentially transfer flood loads or cause wave deflection onto elevated structures. Figures 4-72 and 4-73, respectively, show examples of stairs that are and are not likely to act as obstructions.

Figure 4-72.
Massive stairs that will obstruct flows could deflect waves and debris into the elevated building. This type of stair structure is a violation of the V-Zone free-of-obstruction requirement. (Gulf Shores)

Figure 4-73.
Stairway structures (circled) that will minimize obstructions to flow and potential adverse effects on the elevated building (Gulf Shores)

4.1.4 Debris Impacts

Besides the building damage that resulted directly from storm surge, wave action, and erosion, severe damage was often caused by floating debris. Debris damage was common along the barrier islands, but seemed especially abundant in the back bays due to the large debris fields generated by more seaward damaged or destroyed buildings, decks, and dune walkovers, and by numerous docks along the bay shorelines. It was not uncommon to see debris from barrier islands that had floated across sounds and bays, damaging houses along those inland shorelines. Also, below-BFE enclosures were destroyed by the thousands throughout the storm impact area, adding significantly to the debris field available to damage other buildings.

Typical examples of debris impacts are shown in Figures 4-74 through 4-81.

Figure 4-74.
Large accumulation of debris trapped between house and dune walkover (Gulf Shores)

Figure 4-75.
Ground level photograph of debris shown in Figure 4-74 (Gulf Shores)

Figure 4-76.
Marine pile debris washed into this house in the back bay. (Oriole Beach)

Figure 4-77.
Same marine pile as shown in Figure 4-76. Note the size and the length of the pile, which caused significant damage. (Oriole Beach)

Figure 4-78.
Boats and dock debris from a marina struck this pile-elevated building, deforming floor beams, breaking joist connections, and scarring pilings. (Big Lagoon)

Figure 4-79.
Typical view of destroyed docks contributing to floodborne debris (Big Lagoon)

Figure 4-80.
Small stones from a nearby revetment were likely propelled by waves into this north-facing sound side house, breaking windows and sliding glass doors. (Gulf Breeze)

Figure 4-81.
The small stone revetment contributed stones which were propelled by waves and struck the house, shown in Figure 4-80 (Gulf Breeze)

4.2 Wind

4.2.1 Wood Frames

Most of the wood-frame buildings observed by the MAT were residential buildings, both single family and low-rise condominiums. Overall, the predominant wind related damage to these types of buildings was not structural failure, but a failure of the building envelope, which will be discussed in Chapter 5.

The wood-framed buildings observed by the MAT generally consisted of superstructures supported by the load-bearing exterior wood-framed walls. Building floors and roofs were supported by wood rafters or trusses and plywood decks. This type of construction is known as light-frame construction and consists of nominal 2-inch thick framing members spaced 12 inches to 24 inches together and normally concealed by interior finish materials such as plaster, gypsum board, or wood paneling. Figure 4-82 shows a diagram of a typical residential building designed to meet high wind requirements.

Wood is favored as both a structural material and a finish material for its economy, architectural flexibility, and aesthetics. Although it is rarely used today for commercial buildings, wood is a very favorable material to use for residential buildings. Most construction contractors are familiar with wood as a building material. 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 of construction and the flexibility of wood construction also lead to one of the major problems with it as a system: it can be assembled or modified in so many different ways. Thus, it becomes more difficult to standardize details and to ensure that the contractor follows the plans and specifications. For example, a structural steel frame can generally be assembled only in the way the engineer and fabricator planned it to be. Otherwise, the beams and columns simply will not fit, and field modifications are difficult. In the case of wood framed construction, a supply of the basic raw materials (lumber, plywood, nails) are delivered to the job site, and there are many ways they can be cut and assembled. Wood is also one of the most difficult materials for the designer to master because it is virtually the only building material that is natural rather than manmade, which entails a number of uncertainties. Wood structures may be the simplest to build, but they are among the most complicated to design.

