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HURRICANE IVAN DAMAGE SURVEY

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1. INTRODUCTION

The author conducted aerial and ground damage surveys along the Florida and Alabama coasts after Hurricane Ivan. The purpose of these surveys was to: 1) determine the height of the storm surge, 2) acquire wind velocity data, 3) determine the timing of each, and 4) assess the performance of buildings exposed to wind and water effects. Particular emphasis was placed on delineating wind and water damage. A similar study has just been published by FEMA (2005).

The author rode out Hurricane Ivan near Pensacola, FL then conducted hundreds of site specific inspections the year following the hurricane. Most buildings examined were wood-framed structures. Remaining buildings consisted of concrete masonry as well as multi-story, steel-reinforced, concrete structures. Various building failure modes were observed. Typically, wind exploited poorly anchored or attached roofs and vinyl siding whereas wave action undermined, collapsed and destroyed buildings near the coast. Wind damage generally began at roof levels whereas wave damage attacked the bases of buildings. Both lateral and uplift forces were applied to the buildings from wind and water and examples of such failures will be shown in this paper. Delineating the damage between wind and water involved knowledge of building construction, as well as understanding the direction and magnitudes of the wind and water forces during the hurricane. A primer on the subject had been published by FEMA (1989).

2. WEATHER BACKGROUND

Hurricane Ivan struck the Alabama coast and western Florida panhandle during the late evening on September 15, 2004 and early morning on September 16, 2004 (Fig. 1). According to Stewart (2005), Ivan weakened as it approached the coast due to a number of environmental factors and dropped to category 3 strength on the Saffir-Simpson Scale. Refer to Table 1. The eye of the hurricane made landfall near Gulf Shores, AL around 0700 UTC (2 a.m.) local time and the eyewall tracked northward up the Perdido River along the Alabama/Florida state line.

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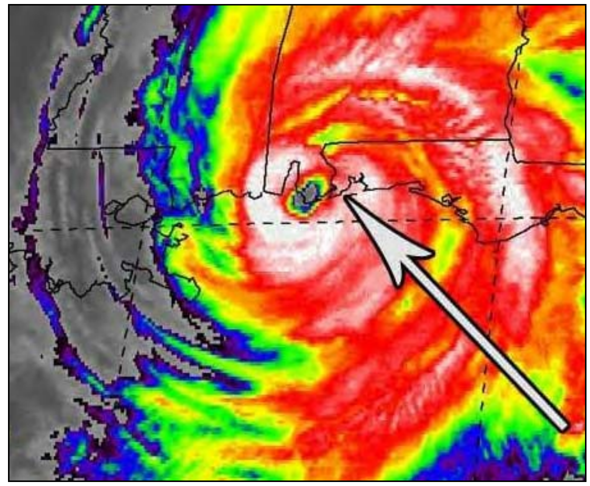

Figure 1. Enhanced color infrared satellite image of Hurricane Ivan at landfall near Gulf Shores, AL around 0700 UTC (2a.m.) on the morning of 16 September 2004. Arrow indicates location of author. Image courtesy of NOAA/NWS.

Analysis of radar data revealed that Hurricane Ivan had a closed eyewall until it was about 100 km (62 miles) from the Alabama coast. According to Stewart (2005), a combination of dry air from Louisiana, upwelling of cooler water near the coast, and increasing wind shear from an approaching upper trough had detrimental effects on storm strength. As a result, the southern half of the eyewall eroded away just prior to making landfall and surface wind speeds decreased (Fig. 2). The north eyewall crossed the Alabama coast around 0600 UTC (1 a.m.) near Gulf Shores, AL with the east eyewall passing over Perdido Key, FL. The eye crossed the coast about an hour later. By 0800 UTC (2 a.m.), the eyewall extended from Mobile, AL to just west of Pensacola, FL.

TABLE 1
SAFFIR-SIMPSON SCALE

NO.	WIND* (mph)	SURGE (ft)
1	74-95	4-5
2	96-110	6-8
3	111-130	9-12
4	131-155	13-18
5	>155	>18

*sustained wind (1 minute average)

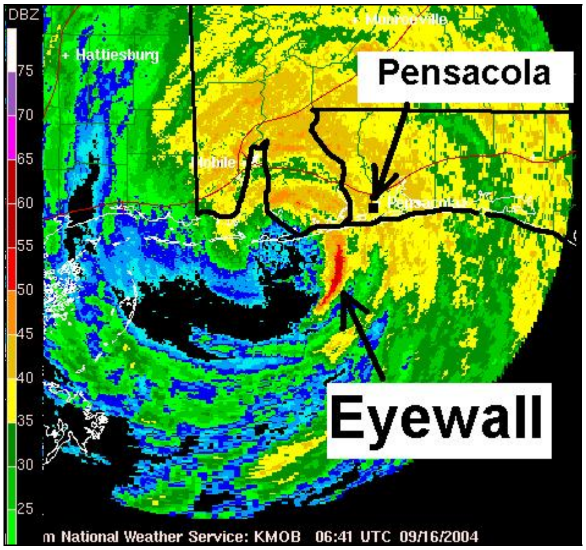

Figure 2. Radar image of Hurricane Ivan at 0641 UTC (141 a.m. local time) on 16 September 2004 as it approached the Alabama and Florida coast. Note erosion of south and west eyewall. Image courtesy of NOAA/NWS.

