MCEER SPECIAL REPORT SERIES

Engineering and Organizational Issues Before,
During and After Hurricane Katrina

HURRICANE
KATRINA

Volume Four

BUILDINGS

Damage to Engineered Buildings and Lifelines from Wind, Storm Surge and Debris in the Wake of Hurricane Katrina

Gilberto Mosqueda and Keith A. Porter

MCEER

EARTHQUAKE ENGINEERING TO EXTREME EVENTS

MCEER is a national center of excellence dedicated to establishing disaster-resilient communities through the application of multidisciplinary, multi-hazard research. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation (NSF) in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission has expanded from its original focus on earthquake engineering to address a variety of other hazards, both natural and man-made, and their impact on critical infrastructure and facilities. The Center's goal is to reduce losses through research and the application of advanced technologies that improve engineering, pre-event planning and post-event recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

Funded principally by NSF, the State of New York and the Federal Highway Administration (FHWA), the Center derives additional support from the Department of Homeland Security (DHS)/Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

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16. Abstract (limit 200 Words)

Hurricane Katrina caused significant damage to engineered infrastructure including levees, commercial and public buildings, roads and bridges, utility distribution systems for electric power and water, waste water collection facilities and vital communication networks. Damage to critical infrastructure such as hospitals and communication systems crippled the affected communities, and more importantly, the response and recovery efforts following the hurricane. In the aftermath of Hurricane Katrina, the important question now is: How can we better prepare ourselves to prevent or minimize the level of damage and the subsequent catastrophe in the next extreme event? A multidisciplinary team of investigators from the Multidisciplinary Center for Earthquake Engineering Research (MCEER), headquartered at the University at Buffalo, conducted post-disaster field reconnaissance to examine the impact of Hurricane Katrina on physical engineered systems and the response and recovery efforts that followed. Their objectives were to examine wind, storm surge and debris damage from a multi-hazard perspective. Implications of lessons learned from this reconnaissance effort are being examined to mitigate damage and improve response and recovery efforts not only from future hurricanes, but also from other extreme events such as earthquakes or terrorist attacks. By collecting this multi-hazard information, MCEER is seeking to develop engineering design strategies and organizational strategies that will make communities more resilient against any extreme event.

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Foreword

On August 29, 2005, Hurricane Katrina made landfall with sustained winds estimated at 125 mph, storm surges as high as 25 feet and winds extending 125 miles from its center. It resulted in over 1,800 lives lost, and caused major flooding and damage that spanned more than 200 miles along the Gulf Coast of the United States.

The extensive damage to the built environment far exceeded the expected damage for a storm of this intensity. Based on measured wind speeds and the Saffir-Simpson scale, Hurricane Katrina reached Category 5 strength while in the Gulf of Mexico, but quickly dissipated to a Category 3 storm before landfall. Although the wind speeds were substantially reduced before striking land, the storm surge apparently maintained the heights associated with a Category 5 storm and appears to have been responsible for most of the damage along the Mississippi coast and in the Mississippi Delta below New Orleans. Levee failure in New Orleans, associated with storm surge, is responsible for most of the property loss in New Orleans. It should be noted that early estimates ranked Hurricane Katrina as a Category 4 storm at landfall; the National Hurricane Center downgraded this ranking after revising wind speeds in December 2005.

Hurricane Katrina caused significant damage to engineered infrastructure including levees, commercial and public buildings, roads and bridges, utility distribution systems for electric power and water, waste water collection facilities, and vital communication networks. Damage to critical infrastructure such as hospitals and communication systems crippled the affected communities, and more importantly, the response and recovery efforts following the hurricane. In the aftermath of Hurricane Katrina, the important question now is: How can we better prepare ourselves to prevent or minimize the level of damage and the subsequent catastrophe in the next extreme event?

Funded by the National Science Foundation, a multidisciplinary team of investigators from the Multidisciplinary Center for Earthquake Engineering Research (MCEER), headquartered at the University at Buffalo, conducted post-disaster field reconnaissance to examine the impact of Hurricane Katrina on physical engineered systems and the response and recovery efforts that followed. Their objectives were to examine wind, storm surge and debris damage from a multi-hazard perspective. Implications of lessons learned from this reconnaissance effort are being examined to mitigate damage and improve response and recovery efforts not only from future hurricanes, but also from other extreme events such as earthquakes or terrorist attacks. By collecting this multi-hazard information, MCEER is seeking to develop engineering design strategies and organizational strategies that will make communities more resilient against any extreme event.

The MCEER special report series “Engineering and Organizational Issues Before, During and After Hurricane Katrina” was initiated to present the findings from the field reconnaissance mission. The topics addressed include advanced damage detection using remote sensing, damage to engineered structures, organizational decision making primarily in hospitals, and environmental and public health issues. The reports will contribute to the development of a better understanding of how to cost-effectively enhance the resilience of the nation’s infrastructure against future extreme events.

Contents

1.0 Introduction

Hurricane Katrina made landfall at 7:00 a.m., Monday August 29, 2005, striking the Gulf Coast states of Louisiana, Mississippi and Alabama (after passing through Florida on August 25). The resulting death toll exceeded 1,800, with over 1,500 deaths in Louisiana (Hunter 2006). Hurricane Katrina is estimated to be the costliest disaster in U.S. history with over $40 billion in insured losses, with half of that amount due to the flooding in New Orleans (AIR Worldwide 2005). Total losses are estimated to exceed $100 billion (Frist 2006) with job losses exceeding 580,000 (Bureau of Labor Statistics 2006).

Hurricane Katrina was a Category 3 Hurricane on the Saffir-Simpson Scale (Knabb et al., 2005), based on the maximum measured one-minute sustained winds at the coastline of 125 mph. In addition to wind, however, Katrina fueled a storm surge as high as 25 feet, and storm tide (storm surge plus astronomical tide) of up to 27 feet. Storm tides overtopped levees south of New Orleans and in parts of New Orleans proper. The structural failure of other levees in New Orleans (Seed et al., 2005) substantially contributed to the damage by flooding 80 percent of the city and damaging or destroying 200,000 homes in New Orleans (NAHB 2006).The combined wind, storm surge and flooding resulting from Hurricane Katrina caused substantial damage to engineered infrastructure including levees, commercial and public buildings, roads and bridges, utility distribution systems for electric power and water, waste water collection facilities, and communication networks. In particular, damage to critical infrastructure such as hospitals (Arendt and Hess, 2006), transportation networks (O'Connor and McAnany, 2008), and communication systems (NIST 2006) hindered the response and recovery efforts following the hurricane.

MCEER organized teams of investigators to conduct post-disaster investigations following Hurricane Katrina. The unique objectives of this study were to examine damage to buildings from a multi-hazard perspective. In particular, damage to the built environment caused by Hurricane Katrina is examined and compared to damage typically observed after earthquakes, with the goals of identifying potential application of seismic mitigation strategies for hurricane prone regions. In this respect, MCEER researchers are seeking to apply their expertise in seismic risk mitigation to other hazards. The data collected in this reconnaissance will be utilized in future studies to examine the feasibility of unified design guidelines for more resilient buildings and infrastructure that can withstand many types of hazards. This extreme event also provided a rare opportunity to evaluate the performance of structures under design level loads and assess current structural design provisions.

Hurricane Katrina was in itself a multi-hazard event: a combination of wind forces, storm surge and flooding all contributed to the damage. It is important to note the multi-hazard nature of Hurricane Katrina because communities, such as the hospitals in New Orleans, were prepared for and faired well during the initial hurricane hazard, but were not able to recover from the second hazard of flooding due to levee breaches in New Orleans (Arendt and Hess, 2006). Similar to the 1906 San Francisco Earthquake in which widespread fires followed the earthquake, the combination of hazards paralyzed a major city. These events underscore the importance of multi-hazard consideration in emergency planning and engineering design towards achieving resilient communities.

