P 7.5

HURRICANE KATRINA DAMAGE SURVEY

Timothy P. Marshall*
Haag Engineering Co.
Dallas, Texas

1. INTRODUCTION

The author conducted aerial and ground damage surveys along the Mississippi and Alabama coasts after Hurricane Katrina. 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. Survey work is continuing at this time and thus, the results presented herein are preliminary and subject to change.

The author rode out Hurricane Katrina in Slidell, LA then conducted hundreds of site specific inspections in the months following the hurricane. Most buildings examined were wood-framed structures constructed on various foundations to include concrete slab, pier and beam, timber pilings, or masonry piers. Various building failure modes were observed. Typically, wind exploited poorly anchored or attached roofs and vinyl siding whereas wave action undermined, collapsed and washed away buildings near the coast. Wind damage generally began at roof levels whereas wave damage attacked the bases of the buildings. Both lateral and uplift forces were applied to the buildings from wind and water and examples of such failures will be shown. 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 Katrina was the costliest natural disaster in U.S. history to date with current estimates exceeding 100 billion dollars. The hurricane caused widespread devastation from Louisiana to Florida making a total of three landfalls in the U.S. before dissipating over the Ohio River Valley. At one point, Katrina reached Category 5 strength on the Saffir-Simpson scale (see Table 1), making it one of the most powerful hurricanes this century. The storm went on to destroy much of the Mississippi coast and levee breaches caused the inundation of a large potion of New Orleans.

*Corresponding author address: Timothy P. Marshall, 4041 Bordeaux Circle, Flower Mound, TX 75022-7050. email: timpmarshall@cs.com

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)

According to Knabb et al. (2005), Hurricane Katrina formed from a tropical wave that traveled westward across the Atlantic Ocean from Africa. It crossed southern Florida on 25 August 2005 at category 1 hurricane then weakened briefly over land before re-emerging over the Gulf of Mexico. Rapid intensification occurred and by 27 August 2005 Katrina intensified to Category 5 strength while in the central Gulf. The cloud shield appeared symmetrical on satellite (like a donut), a sign of a powerful storm. Meanwhile, swells reached the northern Gulf coast ahead of the hurricane resulting in higher than normal water levels.

Around midnight on August 28th, the hurricane began to turn northwest. At the same time, dry air from Louisiana and Texas began to infiltrate the west side of the storm. As a result, the west side of the cloud mass began to erode away and the barometric pressure within the eye began to rise, indicating the storm was filling/weakening (Fig. 1). Katrina weakened to

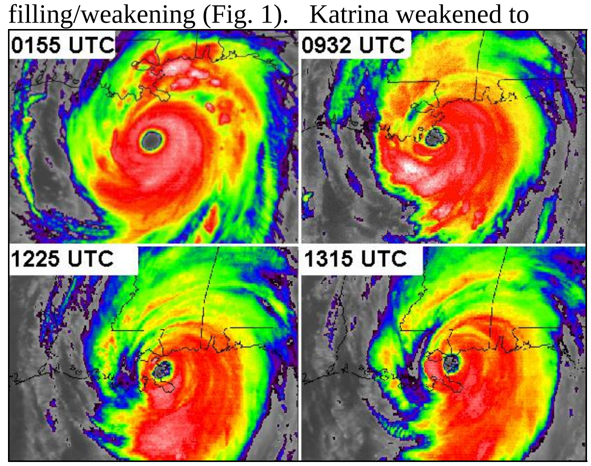

Figure 1. Enhanced color infrared imagery of Hurricane Katrina as it approaches the northern Gulf coast. Note erosion of west cloud shield. UTC times are shown. Image courtesy of NOAA/NWS.

Category 3 strength just prior to making its second landfall south of Buras, LA at 6:10 a.m. on August 29th. Meanwhile, the storm surge rose quickly along the northern Gulf Coast. Waves greater than 15.6 m (50 ft.) broke in the shallow waters on the continental shelf. The result was a record storm surge along the Mississippi coast.

Katrina traveled northward across the Louisiana delta and the eye passed east of downtown New Orleans. Lake Pontchartrain and eastern portions of New Orleans experienced strong north winds in the west eyewall. Water levels rose greater than six feet at the south end of the lake compromising the 17th Street canal levee. Katrina then made a third landfall at the mouth of the Pearl River on the Louisiana and Mississippi border around 1500 UTC (10 a.m.) on 29 August 2005 (Fig. 2).

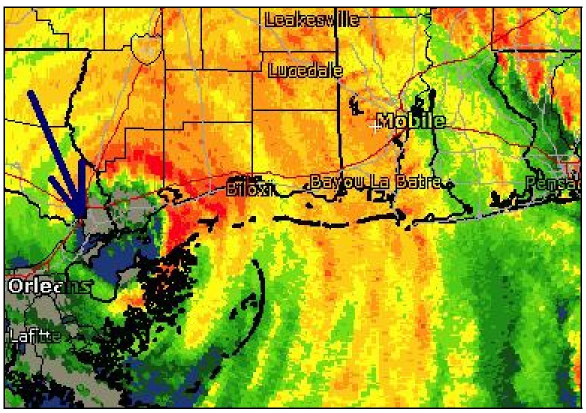

Figure 2. Radar image of Hurricane Katrina at approximately 1500 UTC (10 a.m. local time) on 29 August 2005 as it made landfall at the mouth of the Pearl River. Note the erosion of the southwest side of the storm. Arrow indicates the location of the author. Image courtesy of NOAA/NWS.

Katrina was a large hurricane, especially in comparison to Hurricane Charley which struck Florida the previous year. The large size of Katrina coupled with a long fetch of wind over shallow water resulted in a catastrophic storm surge. Over 320 km (200 mi.) of coastline, from southeast Louisiana, Mississippi, Alabama, and even the Florida panhandle experienced greater than a 3.1 m (10 ft.) foot storm surge.

2a. WIND SPEEDS AND DIRECTION

As typical with northward moving hurricanes, the strongest winds were associated with the north and east eyewall. Communities of Waveland, Bay St. Louis, and Pass Christian, MS experienced the east eyewall and thus, the highest winds.

Wind data was assembled from a number of sources including the National Weather Service/NOAA (2005), National Ocean Service (2005), Texas Tech University (2005), and the Florida Coastal Monitoring Program (2005). Wind records were typically obtained at 10 m (33 ft.) above the ground in open, unobstructed terrain. However, anemometers on buoys 42007 and 42040 were 4.7 m (15 ft.) above the water. Unfortunately, several of the standard reporting stations were not operational during the hurricane. However, Texas Tech University obtained complete records from towers deployed in three locations: Vacherie, LA, Slidell, LA and at the NASA Stennis Space Center northwest of Waveland, MS. Also, the Florida Coastal Monitoring Program obtained records from towers deployed in five locations: Belle Chasse, LA, Galliano, LA, Bay St. Louis, MS, Gulfport, MS, and Pascagoula, MS. However, they reported problems with the wind equipment at Bay St. Louis and Gulfport, MS locations.