2a. WIND SPEEDS AND DIRECTION

The strongest winds from Hurricane Ivan occurred in the north and east eyewall which passed just west of Pensacola, FL. At 0638 UTC (138 am), the Pensacola Naval Air Station reported sustained winds of 39 ms^{-1} (87 mph) with a gust to 48 ms^{-1} (107 mph). At 0644 UTC (1:44 am), the Pensacola Airport reported a wind gust to 47 ms^{-1} (106 mph) from the east-southeast at 10 meters (33 feet) above the ground in open, unobstructed terrain. A Doppler on Wheels (DOW) truck in Gulf Shores, AL also measured a wind gust of 51 ms^{-1} (115 mph). Wind speeds were lower east, west, and inland of the east eyewall. Initially, the wind direction was from the east along the coast. Then, as the eye made landfall, winds east of the eye shifted gradually to the south.

The Florida Coastal Monitoring Program (FCMP, 2004) also had wind measuring stations in several places near the coast. Wind velocities weakened at the Fairhope, AL site indicating that the eye passed over this location. Also, there was a sudden change in wind direction from east-southeast to west-southwest as the eye passed. In contrast, the Pensacola site never experienced the eye (Fig. 3). Winds in Pensacola shifted more slowly from east to southeast to southwest as the eye passed to the west. A peak 3-second gust of just over 49 ms^{-1} (111 mph) was recorded at 0643 UTC (143 am).

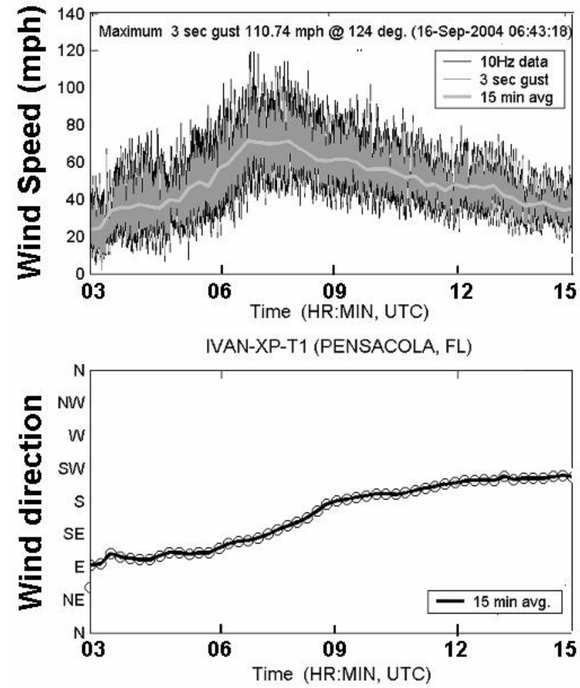

Figure 3. Wind speed (mph) and direction from Pensacola during Hurricane Ivan. Figure courtesy of the Florida Coastal Monitoring Program.

2b. STORM SURGE

The storm surge precedes and accompanies a hurricane. This occurs as the hurricane pushes seawater ahead of it. At the same time, the hurricane moves towards shore. The coast acts as a barrier to the rising sea levels resulting in a “squeeze play” where water is literally pushed onto land. Waves are superimposed on top of the storm surge. As indicated by Simpson and Riehl (1981), the peak storm surge occurs east of the eye and is typically coincident with the peak winds.

The author measured the height of the storm surge using a surveyor’s level and rod. Still water lines in buildings provided the best estimate of the storm surge level. The line was formed by dirt and debris in the water that was deposited on wall surfaces. Generally, the still water level was found in a room that was not breached by wave action. Occasionally, a line of grime was found deposited on glass items or rust on metal items due to contact with salt water. Sometimes scrape marks were noted in wall surfaces from impacts by floating furniture (Fig. 4).

Figure 4. Indications of the height of water: a) dirt line in bathroom, b) rust line on metal fuse box, c) scrape marks on paneling, and d) scrape marks on trees.

In the absence of a building, scrape marks on trees provided a measure of water depth. The scrape marks were formed by repeated impacts of floating debris which abraded and removed the bark. The heights of the scrape marks usually were close to heights of the still water lines provided the debris remained in contact with the trees. Flotsam and debris lines also provided an estimate of the height of the storm surge. The author obtained dozens of still water line measurements from various locations extending as far west as Ft. Morgan, AL and as far east as Fort Walton Beach, FL. Selected measurements appear for the Florida coast appear in Figure 5.

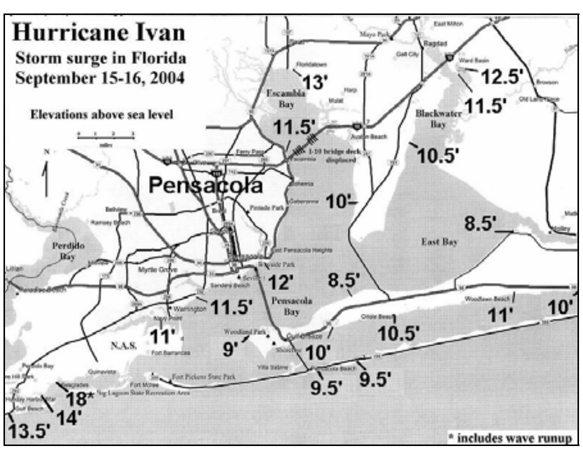

Figure 5. Selected measurements of still water heights (ft.) above sea level for the Florida coast after Hurricane Ivan.

The highest storm surge measured was 4.4 m (14 ft.) at Perdido Key, FL. Storm surges in excess of 3.8 m (12 ft.) were measured in Grande Lagoon, Escambia Bay, Tiger Point, and Blackwater Bay areas. Low-lying areas along the coast (i.e. Grande Lagoon and Tiger Point) were subjected to the full force of the moving water including wave action and sustained the greatest concentration of damage. Barrier islands, which normally protect the mainland coast, were submerged during the storm. Bays that faced south channeled the water such that the north end of Escambia and Blackwater Bays had storm surges nearly equal to the highest levels on the coast. The highest surge (including wave runup) found was 5.6 m (18 ft.) in the Seaglades subdivision southwest of Pensacola, FL.