The scope of the investigations reported herein is on engineered construction, namely commercial and public multi-story buildings (such as office buildings, hotels, apartment buildings hospitals, and schools), and lifelines (including electric power and water distribution systems, waste water collection system, and communication networks). The geographic area of study is primarily in densely populated regions along the Gulf Coast including New Orleans, Louisiana, as shown in Figure 1-1.

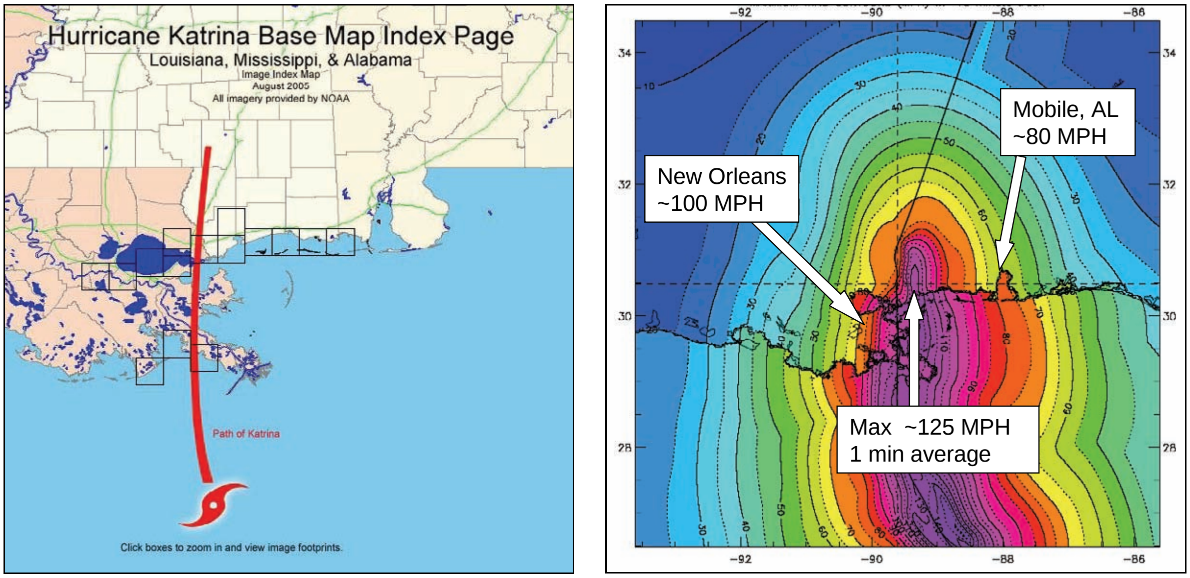
Figure 1-1. Areas of investigation for MCEER reconnaissance of buildings and infrastructure were concentrated in New Orleans and the Mississippi Coast (mainly Gulfport and Biloxi)

2.0 Background Information

Hurricane Katrina caused substantial damage to engineered infrastructure including buildings, bridges, and lifelines and provided a unique opportunity to examine the performance of engineered construction under extreme loading. The forces generated by Hurricane Katrina that caused damage to the built environment are described in this chapter.

Hurricane Katrina formed in the Caribbean and first struck southern Florida August 23, 2005 as a Category 1 storm. Hurricane Katrina caused significant damage in Florida, resulting in about 10 lives lost, but this was only the beginning. By Sunday August 28, Katrina harnessed sufficient energy from the warm waters of the Gulf of Mexico to become a Category 5 storm, the highest intensity measure for a hurricane on the Saffir-Simpson Scale. As the storm moved north towards New Orleans, the wind speeds rapidly decayed to a Category 3 level before striking land. However, the storm surge did not dissipate as quickly and maintained heights associated with a Category 5 storm as it impacted the coastline near the Louisiana-Mississippi border. The storm surge had an estimated height of 25 feet (NIST 2006) at Gulfport, MS near the center of the storm with hurricane level forces extending over 100 miles to the east into the Mobile Bay in Alabama.

Hurricane Katrina made landfall near the town of Buras in Southeastern Louisiana and continued north along the Louisiana-Mississippi state line as shown in Figure 2-1. The Category 3 ranking at landfall is based on the maximum measured one-minute, 10-meter sustained winds on land of 125 mph. The level of damage observed after the storm, however, far exceeds damage expected from a typical storm of this intensity. Although Hurricane Katrina blew Category 3 level winds, other measures of its strength are more characteristic of stronger hurricanes. In addition to winds, Hurricane Katrina caused a storm surge estimated to be as high as 25 ft (see Figures 2-2 and 2-3). Table 2-1 lists the wind speed, expected storm surge, barometric pressure and damage potential for hurricanes of Category 1 through 5. Both the level of storm surge and the barometric pressure reading of 27.11 inches recorded for Katrina are more characteristic of a Category 5 storm. Table 2-1 indicates that Hurricane Katrina was not an ordinary Category 3 storm and may explain, in part, the resulting ‘catastrophic’ level of damage. Based on barometric pressure measurements, Katrina ranks as the third-most powerful storm on record to strike the U.S., after the 1935 hurricane that struck the Florida Keys and Hurricane Camille that struck the Mississippi Coast in 1969. This combination of forces including hurricane strength winds and wind born

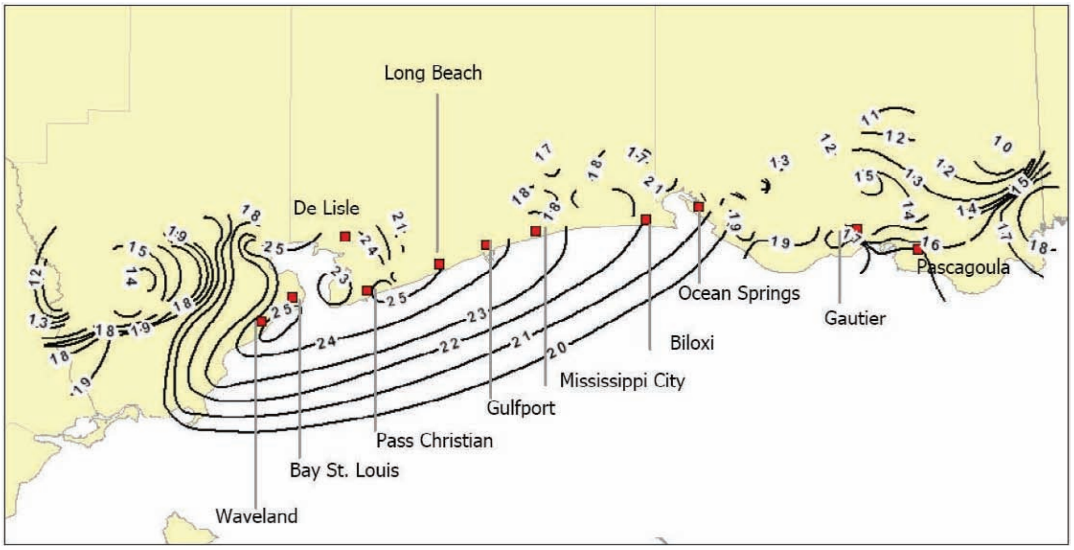


(a)

(b)