The Stennis Space Center site experienced the northern eyewall. They recorded a maximum wind gust of 52.3ms^{-1} (117 mph) with a peak three-second gust of 47.1ms^{-1} (105 mph) around 1500 UTC (10 a.m.). The wind equipment reportedly was at 10 m (33 ft) above the ground in open, unobstructed terrain (Fig 3).

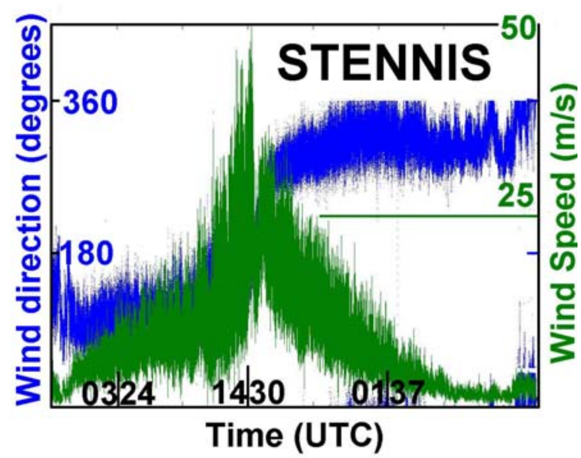

Figure 3. Wind speed (ms^{-1}) and direction from the Stennis Space Center near Waveland, MS during Hurricane Katrina. Courtesy of Texas Tech University.

The Slidell, LA site experienced the weaker west eye wall and recorded a peak wind gust of 44.6 ms^{-1} (100 mph) with highest three-second gust at 38.5 ms^{-1} (86 mph). Again these measurements were obtained at 10 m (33 ft.) above the ground in open, unobstructed terrain. Please note that correction factors would have to be employed to translate these values to different heights and exposures. Wind velocities actually would be higher above 10 m (33 ft.) for the same exposure. In contrast, wind velocities would be lower in forested areas at the same elevation due to frictional effects. Such correction factors can be found in ASCE Standard 7-95 (1996).

2b. STORM SURGE

The northern Gulf coast is quite susceptible to inundation from hurricane storm surges due to its low elevation as well as shallow waters offshore. The area is frequented by hurricanes. According to Canis et al. (1985), the northern Gulf coast has been affected by more than 80 hurricanes during the past 270 years.

Generally, 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.

After Katrina, the author has measured the height of the storm surge at over one hundred locations along the Mississippi and Louisiana coasts 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 on trees where floating debris repeatedly impacted and abraded the bark. In low-lying areas, some debris lines were found on roofs (Fig. 4).

Figure 4. Indications of the height of water: a) dirt line in bathroom, b) water line on wall board, c) debris line on roof, and d) scrape marks on trees.

The highest still water height found was 9.7 m (31 ft.) above the ocean in a school on Coleman Road in Waveland, MS. This area was located just to the right of where the center of the eye had crossed the coastline. Measurements around St. Louis Bay varied between 6.9 m to 8.4 m (22 to 27 ft.) depending on location. A summary of selected observations is shown in Figure 5. Other measurements include 7.8 m (25 ft.) at Pass Christian, 6.9 m (22 ft.) at Gulfport, 6.3 m (20 ft.) at Biloxi, 5.9 m (19 ft.) at Ocean Springs, 5.3 m (17 ft.) at Pascagoula, and 4.7 m (15 ft.) at Slidell, LA (Fig. 5). Variations a few feet either side of these levels occurred depending upon the site location, local topography, tidal influences, and datum level selected. Practically the entire Mississippi coast was inundated. Exceptions were bluffs in Bay St. Louis and Pass Christian that exceeded 9 m (29 ft.) elevations.

Figure 5. Selected still water heights (ft.) above the ocean level for the Louisiana and Mississippi coast from Hurricane Katrina.

Waves were superimposed on the storm surge. The waves attacked the bases of buildings and lifted them off their foundations if the buildings were not well attached. Some buildings floated inland but the direction the building moved also depended on the wind direction as well as the ebb and flow of the water. Some buildings broke apart becoming part of an extensive debris line that extended a few kilometers inland. Buildings that remained intact, had their lowest stories gutted by the surge (Fig. 6).

Figure 6. Examples of storm surge damage to buildings in: a) Waveland, b) Bay St. Louis, c) Pass Christian, and d) Biloxi. In each instance, the bottom two stories had been gutted.

A comparison was made between the heights of the storm surge from Hurricane Katrina and other notable hurricanes that had struck the area (Fig. 7).

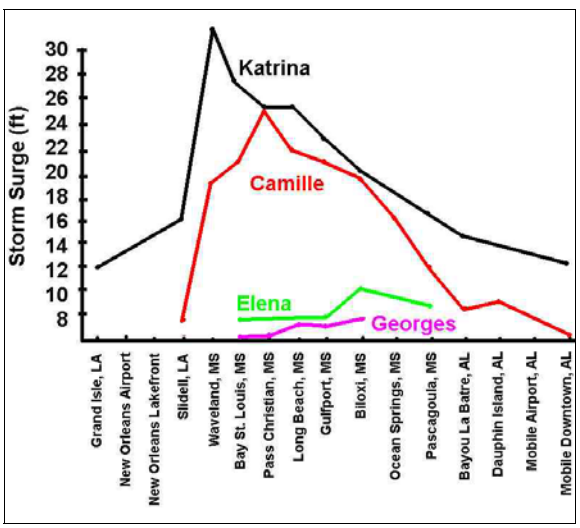

Figure 7. Comparison of storm surge levels from Hurricane Katrina to other notable hurricanes. The surge from Hurricane Katrina reached or exceeded that of Hurricane Camille back in 1969.

In general, Hurricane Katrina water levels exceeded those in Hurricane Camille back in 1969. Many local residents who experienced Hurricane Camille mentioned that they utilized the maximum water depth from Camille as a baseline for comparison. In each instance, the water level from Hurricane Katrina exceeded that of Hurricane Camille. The height and breadth of Katrina's record storm surge was attributed to many factors including the large size of the storm, its high intensity offshore, and the shallow waters off the Mississippi coast. Destruction of buildings along the coast was maximized since many structures were built in low-lying areas and the number of buildings has increased along the coast since Hurricane Camille.