2c. TIMING OF WIND AND WATER

Wind and water data were compared for three sites: Dauphin Island, Pensacola, and Panama City. In each instance, the storm surge exceeded normal high tide during the early morning of September 15th, about 24 hours before the eye made landfall. The storm surge rose steadily throughout the day then increased rapidly as the stronger winds moved ashore. The peak storm surge coincided with the strongest winds (Fig. 6).

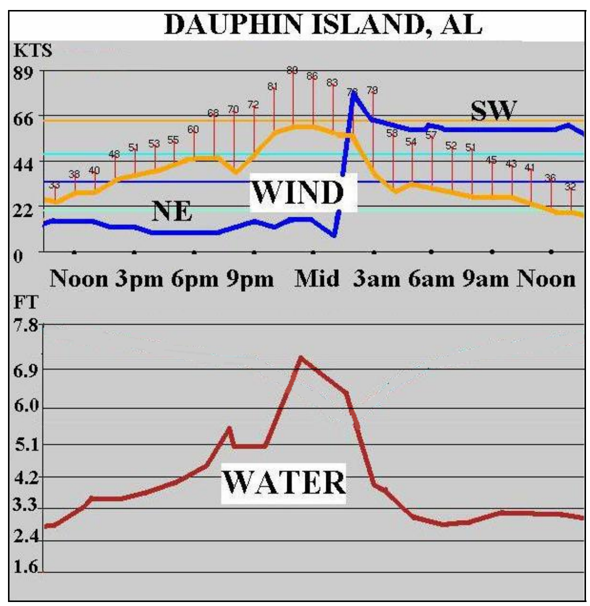

Figure 6. Wind speed (knots), wind direction and water height (ft) from Dauphin Island, AL during Hurricane Ivan. Yellow line indicated sustained winds, and the vertical red line indicated peak gusts. Wind direction is the blue line and water height is the red line. Courtesy of the National Ocean Survey.

3. WIND SPEED-DAMAGE CORRELATION

Mehta et al. (1983) correlated wind speeds with building damage after Hurricane Frederic. Varying degrees of building damage were assigned failure wind speed values depending on the degree of engineering attention to the building.

McDonald (2005) further advanced the concept of wind speed-damage correlation by assigning failure wind speed ranges based on the "degree of damage (DOD)" to 28 types of buildings and objects. For wood-framed residences, McDonald indicated that the removal of roof coverings generally occurs with a three-second wind gust of about 36 ms^{-1} (80 mph). The removal of the roof deck occurs with a three-second wind gust of about 44 ms^{-1} (98 mph), and the removal of the roof structure occurs with a three-second wind gust of 54.5 ms^{-1} (122 mph). Variations up to 20 percent can occur depending on the type of building construction and the extent of anchorage. Also, building items not damaged would give an upper bound failure wind speeds. In this study, wind speed-damage correlations were determined for selected locations and the results are shown in Figure 7 along with actual wind speed measurements.

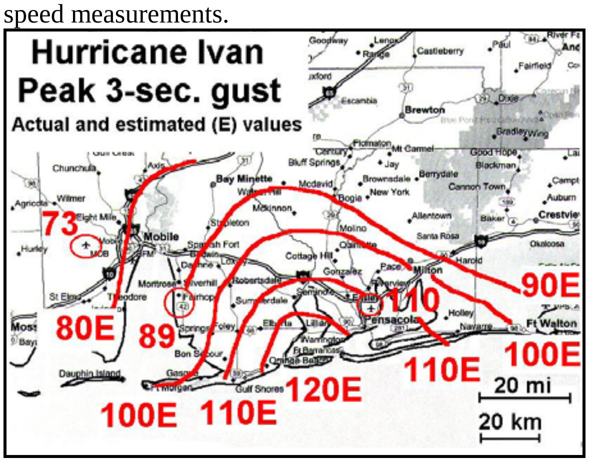

Figure 7. Actual and estimated 3-second peak wind gusts (in mph) at 10m (33 ft.) above the ground in open terrain for Alabama and Florida from Hurricane Ivan. Actual values (circled) are from the Florida Coastal Monitoring Program. Estimated values are based on wind speed-damage correlations.

Actual and estimated three-second peak wind gusts from Hurricane Ivan were then compared to the design three-second gusts as stated in the ASCE 7-95 (1996) standard (Fig. 8). This standard indicates that structures built along the coast should be designed for 130 mph three-second gust. It was found that the Hurricane Ivan's winds were lower than those stated in the ASCE 7-95 standard.

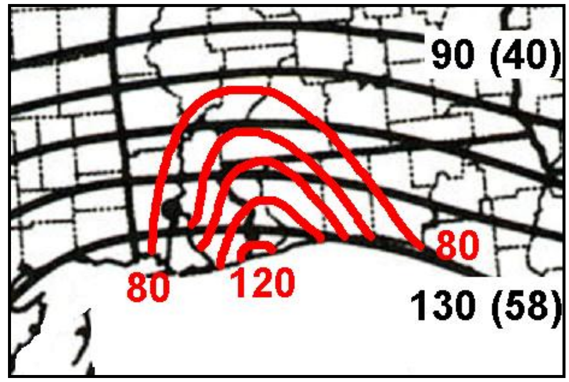

Figure 8. Comparison between the basic design wind speeds in ASCE 7-95 (black lines) with those from Hurricane Ivan (red lines) for Alabama and Florida. Wind speeds are in mph with ms^{-1} in parentheses.