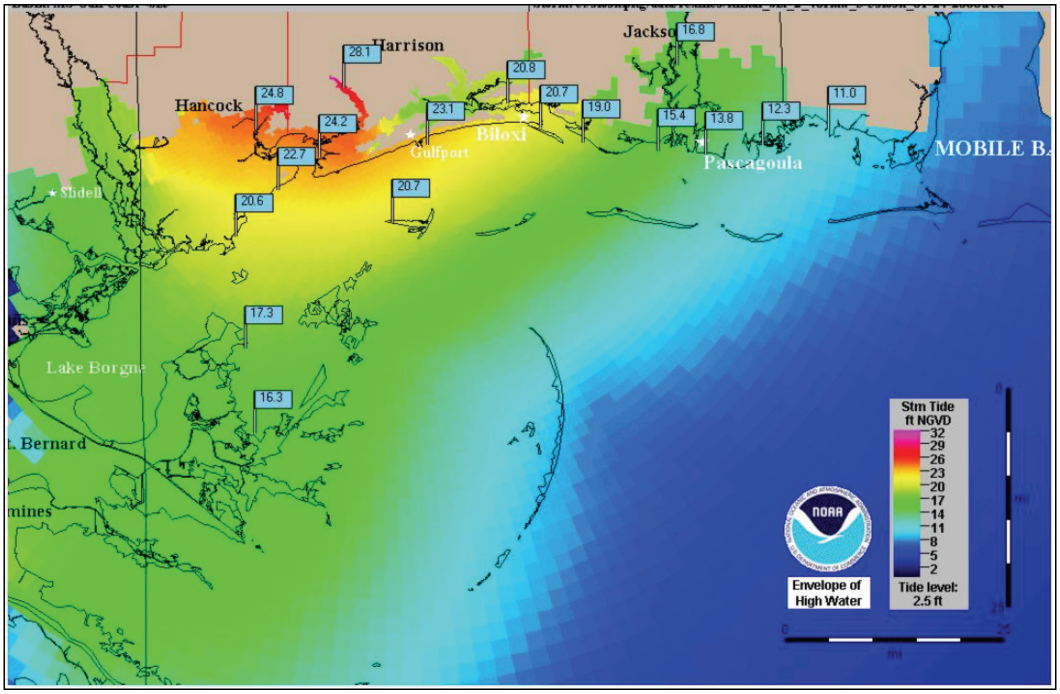
NOAA 2005

Figure 2-1. Hurricane Katrina path at landfall and 1 minute sustained wind speed map



NIST 2006

Figure 2-2 Storm Surge contours for Mississippi, as mapped by FEMA (heights measured in feet). (Source: FEMA, enhanced by Ron T. Eguchi, ImageCat)



NIST 2006

Figure 2-3 Preliminary storm surge hindcast results for Mississppi Gulf coast for Hurricane Katrina using SLOSH (Source: NOAA)

Table 2-1. Saffir-Simpson Hurricane Intensity Scale

Category					
	1	2	3	4	5
Wind Speed	74-95	96-110	**111-130**	131-155	>155
Barometric Pressure	28.94-29.53	28.5-28.91	27.97-28.47	27.17-27.88	**<27.17**
Storm Surge	4-5	6-8	9-12	13-18	**>18**
Level of Damage	minimal	moderate	extensive	extreme	**catastrophic**

ASCE 2005

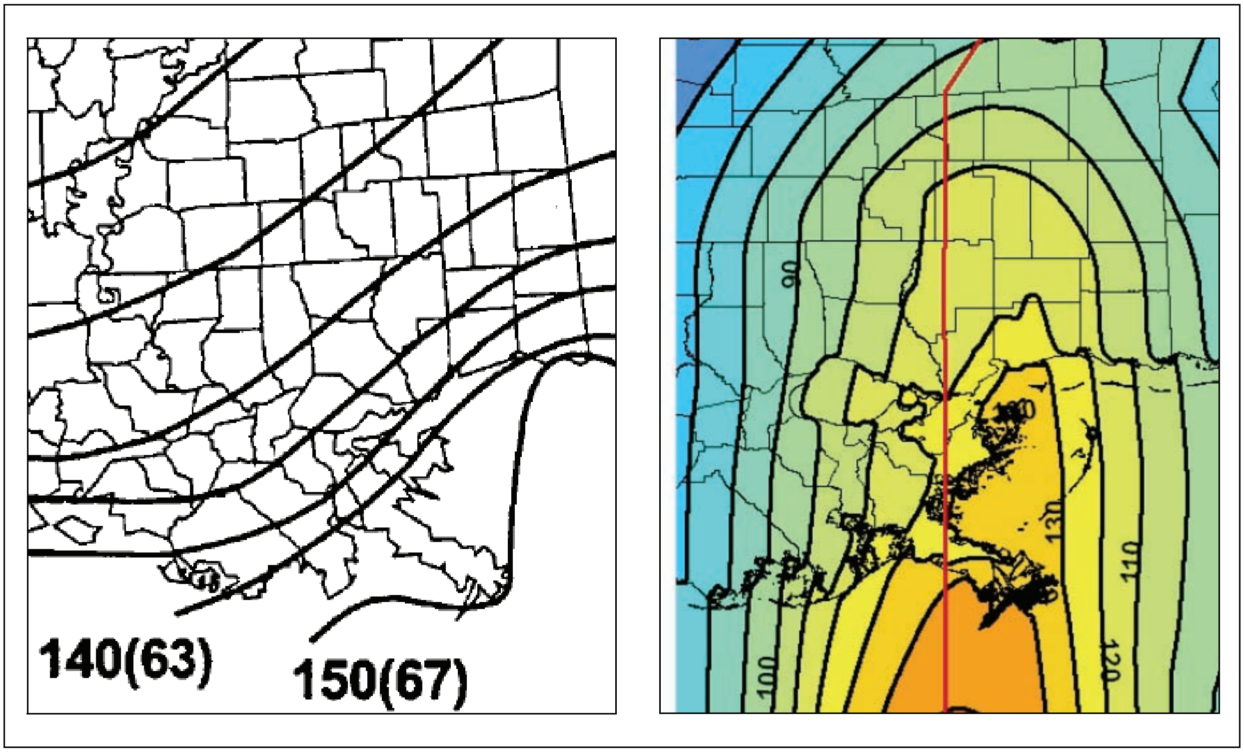
debris, storm surge and surge-born debris, and water damage from rain and flooding produced by Hurricane Katrina are discussed next. The damage sustained by the built environment is presented in the chapters that follow.

2.1 Hurricane Forces

At landfall, Hurricane Katrina produced extreme forces that destroyed residential wood frame construction (van de Lindt et al., 2005; NIST 2006) and damaged several engineered building structures. Bridge spans across bays and inlets through the gulf coast were knocked from their supports (O'Connor and McAnany, 2008). The structural damage to engineered buildings and bridges resulted mainly from storm surge wave forces and impact from large debris carried by the storm surge. Nonstructural damage to architectural cladding and glazing resulted mainly from wind and wind-born debris, while storm surge and flooding contributed to nonstructural damage in the lower levels of buildings near the coastline. Inland, significant nonstructural damage to commercial buildings was observed from wind and wind born debris. In many of these cases, broken windows allowed water to penetrate the interior of buildings resulting in additional damage.

The strong forces generated by Katrina provide a rare opportunity to evaluate the performance of structures under an actual design-level event and evaluate current design standards. In some respects, loading appears to have been less than specified for design by modern codes. Most notably, Vickery (2005) estimates buildings along the Mississippi coast experienced 10-meter, 3-second peak gusts between 100 mph and 130 mph, generally less than that specified in the basic wind speed maps of ASCE 7-05 and earlier editions (Figure 2-4). However, older buildings may not have been designed to current standards.

Loading from storm surge and surge-borne debris did appear to exceed conditions provided for in building codes. For example, storm surge appears to have reached farther inland than advisory base flood elevations, even including Katrina among flooding statistics (Figure 2-5). Furthermore, impact from objects transported by floodwaters (surge-borne debris) is only superficially treated by modern building codes (e.g., ASCE 7-05 [2006] Sec 5.4.5, which simply calls for impact loads to "be determined using a rational approach as concentrated loads acting horizontally at the most critical location at or below the DFE"), but in several cases such impact appears to have caused serious damage.