2c. TIMING OF WIND AND WATER

Wind and tide gauge data were assembled for the northern Gulf coast. Many of the tide gauges failed as water levels rose during the morning of August 29th. However, these data show that water levels began to increase as much as 24 hours in advance of the hurricane and water rose quickly within 12 hours of the eye making landfall. East of the eye, surface winds were initially from the east-northeast (blowing along shore), then switched to the south as the eye came ashore. Comparison of the wind and water data indicated that the highest water levels occurred with the highest winds. To date, the most complete tide gauge data found closest to the eye was at Grand Bay, AL. Water levels were compared to the wind reporting station at nearby Pascagoula, MS (Fig. 8.)

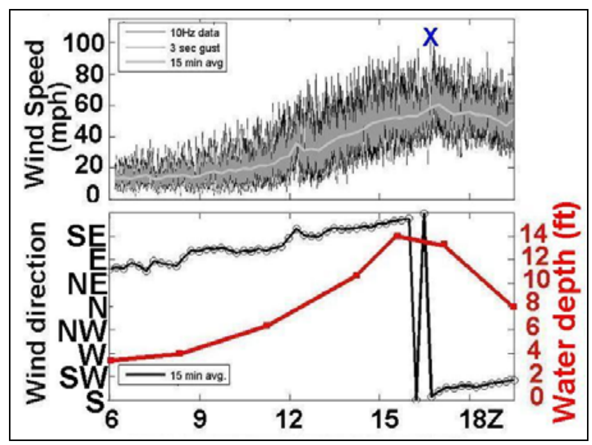

Figure 8. Wind speed (mph) and direction for Pascagoula, MS overlaid with the tide gauge data from Grand Bay, AL. Peak three-second wind gust (X) was 41.5 ms^{-1} (93 mph). Wind data courtesy of the Florida Coastal Monitoring Program. Tide data courtesy of the Grand Bay National Wildlife Refuge.

These data show that the storm surge rose quickly during the morning, reaching its peak about 1600 UTC (11 a.m.), before retreating just as quickly. The peak three-second wind gust at Pascagoula was 41.5 ms^{-1} (93 mph) at 1641 UTC (1141 a.m.). It is interesting to note that the peak winds at Pascagoula occurred about 100 minutes after the peak winds at the Stennis Space Center near Waveland, about 130 km (80 mi.) apart.

Storm chaser Mike Theiss rode out Hurricane Katrina at the Holiday Inn in Gulfport, MS. His video showed the dramatic rise and fall of the storm surge during the morning of August 29th (Fig. 9). The author visited the site and measured various elevations after the storm in order to calculate the height of the storm surge with time.

Figure 9. Storm surge from Theiss video with times indicated. Water crossing Rt. 90 at 1152 UTC, water 1 m (3.2 ft.) deep in hotel at 1357 UTC, water dropping at 1538 UTC, and water gone at 1652 UTC. Video images courtesy of Mike Theiss.

By 1200 UTC (7 a.m.) waves covered the coastal highway, Rt. 90, 3.1 to 3.7 m (10 to 12 ft.) above the normal water level. By 1300 UTC (8 a.m.), water entered the hotel, 5 to 5.6 m (16 to 18 ft.) above the normal water level. By 1400 UTC (9 a.m.), water was at least 1 m (3.2 ft.) deep in the hotel. The peak surge occurred around 1500 UTC (10 a.m.) when water levels reached about 2 m (6.4 ft.) deep in the hotel. This water level was between 7 and 7.6 m (22 to 24 ft.) above normal. Some waves extended to the second floor level. On average, the surge rose about 30 cm (1 ft.) every 15 minutes over a three hour period. The storm surge decreased rapidly after 1530 (10:30 a.m.) and had exited the hotel by 1700 UTC (noon). It is interesting to note that the peak storm surge occurred about one hour earlier in Gulfport, MS than at Grand Bay, AL.

Measurements of the height of the storm surge in Gulfport were overlaid onto the wind chart obtained from Texas Tech University's Stennis site (Fig. 10). The peak winds at the Stennis site occurred very close to the time of the peak storm surge at Gulfport. These sites were about 50 km (31 mi.) apart.

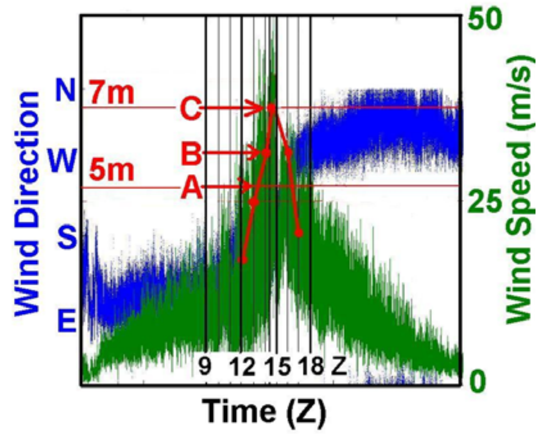

Figure 10. Storm surge height in meters (red) from Theiss video in Gulfport plotted on top of Texas Tech wind data at Stennis. Wind speeds in ms^{-1} (green) and wind direction (blue) are shown. Storm surge entered the hotel in Gulfport at "A", was about 1 m deep at "B", and peaked about 2 m at "C" before dropping rapidly.

The author compared the actual values of wind with Hurricane Research Division (HRD, 2005) model output. Preliminary evaluations indicated that the HRD model overestimated the sustained winds by as much as 25 percent. The maximum sustained (1 min.) wind for the Stennis site was 30.1 ms^{-1} (67 mph) whereas the HRD model indicated the maximum wind was about 40 ms^{-1} (90 mph). Also, the maximum sustained (1 min.) wind for Slidell was 31 ms^{-1} (69 mph) whereas the HRD model indicated the maximum wind was 36 ms^{-1} (81 mph). It was also noted that the maximum winds were predicted too early and too far east.

A comparison also was made between the height of the storm surge at the Gulfport Holiday Inn and predicted storm surge heights as presented by CNMOC (2005). Refer to Figure 11. They utilized the Advanced Circulation Model (ADCIRC) to hindcast the storm surge along the Gulf coast for Hurricane Katrina. Good agreement was found between observed and predicted values in the rate of rise of the storm surge. However, the model overestimated the height of the storm surge at Gulfport, and underestimated its rapid retreat. Also, the peak storm surge predicted by the model arrived about an hour later than it did in reality. Part of the error in the ADCIRC model may be explained by its use of HRD winds.

Similarly, model output was compared with the tide gauge data at Waveland, MS (not shown). The tide gauge ceased at 0900 UTC (4 a.m.) and the peak surge measured was 9.7 m (31 ft.). Again, there was good agreement between observed and predicted values in the rate of rise of the storm surge, however, this time the model underestimated the height of the storm surge in reality.