4. DAMAGE BY COMMUNITY

The following is a summary of damage observations by community.

4.1 FORT MORGAN, AL

Fort Morgan was located at the west end of Highway 80 on the east side of Mobile Bay. The area experienced the northern eyewall with strongest winds from the east. Wind damage to buildings was minimal and consisted of damage to asphalt shingles and vinyl siding. In general, well-built homes sustained little or no wind damage. Maximum wind gusts at 10m (33 ft.) were estimated to be around 45 ms^{-1} (100 mph). The storm surge was around 3 m (9.6 ft.) above normal ocean water level. Up to 1 m (3.2 ft.) of sand was transported into the first floors of coastal homes.

4.2 FORT WALTON BEACH, FL

Fort Walton Beach was located well east of the eyewall in Hurricane Ivan and experienced the strongest winds from the east. Wind damage to buildings was minimal and consisted of damage to asphalt shingles and vinyl siding. In general, well-built homes sustained little to no wind damage. Maximum wind gusts at 10 m (33 ft.) in open terrain were estimated to be around 42.5 ms^{-1} (95 mph). Lower wind speeds occurred in forested areas. Storm surge and wave action inundated the first floors of oceanfront homes and destroyed swimming pools and patio decks.

4.3 GULF BREEZE, FL

Gulf Breeze was located east of the eyewall and experienced the strongest winds from the east-southeast. Some pine trees were uprooted or snapped to the northwest. Wind damage to buildings was minimal and consisted of damage to asphalt shingles and vinyl siding. In general, well-built homes sustained little to no wind damage. Maximum wind gusts at 10 m (33 ft.) in open terrain were estimated at around 49 ms^{-1} (110 mph). Wind speeds were significantly lower in forested areas.

Storm surge and wave action were severe and reached between 3.1 and 3.4 m (10 to 11 ft.) above the normal ocean water level on the Santa Rosa Sound side and between 2.6 and 2.8 m (8 and 9 ft.) on the bay side. Waves were superimposed on the storm surge and severely damaged or completely destroyed those structures on grade at low elevations. One of the worst hit areas was Tiger Point subdivision where houses along Santa Rosa Sound were washed away. Trees and other vegetation were killed by saltwater inundation.

4.4 GULF SHORES, AL

The eye of Hurricane Ivan passed over Gulf Shores with the strongest winds occurring from the east in the northern eyewall. Wind damage to buildings was minimal and consisted of damage to roof coverings and vinyl siding. However, occasional damage was observed to east gable ends and some roof decking was removed. Roof damage occurred when wind was able to get underneath an overhang or enter the building through a broken window or door. In general, metal roofs performed better than three-tab shingle roofs. Well-built homes sustained little to no wind damage. Maximum wind gusts at 10 m (33 ft.) estimated around 51 ms^{-1} (115 mph) in open terrain.

Storm surge ranged between 3.1 and 4 m (10 to 13 ft.) above the normal ocean water level from the west end of the island to the east end. Buildings elevated above the storm surge escaped significant damage. However, buildings were severely damaged or destroyed when waves reached the second story. Floating debris battered and mangled pilings. Up to 2.5 m (8 ft.) of sand was removed from the beach and transported inland covering the main highway, Rt. 182. Pilings that did not have sufficient depth or lateral support rotated. Concrete slabs poured on grade were suspended in the air between the pilings.

4.5 MILTON, FL - BLACKWATER BAY

Blackwater Bay was located to the east of Pensacola and was well east of the Hurricane Ivan's eye. The strongest winds were from the east-southeast. Wind damage to buildings was minimal and consisted of damage to asphalt shingles and vinyl siding. In general, well-built homes sustained no wind damage unless struck by falling trees. Maximum wind gusts at 10 m (33 ft.) in open terrain were estimated to be around 45 ms^{-1} (100 mph). Winds were significantly lower in forested areas. A church in town lost part of its roof when large windows, that faced south, failed.

Storm surge ranged between 3.1 and 4 m (10 to 13 ft.) above the normal water level in the bay. Buildings on grade were gutted by floodwaters. The worst surge damage observed occurred along Ward Basin Road and Peterson Point Road at the north end of the bay.

4.6 NAVARRE BEACH, FL

Navarre Beach was located east of Gulf Breeze and Pensacola Beach. The strongest winds were from the east-southeast. Wind damage to buildings consisted of damage to the roof coverings and vinyl siding. Some roof sections that extended over balconies were removed especially if they faced east or south. In general, well-built homes sustained no wind damage. Maximum wind gusts at 10 m (33 ft.) in open terrain were estimated to be around 47 ms^{-1} (105 mph).

Storm surge ranged between 3.1 and 3.8 m (10 to 12 ft.) above the normal water level along the oceanfront as well as along Santa Rosa Sound. Sand was transported across the entire width of the island and covered Rt. 399. Most of the main highway was destroyed between Navarre Beach and Pensacola Beach. Storm surge even crossed Rt. 98 near the bridge leading to the island. Bridge approaches leading to the island were eroded and had to be rebuilt before the island was opened to local residents. Homes on grade were severely damaged or destroyed by the storm surge.