ASCE 7-05 ARA 2005

Figure 2-4. (left) Extract of ASCE 7-05 [2005] basic wind speed map for western Gulf of Mexico, for exposure category C and (right) Vickery's estimated wind speeds in Hurricane Katrina for open terrain conditions (over land) and marine conditions over water. Both maps are in terms of 3-second gust wind speeds at a height of 10m above the ground.

In addition to areas flooded by storm surge, flooding that resulted from the breaches in the New Orleans levee system was a major contributor to damage caused by Hurricane Katrina. The performance of the levee system and investigations for their failure are reported elsewhere (Seed et al., 2005). Flood damage in the New Orleans area is only documented here for some of the commercial buildings investigated within the scope of this study.

2.2 Geographic Area of Investigation

Winds from Hurricane Katrina damaged buildings along more than 100 miles of coastline along Louisiana, Mississippi and Alabama. Wind damage extended several miles inland. Since the focus of these investigations is on engineered construction, areas of interest included mainly commercial developed districts. The areas investigated are mapped in Figure 1-1. Note that Mobile, Alabama is about 100 miles east of the storms' path.

Damage to infrastructure detailed in this report was collected during two reconnaissance missions to the Gulf Coast. In the first mission, investigators were deployed within a week of the hurricane (September 6-11, 2005) to investigate damage along the Mississippi coast. After the floodwaters had receded from New Orleans and the evacuation order lifted, a second deployment (October 3-9, 2005) focused on this area.

http://www.fema.gov/hazards/floods/recoverydata/maps/katrina_ms-h19.pdf

Figure 2-5. Extract of map showing surge inundation in Hurricane Katrina (blue shading) and advisory base flood elevations including wave effects (heavy yellow line), from FEMA (2006). Inundation in Katrina reached farther inland than 1% annual chance (100-year) stillwater elevations plus estimated wave effects.

3.0 Architectural Damage to Commercial Buildings

The majority of commercial and public buildings constructed of steel or reinforced concrete framing performed well structurally during Hurricane Katrina. However, extensive losses were incurred from nonstructural damage to cladding, windows, and roof-mounted equipment in addition to water damage to the contents and interior finishes of many buildings. Engineered buildings examined for this study were located mainly in commercial areas such as the New Orleans Business District, Downtown Gulfport, and casino/resorts along the Mississippi coastline. Hurricane damage was observed as far east as Gulf Shores, Alabama. A partial list of buildings examined during the field investigations is provided in Table 3-1. The approximate location of the structures is given by the GPS coordinates collected during the field investigations.

3.1 Hotels and Commercial Office Buildings

Most of the buildings that were investigated as part of this study were hotels and office buildings. The following sections report typical damage to commercial buildings.

3.1.1 New Orleans

New Orleans is the largest urban area impacted by Hurricane Katrina. Because New Orleans is situated to the west of Katrina's path, and tropical cyclones in the Northern hemisphere circulate in a counter-clockwise direction, winds affecting New Orleans approached from the north. Building damage was identified to be caused by flooding, wind and wind-born debris. The investigations in New Orleans focused on the wind related damage. In the New Orleans Business District, a cluster of four buildings in particular, were heavily damage (Buildings 1 through 4 in Figure 3-1), while buildings just a block away appeared to be almost unharmed by comparison. These four buildings with extensive damage are described first, followed by detailed investigations of other buildings in the area.

Table 3-1. List of buildings examined during field studies and their approximate GPS coordinates

ID	Name	City	GPS	
			Latitude	Longitude
1	Hyatt Regency	New Orleans	29.9514	-90.0769
2	Amoco Building	New Orleans	29.95148	-90.07692
3	1250 Poydras	New Orleans	29.95071	-90.07638
4	Dominion Tower	New Orleans	29.95181	-90.07894
5	Energy Centre	New Orleans	29.95041	-90.07547
6	1555 Poydras	New Orleans	29.95218	-90.07909
7	US Postal Service	New Orleans	29.95061	-90.07650
8	Plaza Tower	New Orleans	29.94571	-90.07
9	City Hall	New Orleans	29.95220	-90.07712
10	Notre Dame Apts	Bay St. Louis	30.31974	-89.3338
11	Post Office	Bay St. Louis	30.30962	-89.3667
12	Hancock Bank	Gulfport	30.36701	-89.0942
13	US Courthouse	Gulfport	30.36990	-89.08760
14	US Probation Office	Gulfport	30.36961	-89.08678
15	Grand Casino Hotel	Gulfport	30.36301	-89.0987
16	American Legion	Gulfport	30.37908	-89.0443
17	Tulane Hospital	New Orleans	29.95542	-90.07661
18	Charity Hospital	New Orleans	29.95576	-90.07767
19	Singing River Hospital	Pascagoula	30.37492	-88.5336
20	Ocean Springs Hospital	Ocean Springs	30.41413	-88.7847
21	D'Iberville High School	D'Iberville	30.44150	-89.89321
22	Student Center	New Orleans	29.962818	-90.1.516
23	Airport	Gulfport-Biloxi	30.41433	-89.0744

Background image from GoogleEarth

Figure 3-1. Relative location of buildings examined in New Orleans Business District. Numbers correspond to ID in Table 3-1.

The Hyatt Regency 28-story reinforced concrete building suffered extensive window damage as well as some damage to its asphalt shingle roof, loss of some rooftop fans, and extensive damage to the soffit of a mushroom-shaped rooftop structure housing a bar. Three fourths of the glazing on the north facade curtain wall above the 5th floor broke during the storm as shown in Figure 3-2. The curtain wall comprises 1/4-in tempered single-pane vision glass, and 1/4-in non-tempered single-pane black spandrel glass. Wind, water and wind-born debris including pea gravel infiltrated several of the rooms on the north side, the gravel appeared similar that blown off of the tar and gravel roofing of one or more adjacent buildings north of the hotel. As a result of the damaged exterior, furniture, carpets and gypsum drywall that were dampened by the infiltrating water were infested with mold and were being removed at the time of investigation. This building has no basement and stands on a site slightly above the highest level of flooding. (One block to

(a) North and East Facade

(b) South and West Facade

(c) Interior Rooms facing North

Figure 3-2. The Hyatt Regency Hotel in the New Orleans Business District had extensive window damage on the north facade (a) and limited damage on other sides (b). Broken windows allowed wind-driven rain and debris into the building causing additional interior damage (c).

the west, high water was about a foot above grade.). During the investigations in early October, The Hyatt Regency was in limited operation as the FEMA disaster field office, although it had no potable tap water.

<u>The Amoco Building</u> is an approximately 24-story high-rise in downtown New Orleans to the north west of the Hyatt Regency. This building also suffered extensive damage to its glass curtain wall, with 10 to 20% of its glazing broken. Although close inspection was prevented, the glass was judged to be likely 1/4-in annealed. Eastbound lanes of Poydras St. just north

Figure 3-3. The Amoco building in New Orleans Business District had extensive window damage on the north and east facades and limited damage on other sides

of the building were closed because of the risk of falling glass from broken windows. It may be noteworthy that, though the east facade of the Amoco building was heavily damaged (Figure 3-3), the east facade of the adjacent building to the east was largely undamaged (Figure 3-4). These two structures and the Hyatt directly south of them enclose a narrow space, which could perhaps have produced local vortices that aggravated the window damage in the plaza. This serves as a possible explanation to the difference in performance of the east facades of the two buildings. The north facade of the Hyatt, which was also heavily damaged, faces the enclosure.