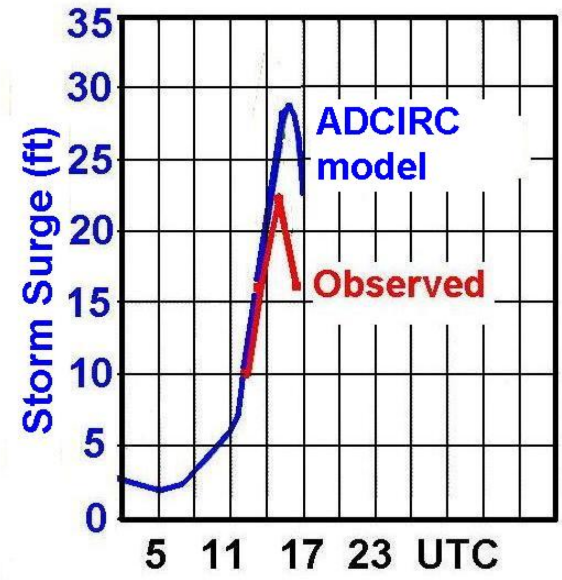

Figure 11. Measured storm surge heights for Gulfport, MS compared to results from ADCIRC model.

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 (2003) 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 12 along with actual wind speed measurements.

Figure 12. Three-second peak wind gusts (in mph) at 10 m (33 ft.) above the ground in open terrain for the Louisiana and Mississippi coastal region. Estimated winds are indicated by the letter E after the number and are based on wind speed-damage correlation.

Actual and estimated three-second peak wind gusts from Hurricane Katrina were then compared to the design three-second gusts as stated in the ASCE 7-95 (1996) standard (Fig. 13). This standard indicates that structures built along the Mississippi coast should be designed for 130 mph three-second gust. It was found that the Hurricane Katrina’s winds were lower than those stated in the ASCE 7-95 standard.

A comparison also was made between the winds associated with Hurricane Katrina and other notable hurricanes that have struck the coast (Fig. 14). In general, Hurricane Betsy in 1965 had stronger winds than Katrina in Louisiana. Hurricane Camille in 1969 had stronger winds than Katrina along most of the Mississippi coast and Hurricane Frederic in 1979 had stronger winds along the Alabama coast. Hurricanes Elena in 1985, Georges in 1998, and Frederic in 1979 had comparable winds to Katrina in the Gulfport – Biloxi, MS area.

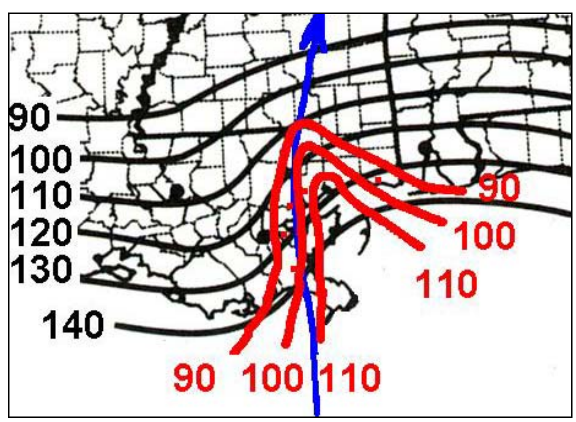

Figure 13. Comparison between the basic design wind speeds in ASCE 7-95 (black lines) with those from Hurricane Katrina (red lines). The track of the eye is shown in blue.

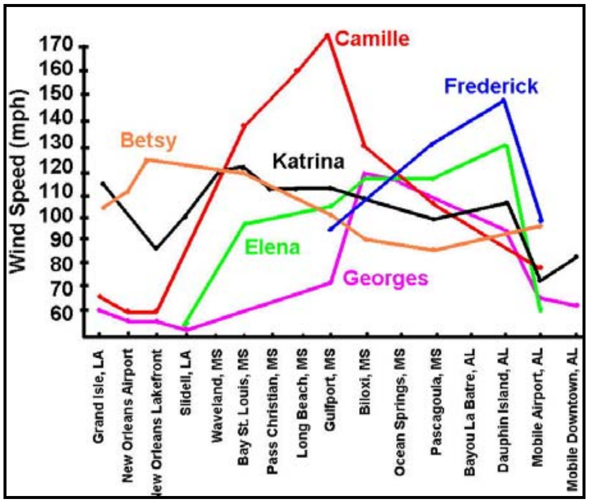

Figure 14. Comparison of peak wind velocities (mph) from Hurricane Katrina with other notable hurricanes that have struck the region.

4. DAMAGE BY COMMUNITY

The following is a summary of damage observations by community:

4.1 BAY ST. LOUIS, MS

The east eye wall of Hurricane Katrina passed over Bay St. Louis. Thus, this community experienced some of the highest winds and storm surge on the Mississippi coast. Wind damage to buildings primarily involved the displacement of the roof covering as well as vinyl siding. Occasional damage occurred to the south and east facing gable ends and some roof decking was displaced. However, almost all the roof structures remained intact. Part of this was due to the fact that many buildings had roofs strapped down to their walls. A number of billboards, signs, and gas station canopies were damaged by wind, however, there were an equal number of undamaged signs and canopies. Numerous pine trees were downed to the west-northwest indicating the strongest winds were from the east-southeast. Peak three-second wind gusts were estimated at about 51 ms^{-1} (115 mph) at 10 m (33 ft.) in open terrain. Winds were considerably lower in wooded areas.

Almost the entire city was inundated by Katrina's storm surge. The exceptions were some of the older buildings located on higher terrain along the shore. Buildings in low-lying areas along the coast were destroyed by wave action leaving "slick" slabs, cleaned of framing and floor coverings. The Rt. 90 bridge as well as the railroad bridge extending across St. Louis Bay to Pass Christian were completely destroyed by the storm surge. Bridge decks ranged between 12 to 15 feet above the water. Deck sections were uplifted by rolling waves and moved northward eventually falling off their supports. Portions of Beach Blvd., the coastal highway, were washed away. Still water lines along the coast ranged from 6.9 m to 8.4 m (22 to 27 ft.) above the normal water level. The highest still water line found was 2.5 cm (1 in.) inch above the floor, on the third story of a residence. Landmarks such as the St. Stanislaus College sustained considerable water damage to its first floor. A still water mark was observed on the cyclone fence on the pedestrian walkway in front of the college.

4.2 BILOXI and BILOXI BAY, MS

The city of Biloxi was located on a low-lying peninsula that extended eastward into Biloxi Bay. Practically the entire peninsula was inundated by Katrina's storm surge. Most of the observed wind damage was to cladding items such as roof shingles and vinyl siding. However, we did observe a few roofs that had been removed on older homes. In these instances, wood rafters were only toe-nailed to the wall top plates and the nails had corroded. Peak three-second wind gusts were estimated to be 47 ms^{-1} (105 mph) at 10 m (33 ft.) in open terrain. Winds were considerably lower in wooded areas.