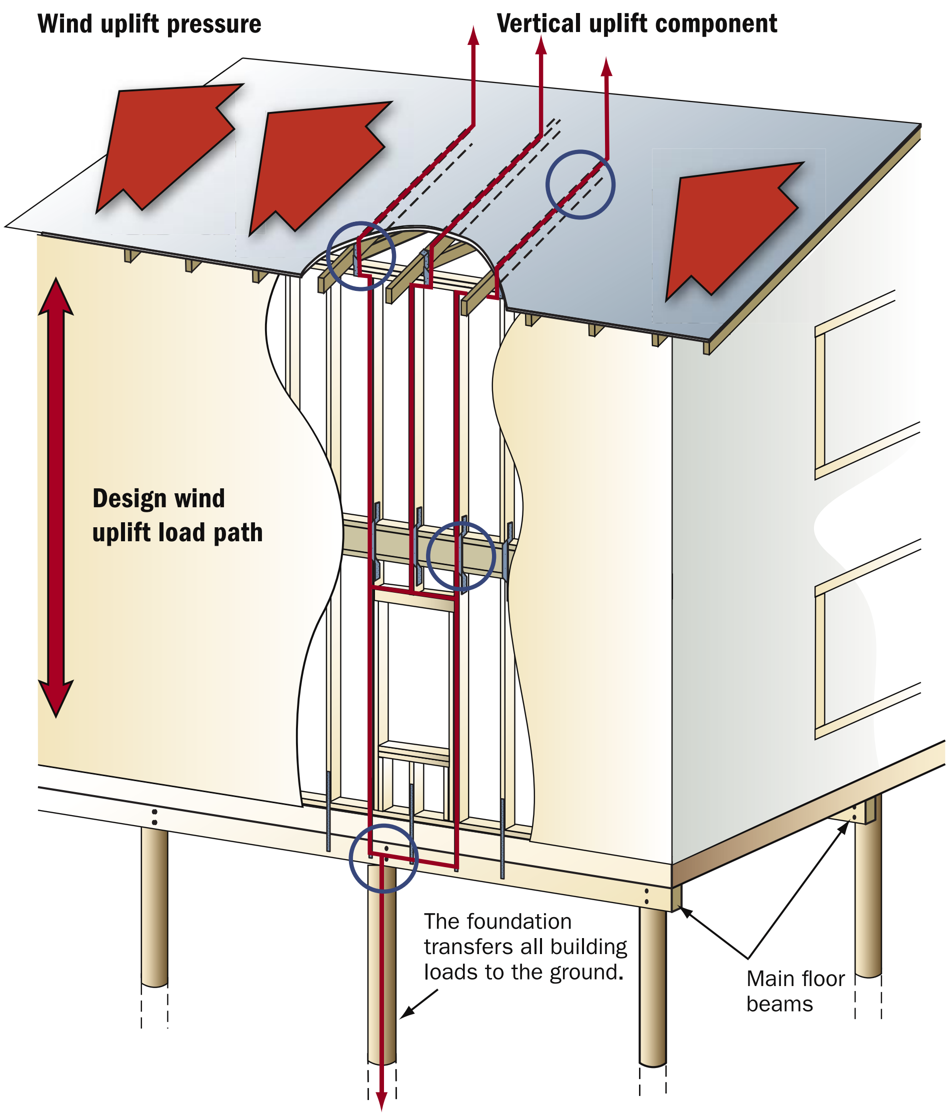

Figure 4-82.
Load path of a two-story building with a primary wood-framing system: walls, roof diaphragm, and a floor diaphragm

In the areas damaged by Hurricane Ivan, the MAT observed few houses new enough to have been built under the FBC 2001 or the IBC 2003. In addition, the actual wind pressures were below the code prescribed pressures; therefore, Ivan could not be considered a true "code design-level test." Therefore, it is difficult to evaluate the effect of new codes. It did appear that newer wood-frame houses generally performed well structurally. Efforts in the last 15 years to increase the quality of coastal construction, such as the 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 as expected, but showed little signs of structural damage due to wind or water (see Figure 4-83).

Figure 4-83.
Storm surge damaged the lower portion of this house, but no wind damage was observed. (Gulf Shores)

The most common wind related structural failures observed in light-framed construction were roof framing failures. They were most commonly observed in older construction, but there were incidents of newer buildings experiencing the same damage. Insufficient attachment of roof sheathing panels to the supporting framing was the most common problem. The discovery of zones of high uplift pressures on the edges of roof surfaces through wind research over the last 25 years has caused newer codes to require much closer nail spacing in these zones. Older construction does not have these closer spacings in the sheathing nail patterns, and, thus, it is more susceptible to uplift damage. Once the sheathing attachments fail, a variety of other failure modes can happen. Attics that have been breached 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.