1250 Poydras is a 24-story building on the southwest corner of Poydras St. and Loyola Ave. and adjacent to the Hyatt and Amoco buildings. Although the east facade appears to have suffered no damage, the backside of the building adjacent to the Amoco building, had significant window damage as shown in Figure 3-4. Note the proximity of this building on the left of Figure 3-4(b) to the Amoco building shown on the right.

(a) East Facade

(b) North and East Facade

Figure 3-4. This office building in the New Orleans Business District had extensive window damage on the west facade (a) and limited damage on opposite sides (b).

The Dominion Tower is 25-story high rise commercial building to the west of the Amoco building, and just east of the New Orleans Superdome. Glazing on this building also suffered widespread damage. About half of the windows on the north and west facades were broken as shown in Figure 3-5. Windows on the east facade appeared to have suffered minimal damage. The glazing was a mix of 1/4-in insulated and annealed glass. Safety film appears to have prevented fallout of some broken glass as shown in Figure 3-5 (c).

Although the Dominion tower was not clustered with three previously described buildings, it had a substantial amount of damage. However, other buildings across the street either north or east of this group survived through the storm almost unharmed. The reason for the concentration of damage to these four buildings was likely the presence of gravel roofs upwind (north) from them. These investigations were carried out in October, over one month after the Hurricane, so much of the debris was cleared off the streets by then. However, on smaller side streets such as one in front of the New Orleans Superdome, gravel had settled throughout the curb as shown in Figure 3-6. Additionally, some smaller gravel remnants were found inside a room that had lost its windows.

(a) West Facade

(b) North and East façade

(c) Fractured Windows

Figure 3-5. The Dominion Tower in the New Orleans Business District had extensive window damage on the north and east facade (a) and limited damage on other sides (b). Many windows were fractured but remained in place.

(a) Gravel in Front of Superdome

(b) Gravel Found Inside Room with Broken Window

(c) Gravel Roof

Figure 3-6. Gravel found on adjacent street curbs and inside substantially damaged buildings in New Orleans (a/b). Source of gravel was likely roofs from building upwind of damaged windows(c).

The Energy Centre, a 40-story building on the southeast corner of Poydras Street and Loyola Avenue, appeared to have relatively little damage and was in limited operation by mid-October 2005. The building, shown in Figure 3-7 (a), is located across Loyola St, to the east of 1250 Poydras. Four windows reportedly broke during the storm, but had already been replaced. The remaining visible damage consisted of broken windows on the two upper stories that housed mechanical equipment. Neighboring buildings to the east also appeared to have similar damage concentrated on the upper story mechanical rooms that were not fully enclosed. The main entry area of this building also had a few soffit tiles missing and damaged supporting grid as

(a) Damage to Mechanical Room Walls

(b) Wind Damage to Soffit

Figure 3-7. Only visible damage to this building appeared to be broken windows on upper levels corresponding to mechanical rooms and soffit near the main entrance.

shown in Figure 3-7 (b). Despite its good performance and recovery, the building was not fully operational because water in the region was not potable. Building tenants were allowed into the building during limited hours.

<u>1555 Poydras</u> is a 22-story high rise building housing retail space at the ground floor and offices above. The superdome is located across Poydras street from this building. The building structural system is reinforced concrete frame with a reinforced concrete elevator core and post-tensioned concrete slabs. The roof, built of two plies of insulation board (3.0 isoboard) with double-ply membrane, had recently been replaced, and performed well. However, the metal facade of the roof equipment penthouse was destroyed. The building and others just north of Poydras St. experienced 1 ft of flooding, which caused damage to finishes at the ground floor and flooding of elevator pits. The ground-floor electrical equipment was only an inch or so above the water level and remained functional. The building had extensive damage to its double-paned glass curtain wall, with 50 to 100 outer panes of glass fractured, and five windows where both inner and outer panes were fractured. Figure 3-8 includes a picture of the south facade and from the north. As of October 6, 2005, the building had electric power but because it lacked potable water, it had not been reoccupied, although some tenants observed during the reconnaissance appeared eager to return to work.

<u>The US Postal Services Building</u> in the New Orleans Central Business district appears to be a 14-story steel-frame building. The south facade of the building had about five broken windows that were boarded up as shown in Figure 3-9. More window damage occurred on the north side shown in Figure 3-9(a), yet fewer than 2% of the windows were fractured. Likely, the most significant source of damage to the Postal Service Building resulted from flooding in the basement. There was no evidence of flooding above the street level at its location. At the time of inspection, the basement flood water had been pumped out and removal of all furniture, electronic components and other items was in progress. Figure 3-9(b) captures the remediation efforts to clean out mold and contaminated equipment from the flooded basement.

(a) South Facade

(b) North Facade

Figure 3-8. Office building in the New Orleans Business District was exposed to wind forces and 1-2 feet of flooding but quickly recovered.

(a) Boarded Windows

(b) Cleanup of Basement

Figure 3-9. The US Postal Service Building had a few fractured windows and flooded basement, tough there was no flooding at street level.

The 41-story Plaza Tower located at the intersection of Howard and Loyola is a reinforced-concrete-frame building with various vertical setbacks up to the 16th level and with a mushroom top extending the square footage of the top three stories. This high-rise building shown in Figure 3-10 was isolated from other tall buildings that could generate any rooftop debris by at least two city blocks. The south side of the building houses an eight-level parking structure with sheet metal cladding, where five of the metal sheets were missing. On the north facade, at least one precast cladding panel had been lost (note the spot around 10th floor level). Broken windows were spotted around the building, with the majority concentrated on the lower stories of the north and west facade. The building appeared closed at the time of investigation.

Figure 3-10. Office building in the New Orleans Business District at a distance from other high-rise structures.

The nine-story City Hall building in New Orleans appeared to have suffered no significant damage during the hurricane. The structural framing appeared to be made of steel. The building was in service at the time of the investigation as indicated by the high traffic of city employees using the south entrance. Potable water was not available, thus occupants were cautioned against coming in contact with the water. Electric power and phone service was currently available in this and surrounding buildings. There were no apparent watermarks above the street level to indicate flooding in the area. Figure 3-11 shows the north side of the building with several open windows at the top level. The only noticeable damage was concentrated on the south side and included a one-third row of broken windows on the top story. Daylight was visible through a few of these windows, indicating that this section of the building was probably used to house mechanical equipment. If roof damage had occurred, the building would have had extensive water damage and likely be out of service. The building is located just north of the Amoco building which suffered extensive glazing damage.

(a) North Side

(b) Damage at Roof Level

Figure 3-11. New Orleans City Hall suffered damage mainly at the roof level.

3.1.2 Bay St. Louis

Bay St. Louis, Mississippi consists mostly of residential communities with a few low-rise commercial buildings along US-90. Hurricane Katrina passed just to the east of this city, subjecting it to some of the most intense wind and storm surge forces. Coastal structures consisting mainly of residential wood frame construction were washed away by the storm, leaving behind only the concrete mat foundations in some cases (Womble et al., 2006). Commercial buildings performed better structurally. Two of the commercial buildings examined in this region are discussed next. Note that reconnaissance of Bay

St. Louis in particular and the Mississippi and Alabama coasts in general occurred less than two weeks after the hurricane. The information presented here is based on observations made during that time.

The "Notre Dame de la Mer Manor Apartments" suffered only minor damage despite being located in one of the areas hardest hit by Hurricane Katrina. The four-story reinforced-concrete shear-wall building shown in Figure 3-12 is located on US-90 about 0.5 miles west of the St. Louis Bay Shoreline. Powerful storm surge and winds in the area are evident by the displaced cars in the parking lot shown in Figure 3-12(a) and trees falling onto the building in Figure 3-12(b). The only damage readily apparent on the exterior on this building was one broken window in the rear of the building and a collapsed canopy at the main entrance. Windows in the upper stories of the building were open at the time of inspection, indicating that residents had returned to the building.