Storm surge damage to coastal structures was extensive. The surge gutted the lowest two stories. Many of the older wood-framed homes floated off their pier and beam foundations. These buildings were not anchored and had been constructed with diagonal tongue-and-grooved wall and floor sheathing. The solid sheathing provided ample buoyancy and floated homes like a boat. Homes on low-lying Langley Point were completely removed by the storm surge leaving "slick" slabs. Many of the casino barges floated inland striking other buildings. Biloxi Bay rose approximately 6.2 m (20 ft.) above normal inundated inlets and bayous.

4.3 GULFPORT, MS

The city of Gulfport received considerable damage from Hurricane Katrina. Winds had damaged asphalt roof coverings including those on older homes that were covered with asbestos-cement tiles. Flying debris broke windows in some of the downtown buildings. The steeple on the First Baptist Church survived although wind removed some of the cladding as well as a section of the roof along the east gable end. Brick masonry toppled from several buildings where it was not well attached. In some instances, we found that metal brick ties were corroded. Peak three-second wind gusts were estimated to be 49 ms^{-1} (110 mph) at

10 m (33 ft.) in open terrain. Winds were considerably lower in wooded areas.

Like Biloxi, Gulfport had a number of casinos along its shore. A storm surge of about 6.9 m (22 ft.) above normal gutted the lowest two stories of coastal buildings or removed buildings from their foundations. Casino and freight barges broke out of their moorings and floated inland. The storm surge did not extend as far inland as in other areas along the coast due to Gulfport's slightly higher elevation.

4.4 PASCAGOULA, MS

Pascagoula was located about 105 km (65 mi.) east of the landfall position of Hurricane Katrina and experienced lower winds and storm surge. Wind damage to buildings was generally minor involving mostly the displacement of roof shingles. As mentioned earlier, a peak three-second gust of 41.5 ms^{-1} (93 mph) was recorded by the Florida Coastal Monitoring Program at 10 m (33 ft.) in open terrain.

Pascagoula was relatively low in elevation as it is located on the eastern shore of the Pascagoula River where it meets the ocean. Most of the city flooded south of Rt. 90 along with a number of inlets. The storm surge extended up to 5.3 m (17 ft.) above the normal destroying many buildings within the first two blocks of the ocean.

4.5 PASS CHRISTIAN, MS

One of the hardest hit communities was Pass Christian, located on a peninsula that extends westward into St. Louis Bay. A storm surge of about 7.8 m (25 ft.) inundated the town, destroyed coastal homes and flooded inland areas. The lowest two stories of most buildings were gutted including the local boat storage facility. Many homes floated that were not well attached to their foundations. Even the local Wal-Mart was gutted to the ceiling. Only the older buildings located on a bluff at the east end of town escaped being damaged by the storm surge.

Wind damage to buildings primarily involved the displacement of the roof shingles and vinyl siding. Occasional damage occurred to the south and east facing gable ends. In a few instances, some roof decking was displaced. However, roof structures remained intact. Numerous pine trees were downed to the west-northwest indicating the strongest winds were from the east-southeast. Peak three-second wind gusts were estimated to be about 51 ms^{-1} (115 mph) at 10 m (33 ft.) in open, unobstructed terrain. Winds were significantly lower in wooded areas.

4.6 SLIDELL, LA

Although Slidell, LA was on the weaker west side of Hurricane Katrina, strong northerly winds toppled numerous pine trees onto homes causing significant damage. Electric power also was out throughout most of the city for weeks. Wind damage in open areas was primarily limited to cladding items such as the displacement of roof coverings and vinyl siding. However, some poorly attached roofs were removed by the wind. In general, metal clad roofs performed better than three-tab shingle roofs. Even the older asbestos-cement tile roofs performed reasonably well. As mentioned earlier, the Texas Tech tower recorded a peak three-second gust at 38.5 ms^{-1} (86 mph).

Storm surge inundated most of the city. Even with northerly winds, water levels rose 4.7 m (15 ft.) or more along the north shore of Lake Pontchartrain. The author observed the peak surge to have occurred near the time of the peak winds between 1400 and 1500 UTC.

4.7 WAVELAND, MS

Waveland, MS was "ground zero" for Hurricane Katrina and was one of the hardest hit communities observed in the survey. Practically all of the buildings south of Rt. 90 were inundated by the storm surge. All coastal homes were destroyed by waves with the exception of two steel-framed structures that had their third stories left relatively intact. The town hall was destroyed. However, a sign dedicated to those who lost their lives in Hurricane Camille survived.

Wind damage to buildings primarily involved the displacement of the roof covering as well as vinyl siding. Occasional damage occurred to the south and east facing gable ends and some roof decking was displaced. Many trees were downed to the west and northwest indicating the strongest winds were from the east-southeast. Peak three-second wind gusts were estimated to be about 51 ms^{-1} (115 mph) at 10 m (33 ft.) in open terrain.

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. 15).

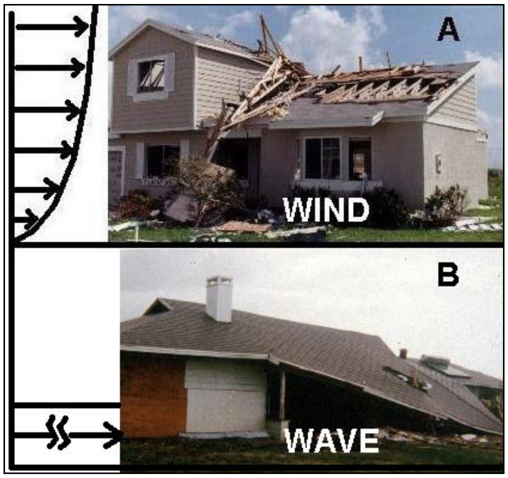

Figure 15. Examples of wind (a) and wave (b) damage to housing. Relative forces are illustrated on left with height above the ground.

Wind interacting with a building is deflected over and around it. Positive (inward) pressures are applied to the windward walls trying 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 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 also can lift wooden buildings on pier and beam foundations as they are buoyant and will float. The author has observed numerous houses that floated landward or out to sea depending on the wind direction during the hurricane. Homes with brick veneer construction tended to rise and sink within the brick veneer shell especially if there are few or no brick ties. Houses invariably did not come back to the same position, causing distortion of the wooden-frame. Wind did 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 inch) in diameter and 30 cm (12 inches) 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 bottom plate and wall corners.

Storm surge destroyed many buildings on slab foundations (Fig. 16). 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 16. Typical home on a stem wall foundation that was completely destroyed by Hurricane Katrina's storm surge.