Figure 4-84. Progressive failure of wood roof framing (Perdido Key)

Another common failure point was wood-frame gable end walls. These are commonly under designed or improperly constructed. Often, a typical roof truss is the only support element behind the wall covering of the gable as shown in Figure 4-85. Trusses are constructed with the weak dimension of the lumber turned normal to the plane of the truss. This means that when a typical truss is used alone as the wall framing for the gable end wall, the truss members must resist the wall's wind forces in their weak direction. On larger buildings, the height of the gable end wall from the plane of the ceiling up to the peak of the gable is often taller than the story heights below. In these cases, even wall studs would have to be strengthened in order to be adequate. The truss members are typically not capable of carrying the bending forces in this manner. In cases where adequate wall stud framing is present in the gables, the problem is typically the absence of adequate bracing where the gable end wall sits on top of the wall below. This point is a hinge and must be braced by framing to transfer the wind loads into the lateral load resisting system. Figure 4-85 illustrates the arrangement of these structural members in typical light-frame construction. The framing shown in Figure 4-86 shows a truss resisting the wind loads with its weak axis. This was in an upscale house under construction, so the problem is still not being addressed in all cases. The condominium building shown in Figure 4-87 had no evidence of any bracing at the hinge point in its gable end wall framing.

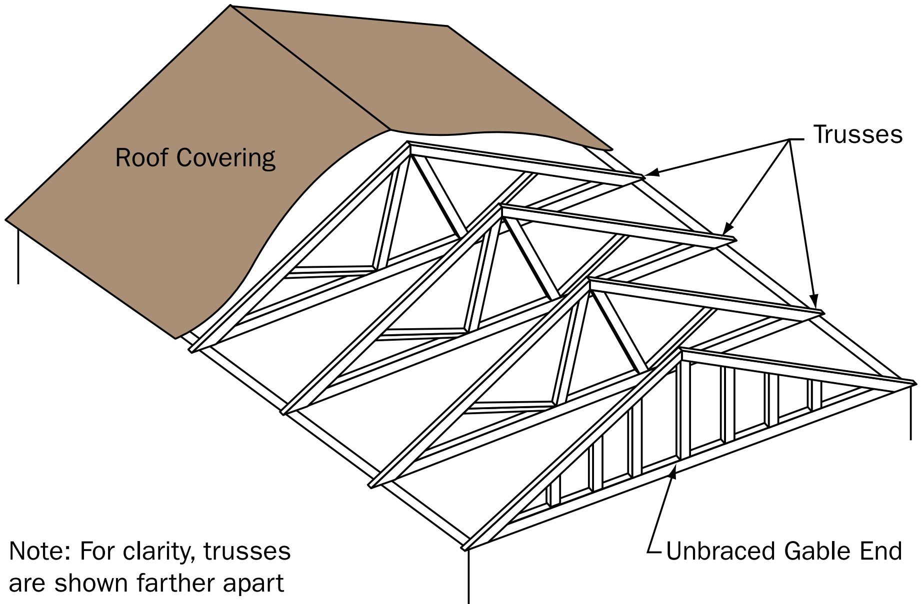

Figure 4-85.
Gable end wall framing diagram

Figure 4-86.
Roof truss with 2x4s oriented in the weak direction resisting the wind loads on a gable end wall (Ono Island)

The final observed failure mechanism in wood framed construction was the connections between the roof and wall members. Particularly evident in older buildings, the roof framing members were often inadequately anchored to the wall framing. Whether caused by no anchors, inadequate anchors, or improperly installed anchors, the failure to complete the load paths, as illustrated in Figure 4-82, was the cause of damage. The MAT observed several buildings such as the ones shown in Figures 4-88, 4-89, and 4-90, which suffered the total loss of the roof framing due to improper anchorage of the roof framing to the walls.