4.7 ORANGE BEACH, AL

Orange Beach was located just east of Gulf Shores and experienced the east eyewall which had the highest winds and storm surge. Buildings in town sustained some of the greatest damage observed in our survey. Two, five-story condominium buildings collapsed after being undermined by the storm surge. Both were steel-reinforced concrete structures. The storm surge ranged between 3.8 and 4.4 m (12 and 14 ft.) above the normal water level. Buildings were severely damaged or destroyed especially when waves reached the second story. Floating debris battered and mangled pilings. Up to 2.5 m (8 ft.) of sand was removed from the beach. Portions of Rt. 182 were washed away between Orange Beach and Gulf Shores.

Wind damage consisted of the removal of asphalt and metal roofing. Occasionally, roof decking was displaced along with the roof structure especially where they extended over a balcony. The strongest winds appeared to be from the south with maximum three-second wind gusts estimated to be about 54 ms^{-1} (120 mph) at 10m (33 ft.) in open terrain.

4.8 PACE, FL - ESCAMBIA BAY

The town of Pace was located northeast of Pensacola at the north end of Escambia Bay. The area was east of the eyewall and strongest winds. Wind damage to buildings consisted of the removal of asphalt shingle roofs and vinyl siding. Maximum wind gusts at 10m (33ft.) in open terrain were estimated to be around 45 ms^{-1} (100 mph). Winds were significantly lower in forested areas. Escambia Bay acted as funnel and channeled the storm surge. The highest storm surge occurred at the north end of the bay along Andrew Jackson Dr. where still water heights reached 4 m (13 ft.) above normal water level in the bay. Waves were superimposed on the storm surge such that the second story floors on elevated homes even were destroyed. Several mobile homes in Floridatown were transported inland as much as one block.

4.9 PENSACOLA

The city of Pensacola experienced the longest duration of strong winds from the hurricane as it was just east of the eyewall. The strongest winds were from the east-southeast and the highest three-second gust reported by the Florida Coastal Monitoring Program was just over 49 ms^{-1} (111 mph) at 10 m (33 ft.) in open terrain. Winds were lower in forested areas. Wind damage to trees was extensive and many trees fell onto buildings. Fallen trees blocked Rt. 90, the scenic highway. Some metal buildings sustained considerable roof damage due to internal pressure effects when overhead doors failed. A metal building just north of the airport collapsed. Damage to the downtown area was relatively minor with broken windows and awnings. Some penthouse structures on buildings were damaged. Light standards lost their equipment. Winds removed some of the exterior insulation and finish system (EIFS) siding on the Sacred Heart Hospital.

Storm surge inundated and damaged Bayfront Blvd. and flooded a newly built subdivision just south of the convention center. Many boats at the local marina were destroyed. Homes on top of the bluff on the east side of town escaped damage from the storm surge. However, homes that were built at the base of the bluff were gutted by the storm surge. A storm surge of up to 3.8 m (12 ft.) even destroyed the railway at the base of the bluff. Both lanes of I-10 were closed when portions of the bridge deck were uplifted and removed by waves. The bridge deck was about 4.7 m (15 ft.) above the normal water level in the bay.

4.10 PENSACOLA - GRANDE LAGOON

One of the worst hit areas observed in our survey was Grande Lagoon located southwest of Pensacola on the way to Perdido Key. Most homes were constructed on grade in this low-lying area and were completely destroyed by the storm surge. Still water heights measured between 3.1 m and 4 m (10 and 14 ft.) with waves superimposed on top of this level. Waves even damaged the second story level on homes. Wind damage to the homes consisted of the removal of asphalt shingle roofs and vinyl siding. Maximum wind gusts were about 53 ms^{-1} (120 mph) at 10m (33 ft.) in open terrain. Winds were lower in forested areas. The highest debris line in our survey was measured along Seaglades Drive and was 5.6 m (18 ft.) above the water level in Big Lagoon Sound.

4.11 PENSACOLA BEACH

Pensacola Beach was located just south of Gulf Breeze. The Corps of Engineers had just completed a beach nourishment project that widened the beach. Hurricane Ivan removed much of this sand and transported it inland burying roads and inundating houses. Sand drifts to 3.2 m (10 ft.) were measured around some of the homes and the sand filled several homes. Many of the older homes built on grade were completely destroyed by the storm surge. In certain areas, sand was transported across the entire width of the island. Portions of Rt. 399 east and west of Pensacola Beach were washed away by the storm surge.

The strongest winds appeared to have been from the south-southeast. Wind damage to buildings consisted of damaged roof coverings and vinyl siding. Wind removed some of the exterior siding on high rise condominiums. Some gable ends that faced south and east blew inward. Roof structures were displaced especially where they extended over a balcony or where internal pressure had occurred from breakage of a windward window. Maximum wind gusts at 10 m (33 ft) in open terrain were estimated to be around 51 ms^{-1} (115 mph).

4.12 PERDIDO KEY

Perdido Beach was located just east of Orange Beach and experienced the east eyewall. The strongest winds appeared to be from the south. Wind damage to buildings consisted of damaged roof coverings and vinyl siding. Wind removed some of the exterior siding on certain high rise condominiums. Roof structures were displaced especially where they extended over a balcony or where internal pressure resulted from breakage of a windward window. Maximum wind gusts at 10 m (33 ft.) in open terrain were estimated to be around 56 ms^{-1} (125 mph).

The storm surge was about 4 m (14 ft.) above the normal water level. Buildings were severely damaged or destroyed especially when waves reached the second story. A seven-story, steel-reinforced, condominium building partially collapsed at the east end of the island when it was undermined by storm surge. Floating debris battered and mangled pilings on coastal homes. Up to 2.5 m (8 ft.) of sand was removed from the beach.