Buildings that were completely destroyed still left evidence as to the direction and magnitude of the applied forces (Fig. 17). 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.

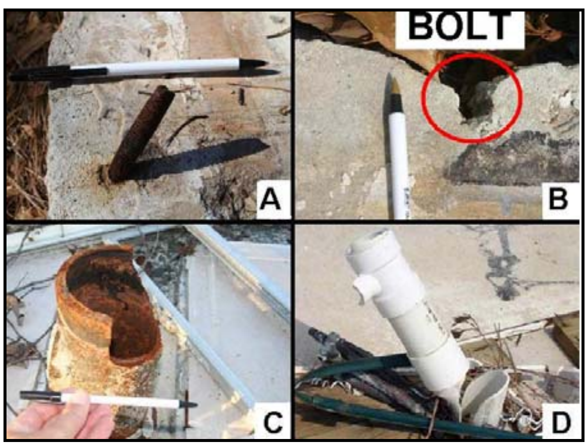

Figure 17. Indicators of direction and magnitude of the applied force: a) bent bolt, b) bolt broke out of leeward side of slab, c) broken iron piping, and d) broken PVC piping.

In many instances, unbroken items were found on or near slabs. These included glass doors, windows with screens, mirrors, dishes, and lights. Ceiling fans were found with blades and glass globes still attached. The lack of damage to such brittle items resulted when the home was dismantled slowly and the items fell into the water. Items beneath the water remained protected (Fig.18).

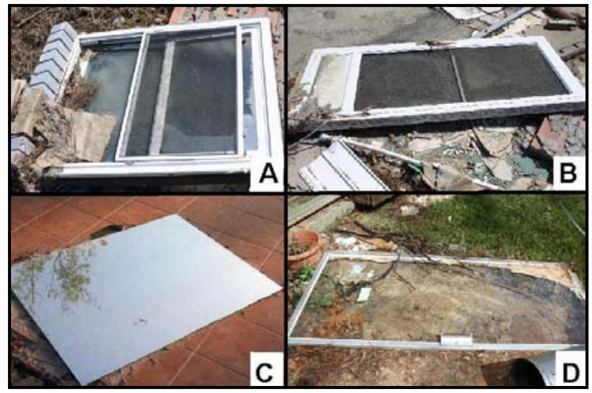

Figure 18. Unbroken items left on or near the concrete slab where houses were completely destroyed: a) window with screen, b) door with screen, c) mirror, and d) glass door.

In certain instances, scrape marks were found on concrete slabs indicating where sharp objects, such as nails and bolt stems, were repeatedly pushed back and forth due to wave action (Fig. 19).

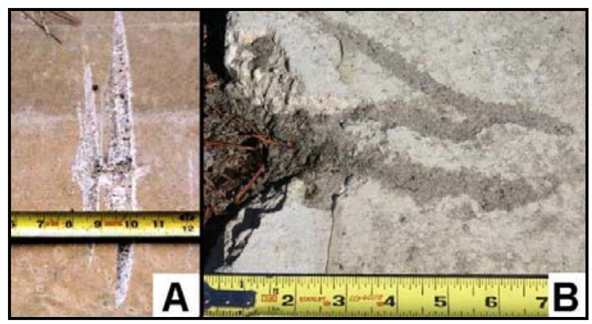

Figure 19. Examples of scrape marks on concrete slabs from a) nailed wall bottom plates, and b) bolted wall bottom plates. Wave action caused the walls to move back and forth resulting in these marks.

When destroyed buildings were encountered, an attempt was made to examine other buildings nearby 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.

Additional evidence was obtained regarding wind and wave forces when portions of the building remained. Waves pushed the bases of walls inward on the ocean side and pushed out the bases of walls on the back side of the building (Fig. 20). If enough loadbearing walls were compromised, the building collapsed. Usually, the building collapsed on the oceanfront side first, appearing "pitched down" toward the water. Sometimes the roof remained upright on the ground. In other instances, the roof broke apart becoming part of the debris line. Low-level forces from wave action actually created a hinge at the top of the walls. In contrast, wind forces pushed the tops of the walls inward on the windward side of the building. Thus, the hinge point for wind was at the base of the wall.

Figure 20. Surge damage to walls: a) base of wall pushed inward on oceanfront side, and b) base of rear wall pushed outward. Walls were subjected to low-level forces from moving water.

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. 21). However, in some 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.

Figure 21. Examples of wind damage to wood-framed residences from Hurricane Katrina: a) displaced roof covering, b) loss of roof deck, c) loss of roof structure, and d) tree impact damage.

A number of items susceptible to wind forces were found undamaged even in the hardest hit areas. These included satellite dishes, cupolas, weathervanes, bird houses, and signs. Such undamaged items indicated that the wind velocities were not very high (Fig. 22).

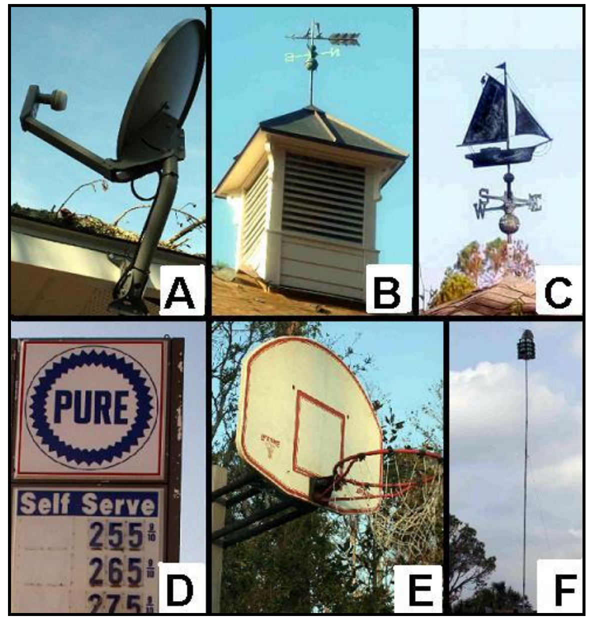

Figure 22. Items not damaged by wind in Bay St. Louis and Pass Christian, MS in and close to the east eyewall: a) satellite dish mounted to an eave with only two screws, b) copper clad cupola, c) weathervane, d) gas station sign including plastic numbers, e) basketball backstop, hoop with net, and f) a birdhouse mounted on a 15.6 m (50 ft.) pole.

7. BUILDINGS ON TIMBER PILINGS

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 piles and resist soil erosion.

Wood girders were usually set into notches and bolted to the tops of the piles. 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. 23).