(a) Damaged Entrance Canopy

(b) Tree over Building

Figure 3-12. Apartment building in Bay St. Louis.

The Bay St. Louis Post Office is housed in a one-story building that performed well structurally, but 4 to 6 ft of flooding from the storm surge caused extensive nonstructural damage. Plaster and other interior finishes were removed and the building underwent environmental remediation. The post office was expected to be in operation within two weeks of the hurricane. On the exterior, there was only limited window breakage, as shown in Figure 3-13. Most of the damage appeared to be storm surge related.

Figure 3-13. Post Office in Bay St. Louis.

3.1.3 Gulfport

The downtown area of Gulfport, Mississippi, located about one-half mile north of the shoreline, generally appeared to have experienced 1-2 feet of storm surge. All of the buildings in the region had water damage at the ground level, as shown in Figure 3-14(a). Many other buildings had additional wind and wind-debris related damage at the upper stories. A few collapsed building were observed in the area as well. Figure 3-14(b) shows a collapsed unreinforced masonry structure at the forefront. The background shows the Hancock Bank building, which appeared to be the tallest building in the downtown area at 14 stories. About 30 percent of the windows were shattered on the south face above the third level. The windows that appear tinted black lost the exterior pane only. The concentration of damage at the lower levels suggests that the windows were shattered from debris picked up by the wind from the ground. At the time of investigation, restoration efforts were under way to clear debris and repair water damage to building interior from water that penetrated it through the damaged windows.

Two government buildings in Gulfport, the US Courthouse and the adjacent US Probation Office, were rendered inoperative after Hurricane Katrina due mainly to water damage. In particular, the US Courthouse is a relatively new eight story building that had been in service for about two years. The property manager for the facility noted that blast loads were considered in the design of this steel frame building with pre-cast concrete exterior cladding


(a) Damage at Street Level Shops (b) Wind Debris Damage

Figure 3-14. Flooding and wind damage in downtown Gulfport.

panels. The building site is about 28 feet above sea level and interior markings indicate a storm surge level of 2 feet. In addition to flooding, this building also suffered minor nonstructural damage including three broken windows and some roof damage.

3.1.4 Mississippi Coast

The extent of damage along the Mississippi coast is demonstrated by the beachfront 17-story Grand Casino Hotel constructed of reinforced concrete frame with shears walls. The approximately 20 ft. first story was partially enclosed, probably with break-away walls, to serve as a welcome lobby with access to stairs and elevators. Only the bare structural concrete columns and shear walls remained at this first level, with all else apparently swept away by the storm surge. The second and third stories, with heights of about 15 feet each, housed reception, shops and banquets rooms, among others. A light steel frame extended these two levels over the drive-thru valet parking. The exterior of these two stories suffered extensive damage to cladding. Figure 3-15(a) shows the front view (east facade) of the hotel building, and the exposed nonstructural framing. The building exterior was finished with layers of gypsum board, Styrofoam foam board that allowed for contouring the surface, and fabric lathe with a thin coat of colored plaster. These finishes were stripped from the nonstructural steel stud framing. As a result of exterior damage, high winds entered into the building and destroyed the interior space as shown in Figure 3-15(b). The exterior cladding was also stripped at several locations above the third-story level, exposing the steel stud framing. The casino barge associated with this hotel remained anchored

(a) Exterior Damage (b) Interior Damage

Figure 3-15. Beach front casino/hotel in Gulfport.

to the south east of the building, and also appeared to be severely damaged. The parking structure, located further to the south, partially collapsed and is discussed in Chapter 4.

Many casinos, which were originally stationed along the Mississippi shoreline, were carried inland by the storm surge. A few of the casinos were deposited north of the coastal US 90 as shown in Figure 3-16(a). Impact between the barges and structures along the coast resulted in the partial collapse of at least one building and one parking structure. The casinos themselves were severely damaged on the exterior and interior. Figure 3-16(b) shows a close-up view through the third-level opening of another casino that crossed the US-90.

(a) Barge on Land (b) Damage to Barge

Figure 3-16. Casino barge floated in-land with storm surge.

A light steel frame building located on US 90, opposite to the coast in Gulfport, was also severely damaged. The building consists of a two-story rectangular frame adjoined with a single story frame that appears to have served as an auditorium for the American Legion Post 119. The majority of the cladding, made of insulated metal panels, has been stripped from the frame as shown in Figure 3-17(a). Also, the southern bay of the single story portion of the building collapsed as shown in Figure 3-17(b).

(a) South Side

(b) Partially Collapsed Frame

Figure 3-17. Damage to steel building in Gulfport coast.

3.2 Hospital Buildings

Few hospital buildings were investigated in New Orleans and in Mississippi (Arendt and Hess 2006). Due to heightened security in the aftermath of Hurricane Katrina, many hospitals were not accessible. In New Orleans, hospitals were severely impacted by flooding and loss of power, which led to their closure. Hospitals investigated in Mississippi were miles east of the storm's center and suffered minor damage, and were able to remain operational. Hospitals close to the storms center were not investigated mainly due to limited access to the facilities and roads in the area.

Tulane University Hospital Clinic is housed in a seven-story steel-frame building that flooded to a depth of approximately 1m for about two weeks. It has no basement, no major building service equipment at first-floor level, and few broken windows, so damage was limited primarily to architectural finishes at the ground floor. At the time of the MCEER reconnaissance, a contractor was demolishing ground floor drywall and drying the building as evident in Figure 3-18(a). Subsequently, Tulane University Hospital & Clinic

(a) Tulane Hospital (b) Charity Hospital

Figure 3-18. Hospitals in New Orleans were closed after flooding.

was the first hospital to reopen in downtown New Orleans in February 2006 (Simon 2006).

The 13-story Charity Hospital of New Orleans, one block away from Tulane Hospital, was also rendered inoperative by Hurricane Katrina and the flooding. Various windows on all side of the building were broken. Watermarks showing the height of flooding indicate that the first floor entry level, elevated about four feet from the street level, was not flooded. The basement, however, was still flooded at the time of inspection. No remediation efforts appeared to be underway as in Tulane Hospital. Figure 3-18(b) shows the north facade of the main building with a view of the damaged windows.

The Singing River Hospital shown in Figure 3-19(a) is located in Pascagoula, MS on the 2800 block of Denny Ave (US 90). The area surrounding this hospital did not appear to be as significantly damaged by Hurricane Katrina as other areas closer to the shore and to the west. However, the hospital building suffered some nonstructural damage as shown in the soffit of the main entrance canopy shown in Figure 3-19(b). Additionally, glass was missing from the exposed light metal nonstructural framing, though there were no signs of glass debris nearby. OSB and plywood sheets were placed on the inside of the framing in this area while most other doorways were completely sealed around the exterior. The boards, particularly on the exterior, appear to have been placed before the hurricane. Other damage to the hospital appears to be a few broken windows on the backside of the hospital. The hospital remained in operation through and after the hurricane using emergency generators. Staff at the hospital reported that during the hurricane, they had to scramble to move patients out from rooms with broken windows.

Oceans Spring Hospital shown in Figure 3-19(b) is part of the Singing River Hospital system. Similar to the Singing River Hospital building in Pascagoula, MS, the hospital building suffered minor structural damage.

(a) Singing River Hospital

(b) Ocean Springs Hospital

Figure 3-19. Hospitals in Mississippi mile at a distance from the coast had minor damage and remained operational through storm.