5. WIND VERSUS WATER

One issue in assessing hurricane damage is whether wind or wave action or a combination of both damaged a building. This issue arises since there are separate insurance policies for wind and wave damage. Not every building owner has both insurance policies. Therefore, an accurate determination of the causes and extent of building damage must be made. Wind and wave forces attack a building differently. Wind forces are greatest at roof level whereas wave forces attack the base of the building (Fig. 9).

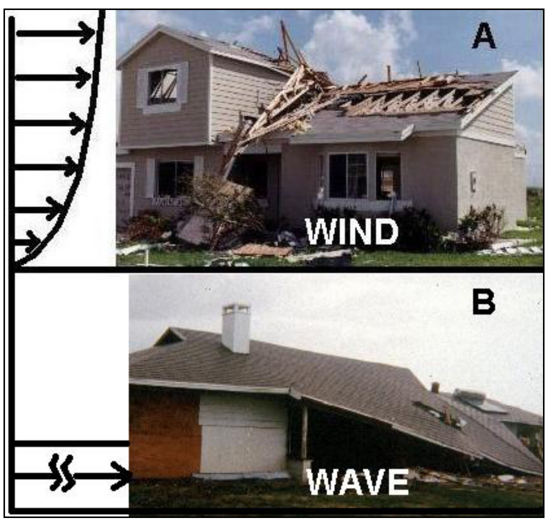

Figure 9. Examples of wind (a) and wave (b) damage to housing. Relative forces are illustrated on left with height above the ground.

Wind interacting with a building is deflected over and around it. Positive (inward) pressures are applied to the windward walls and try to push them down. Therefore, it is important that a building be anchored properly to its foundation to resist these lateral forces. Negative (outward) pressures are applied to the side and leeward walls. The resulting "suction" force tries to peel away siding. Negative (uplift) pressures are applied to the roof especially along windward eaves, roof corners, and leeward ridges. These forces try to uplift and remove the roof covering. The roof is particularly susceptible to wind damage since it is the highest building component above the ground. Wind pressures on a building are not uniform but increase with height above the ground and especially at roof corners. Generally, damage to a building from wind typically begins at roof level. Thus, the last place wind damage occurs is to the interior of the structure.

Wind damage begins with such items as television antennas, satellite dishes, unanchored air conditioners, wooden fences, gutters, storage sheds, carports, and yard items. As the wind velocity increases, cladding items on the building become susceptible to wind damage including vinyl siding, gutters, roof coverings, windows, and doors. Only the strongest winds can damage the building structure. Marshall et al. (2003) described the various failure modes in wood-framed buildings from high winds.

Water forces are greatest at the base of the building with a tendency to undermine foundations and destroy support walls, thereby leading to collapse of part or all of the building. Moving water possesses a much greater force than that of air. A one foot tall wave traveling at ten miles per hour possesses as much kinetic energy as a 280 mph wind. Homes along the coastline are at greatest risk for being damaged by waves.

Water can lift wood buildings on pier and beam foundations as such buildings are buoyant and can float. Houses float landward or out to sea depending on the ebb and flow of the water as well as the wind direction during the hurricane. Homes with brick veneer construction tend to rise and sink within the brick veneer shell especially if there are few or no brick ties. Generally, these houses do not come back down to the same position, causing distortion of the wooden-frame. Wind does not cause this condition.

6. BUILDINGS ON CONCRETE SLABS

There were numerous buildings erected on concrete slab foundations in the survey area. Concrete slab foundations were either poured on-grade or elevated by a stem wall. A stem wall involved the construction of a concrete masonry perimeter wall built on a concrete footing. The interior area was then filled with dirt or sand then compacted. Most concrete slabs measured 10 cm (4 in.) thick and contained some steel reinforcement.

Wood-framed buildings on concrete slab foundations were usually secured with steel anchor bolts. These bolts were 1.3 cm (1/2 in.) in diameter and 30 cm (12 in.) long and had a J-shaped profile that provided significant pull-out resistance in the vertical direction. The anchor bolts were inserted into the concrete slab when the slab was poured. Bolts had to have sufficient height above the slab in order to pass through the wood bottom plate and accept a steel nut and washer. Anchor bolts were spaced 1 to 2 m (3.2 to 6.4 ft.) apart and were located within 30 cm (12 in.) of the end of the plate and wall corners.

Storm surge destroyed many buildings on slab foundations (Fig. 10). Typically, the building frame was removed from the slab along with most of the contents and finish items. Occasionally, bolted wood plates remained. The force of moving water sometimes removed the carpeting and hardwood flooring. In some cases, sand was scoured adjacent or beneath the slab. The most extensive damage involved collapsing and breaking up of the concrete slab.

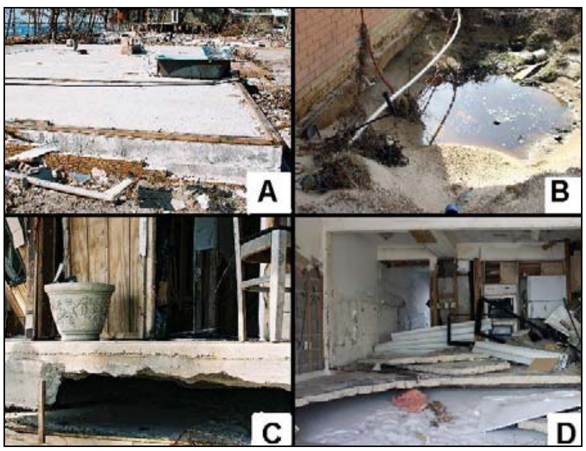

Figure 10. Examples of storm surge damage to buildings on concrete slab foundations from Hurricane Ivan: a) cleaning, b) scouring, c) undermining, and d) collapsing.