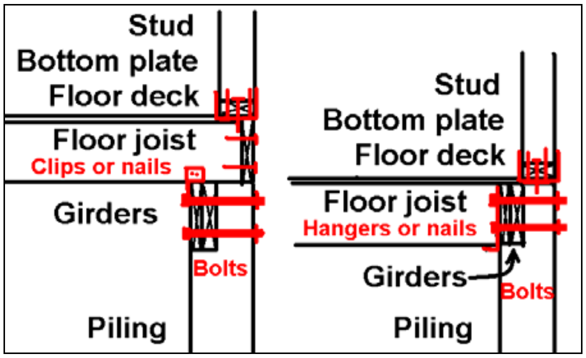

Figure 23. Different floor details on buildings elevated on timber piles.

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.

Analysis of the pilings revealed evidence of both lateral as well as uplift forces. Piles rotated or broke when impacted by lateral forces sufficient to damage them. The direction of the applied force could be determined by the direction the piles rotated. Sometimes piles were abraded or scarred by floating debris (Fig. 24). Uplift forces from wave action bent bolts at the tops of the pilings that had secured the girders. Bolts were bent in the direction of the applied force.

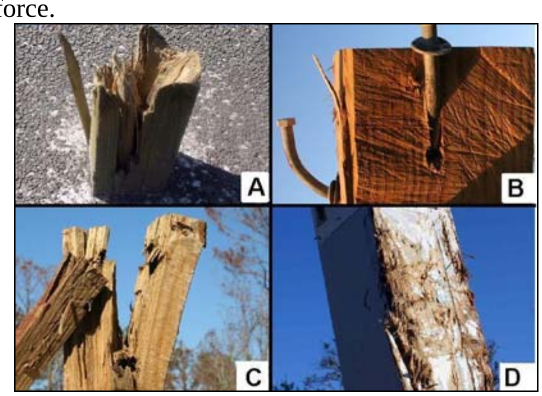

Figure 24. Damage to pilings from storm surge: a) broken piling, b) bolts bent upward that had secured floor girders, c) bolts lifted out of top of piling, and d) abraded and leaning piling from repeated impacts of floating debris.

Waves high enough to reach the second story floors, frequently bent the girders landward or uplifted them from the tops of the pilings (Fig. 25). In some instances, the girders were removed along with their bolts. However, in other instances, the girders broke around the bolts leaving the bolts in the pilings. Wind was not a factor in damaging floor girders as bolted connections between girders and pilings were usually the strongest in the building. Instead, wind exploited weaker connections above (i.e. where walls were attached to floors or roofs were attached to walls). Girders that remained intact some times contained rub marks where floor members abraded the wood. In some instances, ocean debris, such as flotsam and seaweed, had been draped over the girders.

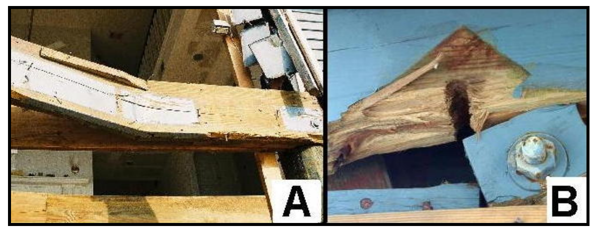

Figure 25. Surge damage to girders: a) girder bent landward (lateral force), and b) girder lifted by wave action (uplift force) breaking out of bolted connection.

The first sign of wave damage to elevated floors was the rotation or removal of blocking in between the floor joists. Then moving water would sever the nailed connections between the floor joists and the girders. Loose floor joists then became part of the mass of debris that helped impact and dismantle the rest of the floor. In some instances, loose floor joists were pushed inland and stacked together on the landward side of the building. Galvanized metal clips or straps between the floor joists and girders were bent or broken. Connections between floor joists and girders were generally weaker than between girders and pilings. Thus, in many instances, floor sections were missing but girders remained bolted to the pilings.

Uplift forces from wave action lifted the floor joists out of their hangers or pulled apart strapped connections. Floors then broke up into sections and floated away or continued to strike the floor. The break up of floors did not occur all at once but occurred progressively as each wave raised and lowered the floors. Some times this up and down movement was recorded when joists abraded other boards or nails scribed marks in the wood (Fig. 26). If a sufficient number of floor joists were removed, the floor collapsed leaving walls suspended from their top plates or portions of the structure collapsed into the water.

Wind was not a factor in damaging the elevated floor structure. In fact, elevated buildings damaged by wind left the floor systems intact.

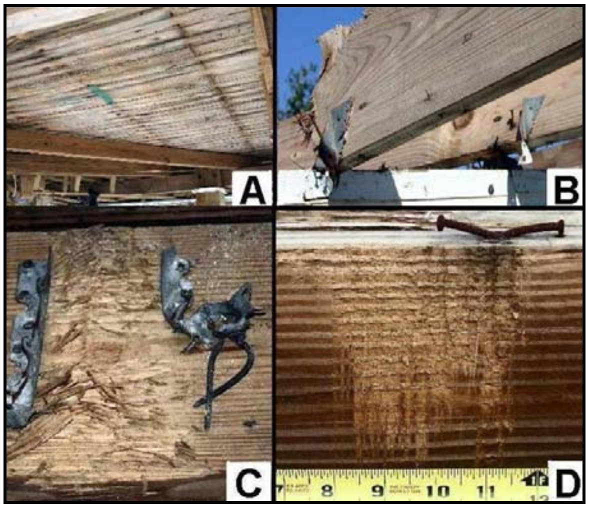

Figure 26. Surge damage to floor joists: a) lateral movement of joists, b) uplift of joists which bent and broke the straps, c) and d) rub marks where joists moved up and down repeatedly against girders.

Subflooring consisted of plywood sheathing that was nailed to the tops of the joists. Rolling waves lifted floor sheathing causing the nails to back out of the wood. This process did not occur all at once but progressively as each wave struck the floor. Continued wave action dislodged sections of the floor and it floated away. However, in some instances, flooring was shuffled together and stacked like playing cards (Fig. 27). Wind did not cause this condition.

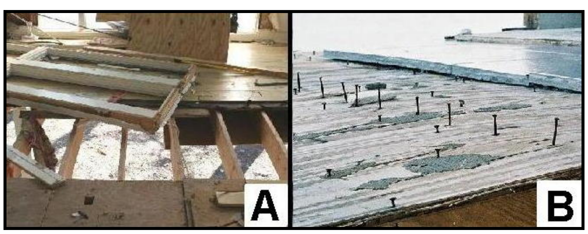

Figure 27. Storm surge damage to subflooring: a) dislodged plywood sheets, b) backing out of nails in the plywood due to repeated wave action.

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 began at roof level, 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 intact in wind caused failures. (Fig. 28).

Figure 28. Examples of wind damage to buildings elevated on timber pilings: a) removal of roof covering, b) roof deck failure, c) gable end pushed inward, and d) loss of roof canopy over balcony.