Noticeable damage included the equipment enclosure on the roof and a broken window on the back side. The windows were lined with shatter-resistant window film. A small hole in the window suggested that the window might have been struck by sharp debris. The hospital appeared to be in full operation and had emergency generators on site.

3.3 Schools

During these investigations, an effort was also made to study building structures in schools. One of the schools examined is D'Iberville High School just north of Biloxi, MS, across Biloxi Bay. The high school is a set of single-story buildings and a gymnasium. Figure 3-20(a) shows the west side facade of the school, where the gymnasium is located. The main wind force resisting system appeared to be unreinforced masonry (brick) walls supporting open-metal joists and fiberboard roof panels with built-up roofing. The buildings suffered moderate roof damage. Hallway, gymnasium, and cafeteria roofs appeared to have flexed upward but did not blow off. Several but not all rooftop air conditioning units were damaged, and a 25-ft-by-50-ft light metal entrance canopy shown in Figure 3-20(b) was destroyed. The gymnasium structure, a concrete or steel-frame building, suffered damage to its masonry veneer. The school is located in a suburban neighborhood, in an area that was lightly wooded with pine trees; there was a debris field of pine boughs and pinecones. Approximately 10% of the windows were broken.

(a) Gymnasium

(b) Collapsed Canopy

Figure 3-20. D'Iberville high school in Biloxi Bay.

(a) Mold in Floor Level

(b) Stripped Frame

Figure 3-21. Flood damage to new student center in university near New Orleans.

The three-story reinforced-concrete Student Center at Xavier University of Louisiana in New Orleans was three years old when Hurricane Katrina struck. It suffered minimal wind damage, some damaged flashing, and no broken windows or roof failure. The ground floor flooded to a depth of approximately 2-1/2 ft as indicated by the mold line in Figure 3-21. However, mold also infested the third floor in the humid conditions. The environmental damage required demolition and replacement of all wallboard, wall insulation, suspended ceiling tiles, carpeting, and tile work at all three stories, demolition and replacement of underground electrical conduit, demolition and replacement of ductwork at the ground story, and cleaning of all ductwork at the second and third stories. After floor finishes were removed, concrete slabs were to be chemically treated. The building houses a cafeteria, bookstore, meeting rooms, and offices.

3.4 Airports

The three-story Gulfport-Biloxi International Airport shown in Figure 3-22 was served by four major airlines, had four existing gates and two under construction at the time of Hurricane Katrina. Its structural system is a steel moment frame clad with gypsum wallboard partition over metal studs. There was no flooding in the terminal and no structural damage, although window breakage and roof damage caused extensive architectural damage to two of four gates. Some window breakage occurred in the air traffic control tower, but not at the level of the control room. There was extensive damage to

(a) Damage to Gates under Construction (b) Window and Architectural Damage

Figure 3-22. Gulfport-Biloxi airport was under construction and suffered damaged to existing and new gates.

exterior architectural finishes of the terminal. Baggage handling equipment and ticketing counters were undamaged. By Thursday September 8, 2005, the airport was partially operational with one airline providing flights.

4.0 Structural Damage to Commercial Buildings

4.1 Introduction – Design Loads and Experienced Loads

Buildings that suffered structural damage along the Gulf Coast were exposed to extreme loads from wind pressure, windborne-debris, storm surge, and surge-borne debris. In some respects, loading appears to have been less than specified for design by modern codes. Most notably, according to Vickery's (2005) estimates, buildings along the Mississippi coast experienced 10-meter, 3-second peak gusts between 100 mph and 130 mph, generally less than that specified in the basic windspeed maps of ASCE 7-05 and earlier editions (Figure 2-4). This may be the reason that little structural damage to commercial buildings from wind pressure, and no structural damage to commercial buildings from wind-borne debris was observed.

However, loading from storm surge and surge-borne debris did appear to exceed conditions provided for in building codes. For example, storm surge appears to have reached farther inland than advisory base flood elevations, even including Katrina among flooding statistics (Figure 2-5). Furthermore, impact from objects transported by floodwaters (surge-borne debris) is only superficially treated by modern building codes (e.g., ASCE 7-05 [2006] Sec 5.4.5), but in several cases, such impact appears to have caused serious damage. Examples of damage from the various loading conditions are presented next.

4.2 Structural Damage to Buildings from Wind Pressure

In a few observed cases, wind pressure alone appears to have caused structural damage to unreinforced masonry walls in commercial buildings. Figure 4-1 shows a single-story unreinforced masonry building in downtown Gulfport, MS, that experienced partial collapse. The cause was most likely wind pressure, as surge levels were relatively low here and no surge-borne debris was observed in or near the damaged building. No evidence of wall anchors was observed in the damaged building. According to Figure 2-4, 10-meter peak gust velocity here was approximately 130 mph.

Similar damage was observed in an unreinforced masonry bearing-wall building in downtown New Orleans (Figure 4-2), where according to Vickery (2005), 10-meter peak gusts in exposure C were approximately 90 mph.

Figure 4-1. Left: partial collapse of unreinforced masonry bearing-wall building, downtown Gulfport MS. Debris from this building may have impacted a high-rise building downwind, causing extensive wind damage (right).

K Porter for National Institute of Standards and Technology

Figure 4-2. Partial collapse of New Orleans unreinforced masonry bearing wall building.

Accounting for the building’s exposure category (B), peak gust velocity at 10 meters elevation were approximately 65 mph. Elsewhere in New Orleans, several 30-ft-high unreinforced masonry walls of recent construction, which served only as visual screens at steel-frame parking structures belonging to an apartment complex, also collapsed.

In California, positive connection between the roof and the walls is typically employed to strengthen unreinforced masonry bearing wall buildings to resist seismic loads. Note however that the damage to the Gulfport building (in Figure 4-1a) could conceivably have been initiated by uplift of the roof, a loading condition that could have imposed vertical tension on the bearing walls for which typical seismic-restraint details provide no resistance. Debris from the partial collapse of this building may be implicated in the cladding damage to the downwind high-rise office building shown in Figure 4-1b, as discussed earlier.

The brick wall shown in Figure 4-3 was located in downtown New Orleans. It collapsed towards the north, smashing two cars parked on the street. The wall enclosed the open-air loading area for the adjacent building. No reinforcement was evident in these walls.

The Standard Parking Structure is a seven-story reinforced concrete frame with unreinforced masonry infill. The masonry walls collapsed at several locations, including the first level (Figure 4-4 a) and the second level (Figure 4-4 b). There was no rebar present within the rubble of hollow core blocks. The Standard Parking structure is located at the 100 block of S. Rampart St., in New Orleans.

Figure 4-3. Collapsed unreinforced masonry wall.

(a) First Level

(b) Second Level

Figure 4-4. Masonry infill damage.

4.3 Structural Damage to Buildings from Impact from Surge-borne Debris

A five-story reinforced concrete building with unreinforced masonry infill located on US Route 90 in Biloxi, Mississippi partially collapsed (Figure 4-5 left). The primary damage to the structure clearly appeared to be caused by the impact of a three-story casino barge that floated ashore with the rising storm surge. One corner column on the front southeast corner of the building was impacted, resulting in the collapse of one-bay by one-bay at the bottom four stories of the building. The beams at the fourth level were sufficiently strong to form a redundant load path for the load carried by the remaining column at the upper story. Other than a few missing window panes, the south facade of the structure appeared in good shape apart from the region of impact. Thus it is probable that this building would have faired well through the storm, with the exception of flood damage to the lower levels.

In a similar situation, a five-story (six-level) parking structure constructed of cast-in-place reinforced concrete partially collapsed. The parking structure formed part of a hotel and casino complex in Biloxi, with adjacent barges housing the gambling halls. Four bays on the west facade collapsed, apparently because of impact from the adjacent casino barge that impacted four columns as it was raised by the storm surge (Figure 4-5 right).