Buildings that were completely destroyed still left evidence as to the direction and magnitude of the applied forces (Fig. 11). Anchor bolts were bent along the direction of the applied force and in some instances, broke out of the leeward side of the concrete slab. Nails that secured the wall studs to the wall bottom plates also were bent along the direction of the applied force. Copper piping was quite malleable and easily bent. Brittle materials such as PVC and cast iron piping frequently were broken out on the opposite side of the applied force.

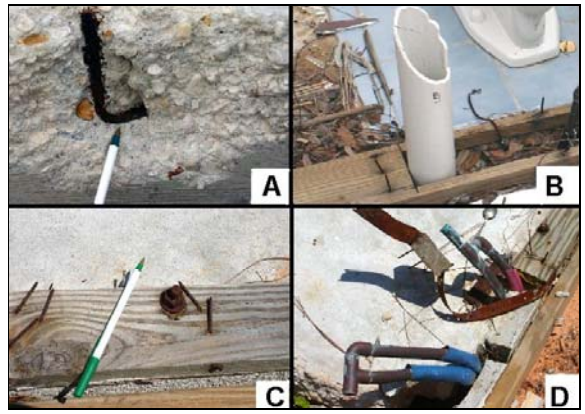

Figure 11. Indicators of direction and magnitude of the applied force: a) bolt broken out on the leeward side of the slab, b) broken PVC piping from an applied force from left-to-right, c) bent nails on wood bottom plate, and d) bent copper plumbing from a force from right-to-left.

When destroyed buildings were encountered, other buildings nearby were examined which survived. This comparative analysis was done in order to determine the height of the storm surge and resultant damage, as well as to determine the extent of any wind damage that might have occurred before the building was destroyed.

Wind damage to buildings on concrete slab foundations was limited mostly to cladding items such as roof shingles, brick masonry, vinyl siding, or windows (Fig. 12). However, in rare instances, portions of the roof deck were removed and gable ends were either pushed inward or outward. Roof structures were usually strapped to the wall top plates, and therefore, few roofs were removed. The most significant damage to homes from wind occurred indirectly from trees falling on them. Trees penetrated roofs and walls causing localized structural damage as well as rainwater entry. Concrete slab foundations were not damaged by wind.

Figure 12. Examples of wind damage to buildings on concrete slab foundations after Hurricane Ivan: a) displaced roof covering, b) uplift of roof decking, c) removal of gable end/siding, and d) complete roof failure.

7. BUILDINGS ON TIMBER PILES

Timber piles were either round or square and ranged from 15 cm (6 in.) to 30 cm (12 in.) across and up to 11 m (36 ft.) deep. Piles were driven into the sand and extended as high as 3.2 m (12 ft.) above grade. In many instances, a concrete slab was poured on-grade around the pilings. The slab helped stiffen the pilings and resist soil erosion.

Wood girders were usually set into notches and bolted to the tops of the pilings. Wood floor joists extended perpendicular to the girders. About half the time, floor joists were installed in the same plane as the girders and hung by metal straps or just nailed to the girders. In other instances, the floor joists were set on top of the girders and were toe-nailed to the tops of the girders or secured with metal straps. The plywood subfloor was then nailed to the floor joists. Walls were then erected on top of the floor. Bottom wall plates were usually straight nailed or occasionally strapped to the floor framing (Fig. 13).

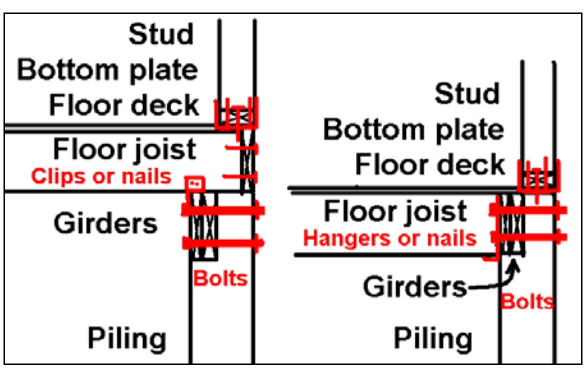

Figure 13. Different floor details on buildings elevated on timber piles.

Storm surge damage to buildings elevated on timber pilings varied considerably from none to complete destruction depending on the height of the building above the water, depth of the pilings, and exposure to wave action. Not surprisingly, buildings adjacent to the coast suffered the greatest structural damage from the storm surge. Minor damage involved removal of cross bracing between the pilings. Moderate damage involved eroding sand around the bases of the pilings and rotating the pilings. Concrete slabs around the pilings were left elevated or collapsed when sand was removed. Severe damage involved broken and crushed pilings causing partial or complete collapse of the building. Pilings were some times abraded or scarred by floating debris (Fig. 14).

Figure 14. Damage to pilings from wave action: a) breaking of cross bracing, b) erosion of sand around the pilings, c) rotation of pilings, and d) breaking of pilings.

Floor systems exposed to wave action experienced lateral forces from the moving water as well as uplift forces from rolling waves. Minor damage to floor systems involved the bowing of floor girders and/or rotation or removal of blocking between the floor joists. In some instances, the plywood subfloor was uplifted causing nails to back out of the wood. Moderate damage involved breakage of some of the floor girders and removal of joists along the side of the building that faced the water. Occasionally, bolts that secured the girders were bent landward and/or upward in the direction of the applied force. Some times, lateral wave forces broke the floor joists or pushed them together, stacking them toward the landward side of the building. Uplift forces from rolling waves lifted the joists out of their hangers. Loss of floor support led to progressive collapse of the building with the worst damage occurring on the side of the building that faced the water. The effect of wave action on buildings elevated on pilings was to dismantle them from below (Fig. 15).