8. TORNADOES

No tornado damage had been observed along the Mississippi or Louisiana coast to date. However, the author has encountered a number of people who believe that tornadoes occurred. A popular misconception was 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 the 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 one hundred miles of 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 (2005) and the USGS (2005) were invaluable in delineating wind versus wave damage zones.

Another point of confusion was the issuance of tornado warnings for counties affected by high winds in the eyewall. The general perception among the public was that the warnings were issued for tornadoes, not the high hurricane winds. 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. The public needs to understand that hurricane winds do almost all of the wind damage. Tornadoes are rare, even in hurricanes.

9. SUMMARY

The author conducted ground and aerial surveys of the Gulf Coast after Hurricane Katrina in an attempt to ascertain the extent of damage from wind and water effects. Survey work is still ongoing. To date, hundreds of specific site inspections have been conducted in Louisiana and Mississippi. Wind damage was found to be widespread due to the large size of the hurricane. However, much of the direct wind damage to buildings was limited to cladding items such as the roof coverings and vinyl siding. In rare instances, wind removed some roof decking and/or portions of the roof structure. Using the concept of wind speed-damage correlation, the author found that peak three-second wind velocities were below the 130 mph basic design wind speeds for the area as specified in ASCE 7-95. Hurricane Katrina had winds comparable to other notable hurricanes that had struck the region. No tornado damage was found along the coast. Also, no areas of category 3 winds were found in the survey.

Hurricane Katrina had a record storm surge. The highest still water line measured to date was about 9.7 m (31 ft.) in the community of Waveland, MS. The storm surge was greater than 4.7 m (15 ft.) along the entire Mississippi coast including portions of the north shore of Lake Pontchartrain. As a result, complete destruction of coastal buildings occurred in a swath of more than 160 km (100 mi) along the coast. Buildings inland from the coast were flooded. Many homes floated that were not anchored well to their foundations.

Analysis of available data indicated that the storm surge preceded and accompanied the strongest hurricane winds. The storm surge increased gradually at first and became noticeable in tide gauge data 12 to 24 hours before eye made landfall. A "double whammy" effect occurred along the coast where water was driven ahead of the storm then squeezed by the approaching higher winds that impinged on the coast. Comparison of the wind and water data indicated that the highest water levels occurred with the highest winds. Certain models overestimated the magnitude of the wind and/or the timing of the storm surge.

10. ACKNOWLEDGEMENTS

The author would like to thank each of the cities affected for help in obtaining access to the disaster area after the storm including all the volunteers and relief organizations. The Florida Coastal Monitoring Program, Hurricane Research Division, National Buoy Data Center, National Hurricane Center, National Ocean Service, National Weather Services, and Texas Tech University provided much of the wind and water data. Mike Theiss provided invaluable information about the storm surge in Gulfport. Skip Jiles with the Pensacola Aviation Center piloted the aircraft during the aerial survey. John Stewart, Jim Weithorn, Polly Lawler, Kay Marshall, and C.S. Kirkpatrick reviewed the paper.

11. REFERENCES

ASCE Standard 7-95, 1996: Minimum Design Loads for Buildings and Other Structures, Amer. Soc. Of Civil Engineers, 214 pp.

Canis, W.F., Neal, W.J., Pilkey Jr., Orrin, and Orrin Pilkey Sr., 1985: Living with the Alabama-Mississippi shore, Duke University Press, Durham, NC, 215 pp.

CNMOC, 2005: Preliminary Model Hindcast of Hurricane Katrina Storm Surge, Stennis Space Center, MS, [Available at: http://www.fnmoc.navy.mil/products/KATRINA/Notice.pdf]

FEMA, 1989: Is it Wind or is it Water?, Federal Emergency Management Agency Publication, 46 pp.

Florida Coastal Monitoring Program, 2005: Hurricane Katrina Deployments, [Available at: http://www.ce.ufl.edu/~fcmp]

Hurricane Research Division, 2005: Hurricane Katrina http://www.aoml.noaa.gov/hrd/Storm_pages/katrina2005/wind.html

Knabb, R.D., Rhome J.R., and D.P. Brown, 2005: Tropical Cyclone Report on Hurricane Katrina, National Hurricane Center. [Available online at: [http://www.nhc.noaa.gov/2005katrina.html?]

Marshall, T. P. W. Bunting, and J.W. Wiethorn , 2003: Procedure for assessing wind damage to wood-framed residences, The Symposium on the Fujita Scale and Severe Weather Damage Assessment, 83rd Annual Meeting, Amer. Meteor. Soc., Long Beach, CA, [CD-ROM available from http://www.ametsoc.org]

Marshall, T. P., 1993: Lessons learned from analyzing tornado damage, The Tornado: It's Structure, Dynamics, Prediction, and Hazards. Geophysical Monograph, 79, American Geophysical Union, p. 495-500.

McDonald, J.R., 2003: The Enhanced Fujita Scale, [available at http://www.wind.ttu.edu/EFscale.pdf]

Mehta, K. C., J.E. Minor, and T. A. Reinhold, 1983: Wind Speed-Damage Correlation in Hurricane Frederic, American Society of Civil Engineers, Journal of Struct. Engr. Vol 109, No. 1. 37-49.

Minor, J.E., 1982: Tornado Technology in Professional Practice, Journal of the Struct. Div., Proc. Of the Amer. Soc. Of Civil Engineers., Vol. 108, No. ST11, p. 2411-2420.

Minor, J.E., McDonald, J.R., Mehta, K.C., 1993: The Tornado: An Engineering-Oriented Perspective, Southern Region, NWS SR-147, 196 pp. [Available at http://www.srh.noaa.gov/ssd/html/techmemo.htm]

National Ocean Service, 2005: Preliminary Water Levels Report for Hurricane Katrina, available online at:
[http://140.90.121.76/publications/NOS_Preliminary_Water_Levels_Report_Hurricane_Katrina_2005.pdf]

National Weather Service/NOAA, 2005: Post Storm Data Acquisition: Aerial Wind Analysis and Damage Assessment for Hurricane Katrina., available at: http://www.weather.gov/om/data/pdfs/KatrinaPSDA.pdf]

NOAA, 2005: Aerial photographs after Katrina. [Available at:
http://hgs.woc.noaa.gov/katrina/KATRINA0000.htm

Simpson, R.H., and H. Riehl, 1981: The Hurricane and Its Impact, Louisiana State Univ. Press, Baton Rouge, LA, 391 pp.

Texas Tech University, 2005: Hurricane Katrina Deployments. [Available at:
http://www.atmo.ttu.edu/wemite/Deployments.htm]

USGS, 2005: Coastal impact studies after Hurricane Katrina. [Available at:
http://coastal.er.usgs.gov/hurricanes/katrina]