The MAT observed several wood framed houses under construction at the time of the storm. It allowed an opportunity to observe current construction practices. Although in general the quality of residential construction has improved over the last 30 years, there were still examples of poor practices being followed in new wood frame construction. Several improper installations of wood framing connectors were observed by the MAT. Several of these installations seemed to indicate a lack of understanding of the load path concepts illustrated in Figure 4-82. The houses in Figures 4-91 and 4-92 had connectors in place, but they were the wrong type, in the wrong place, installed without the proper number of nails, or were already corroding. Figures 4-93 and 4-94 show the wall studs between two garage doors in an upscale house under construction. The beams above the doors carry all the uplift of the roof framing above. However, note the lack of properly installed connectors to transfer these uplift forces from the beams to the wall studs and from the wall studs to the foundation. Progress is still needed in the design and construction of the load paths in wood framed buildings.

Figure 4-87.
Gable end wall failure due to lack of bracing at hinge point in wall (see arrow) (Perdido Key)

Figure 4-88.
Roof framing damage due to lack of connections from roof to wall (Orange Beach)

Figure 4-89.
Roof framing damage due to lack of connections from roof to wall (Pensacola Beach)

Figure 4-90.
Roof framing damage due to lack of connections from roof to wall (Ono Island)

Figure 4-91.
Improper use of a wood truss press plate connector to substitute for stud hold-downs (Oriole Beach)

Figure 4-92.
Already corroded anchor bolt in new construction (Oriole Beach)

Figure 4-93.
Improper strapping (Ono Island)

Figure 4-94.
Wall studs between garage doors with inadequate hold-downs (Ono Island)

4.2.2 Concrete Buildings

High-rise buildings, typically built of cast-in-place concrete, suffered little or no wind damage to the primary structural frame. The observed damage was to the building envelope. The building envelope performance is described later in Chapter 5.

4.2.3 Commercial Buildings

Masonry construction is commonly used for commercial buildings, such as shopping centers and office buildings. These buildings were supported on reinforced concrete foundations with shallow spread or deep foundation systems. Exterior load-bearing walls were constructed utilizing concrete masonry unit (CMU). The roof decks were observed to be supported by open web steel joists with metal deck. Very little structural damage was observed in this type of construction. Where structural damage was observed, it seemed to be isolated and a result of poor design or construction or a problem with a particular type of material installation such as shown in Figure 4-95. This building was in an area of relatively low wind speeds, yet suffered catastrophic failure while an adjacent retail center had only minor damage.

Figure 4-95.
Metal roofing failure (Foley)

4.2.4 Pre-Engineered Metal Buildings

A pre-engineered steel building system is generally the most economical commercial building system and is normally utilized for purposes such as warehouses, storage facilities, airplane hangars, and other similar open interior uses. These buildings are easily recognized by their sheet metal siding, tapered rigid frames, and long spans with open spaces. Secondary structural members consisting of girt and purlins are installed to support the metal siding and roofing panels.

As previously observed after other storms, of all the permanent structural framing systems evaluated, the pre-engineered metal framed systems performed the poorest. Exterior walls consisting of thin sheet metal siding failed prematurely, resulting in a penetrated building envelope and causing failure of the main structural framing members. It appeared that the age of the buildings was a factor in their performance, either because of the aging and corrosion of the materials or because of better design practice in more recent times. The MAT noted many newer metal buildings that performed adequately; however, all of the large boat storage facilities, new or old, were observed to have suffered significant damage that was out of scale for a wind event of this magnitude, as shown in Figures 4-96 and 4-97. Frequently, damage to boat storage facilities is caused by wind getting into the building and resulting in internal and external pressure acting simultaneously on the building. Therefore, even at lower wind speeds, these forces will cause significant damage to these types of open structures.

Figure 4-96.
Heavily damaged pre-engineered boat storage building (Orange Beach)

Figure 4-97.
Heavily damaged pre-engineered boat storage building (Orange Beach)

4.2.5 Accessory Structures

Structural damage to accessory structures was observed by the MAT throughout the path of Hurricane Ivan. Carports, canopies, fences, and screen walls were all observed to sustain wind damage. Typical metal canopies between buildings on school campuses did not fare well, as shown in Figure 4-98.

Figure 4-98. Collapsed metal canopy at a middle school (Pensacola)