Figure 15. Damage to floor systems from wave action: a) loss of floor girders, b) rotation of blocking, c) stacking of floor joists, and d) uplift of the plywood subfloor.

Wind damage to buildings elevated on pilings usually began at roof level with the loss of roof shingles, chimney caps, or antennas. In some instances, portions of the roof deck were removed along windward roof corners and eaves. Wind damage progressed downward, in contrast to wave damage. In rare instances, wind pushed the tops of frame walls inward or outward causing the walls to rotate about their bases. Failure occurred when straight-nailed wall bottom plates simply pulled out of the subfloor. A hinge formed at the base of the wall. Lack of proper strapping and bracing contributed to such wall failures. Floor systems were left unaffected (Fig. 16).

Figure 16. Examples of wind damage to buildings elevated on timber pilings: a) removal of roof covering, b) gable end and roof deck failure, c) windward wall failure, and d) nailed wall bottom plate pulled out of the floor.

8. TORNADOES

The author encountered a number of people who believe that buildings exploded from the low barometric pressure in a tornado, when actually, the buildings were gutted by the storm surge. Another myth was that twisted trees indicated rotating winds when actually, the trees twisted in straight-lined winds. Minor (1982), Minor et al. (1993), and Marshall (1993) have addressed many of these myths.

Where buildings had floated, some people believed that houses were picked up and set back down like in the movie *Wizard of Oz*. However, an examination of these homes usually revealed pictures were still hanging on the walls, and glassware was standing upright in cabinets. This indicated that the houses moved slowly (low velocity) and came to rest slowly (low impact). Wind would have broken such items if the house moved rapidly (high velocity) and came to rest suddenly (high impact). Numerous homes were completely destroyed in the surge zone but nearby trees remained upright. Some people believed that tornadoes simply destroyed the homes while skipping over the trees. Generally, there was a lack of debris up in the trees (above the surge line) and trees had not been impaled by flying debris. Damage to homes within the surge zone was no different than the damage to homes similarly situated along the coastline. The reason why buildings farther inland survived was not because a tornado skipped over them, but that the force of moving water (and wave action) was less than near the coast. The author found that aerial photographs taken by NOAA (2004) and the USGS (2004) were invaluable in delineating wind versus wave damage zones.

Some people believed that hundreds or thousands of tornadoes descended upon a particular county as the eye approached, when in fact, tornadoes did not occur in their county. The public needs to understand that hurricane winds do almost all of the wind damage. Tornadoes are rare, even in hurricanes. Ivan did produce tornadoes but these were well to the north and east of the center, and occurred mostly after the eye made landfall.

9. SUMMARY

Hurricane Ivan struck the Alabama coast and western Florida panhandle during the late evening on September 15, 2004 and early morning on September 16, 2004. The author rode out the storm near Pensacola, FL then conducted aerial and ground surveys of the area. Detailed assessments were performed to individual buildings during the year following the hurricane. The purpose of these surveys was to: 1) determine the height of the storm surge, 2) acquire wind velocity data, 3) determine the timing of each, and 4) assess the performance of buildings exposed to wind and water effects. Particular emphasis was placed on delineating the damage between wind and water effects.

Storm surge from Hurricane Ivan was considerable reaching between 3.1 to 4.4 m (10 to 14 ft.) from Gulf Shores, AL to Navarre Beach, FL. Bays and sounds magnified the storm surge. Homes on grade were severely damaged or destroyed as a result of storm surge. Even homes elevated on concrete or timber pilings sustained significant damage in the highest surge areas. Many of these buildings were constructed too close to the ocean. Such buildings need to have significant set back from the water. In addition, there was a lack of dunes in front of the buildings. It should be recognized that dunes play a significant role in protecting the beach as well as beachfront buildings.

The highest winds occurred from Orange Beach, AL to Perdido Key, FL where the eyewall made landfall. Wind speed-damage correlations suggest that the highest wind gusts were 120 mph at roof level. Lower wind speeds occurred inland and in wooded areas. Three-tab asphalt shingle roofs performed poorly while buildings covered with heavier architectural shingles and metal performed better. In general, vinyl siding performed poorly. A better alternative would be to install hardboard siding. Well-built homes sustained no structural damage due to wind. These homes were built to meet or exceed the basic design wind speed in the Florida Building Code of 130 mph (3-second gust, open terrain). No tornado damage was found along the coast. Also, no areas of category 3 winds were found in the survey.

Buildings damaged by the storm surge and wave action were dismantled from below. In contrast, buildings damaged by wind had the greatest damage at roof level. The magnitudes of the forces involved differed between wind and wave. In general, buildings struck by moving water sustained more damage than that caused by wind. A number of building deficiencies were exploited by the storm. Such deficiencies included inadequate pile embedment and poor attachment of walls to floors and roofs to walls.

10. ACKNOWLEDGEMENTS

The author would like to thank the cities of Pensacola, Orange Beach, and Pensacola Beach for help in obtaining access to the disaster area after the storm as well as the Escambia County Sheriff Department. In particular, thanks to Debbie Norton with the Emergency Operations Center on Pensacola Beach. The National Weather Service, U.S.G.S, FEMA, Jim Leonard, and National Ocean Service provided much of the data within this report. Skip Jiles with the Pensacola Aviation Center was quite helpful as the pilot during our aerial survey. C.S. Kirkpatrick, Polly Lawler, Kay Marshall, Scott Morrison, John Stewart and Jim Wiethorn reviewed the paper.

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