Figure 4-5. Structural damage resulting from surge-borne debris.

4.4 Structural Damage to Parking Structures from Storm Surge

Several parking structures in Biloxi and Gulfport, Mississippi were examined after Hurricane Katrina. Five parking structures were constructed of precast concrete with pretensioned double-tee beams for decks; the other three were of cast-in-place reinforced concrete. All were either on the shore of the Gulf of Mexico or facing the Gulf across coastal US Highway 90, and were subjected to storm surge estimated to exceed 20 ft in height in at least some cases, judging from the elevation of debris observed on parking structure decks and architectural components. While none of the cast-in-place structures suffered any structural damage (with the exception of one that partially collapsed from impact by a casino barge), all of the precast concrete structures suffered partial collapse of the second-floor deck. Storm surge seems to have reached the level of this deck, which was typically 10 to 15 ft or so above grade (grade being roughly 3 ft above normal sea level), but not the third-level deck, which was generally 20 to 25 ft high. In cases where only part of the deck collapsed, it was typically on the side from which the waves approached.

The concentration of collapsed deck on the seaward side, where wave action would be strongest, implies that wave action played a role in the collapse, either vertically, through uplift of the deck beams, or horizontally via the spandrel beam. Evidence of horizontal pounding by waves can be seen in Figure 4-6. Note the holes in spandrel beams where the shear key in the end of the deck-beam web notched into the socket of the spandrel beam; the shear key appears to have punched the holes. But this horizontal action may not have been the principal cause of the failure. In some cases, the collapsed deck beams had been oriented parallel to the seashore, as in Figure 4-7; in others, perpendicular to it, as in Figure 4-8. In some cases, the spandrel beam rested on the outside of the column (Figure 4-9), and could only have moved inward at mid-span, in flexure. (Some flexure, of course, is clearly possible, as shown in Figure 4-10).

Figure 4-6. Evidence of horizontal pounding by waves. Deck-beam shear key appears to have punched holes in the spandrel beam.

Figure 4-7. Collapsed deck beams oriented parallel to the seashore.

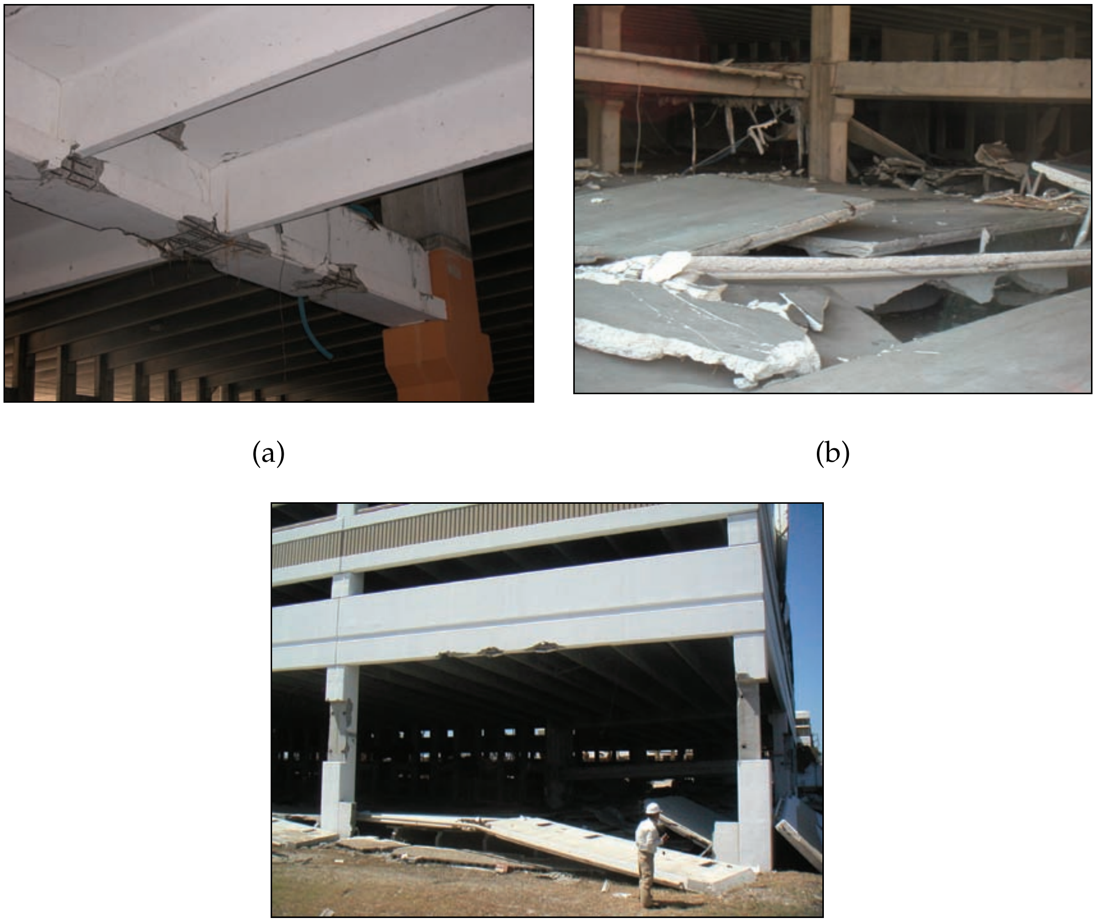
Figure 4-8. Collapsed deck beams oriented perpendicular to the seashore.

Figure 4-9. Support of spandrel beam on the outside of the column.

Figure 4-10. Flexibility of spandrel beams.

Vertical loading was clearly substantial. Shear failure was observed in deck-beam shear keys (Figure 4-11) and in supporting girders (Figure 4-12(a), the interior girders in the background of Figure 4-12(b), or the three bites in the 3rd-level spandrel beam in Figure 4-12(c)). Such loading could have been caused by pounding resulting from deck beams being lifted and then dropped, or by the weight of water accumulated on the top of the deck before it could pour down a ramp. If the latter occurred though, why would damage tend to be concentrated at the seaward side or corner of the deck? Water would probably flow quickly enough to distribute around the entire second-floor deck and cause more general damage.

Figure 4-11. Shear failure in deck-beam shear keys.



(a) (b)

(c)

Figure 4-12. Shear failure in girders supporting deck beams.

If it were uplift and dropping of the deck beams, rather than the weight of water, what caused the uplift? Wave action alone might conceivably have lifted the deck beams, but it seems likely that buoyant forces contributed strongly. The deck beams and their concrete topping weigh approximately 150 pcf; seawater weighs approximately 66 pcf. By Archimedes' Principle, buoyancy alone would have reduced the downward vertical load on the deck beams by almost half, a loading condition for which these pre-tensioned members were probably not designed. In addition to buoyancy of the deck beams and topping, the shape of the double-tees, whose ends were enclosed by their supporting girders, would have allowed for the creation of air pockets (Figure 4-13). As the storm surge rose to the soffit of the second-level deck, the concrete topping over the deck would have greatly limited the

Figure 4-13. Space where air pockets could have been created.

ability of air to escape, and additional buoyant force equal to the weight of water displaced by the air pocket would have been applied upward to the deck beams, potentially reaching or exceeding the self-weight of the deck beams and their topping.

Under such a condition—buoyancy caused by air pockets and the volume of the deck concrete itself neutralizing the self-weight gravity loading—the negative bending moment induced by the pretensioning would have been unopposed by gravity-induced positive bending in these simply supported beams. The negative bending induced by pretensioning is greatest in the region of the midspan, so if uplift were the cause of the collapse, one would expect to see evidence of negative-bending flexural damage at the midspan, such as concrete spalling at the bottom fiber at midspan and diagonal cracks radiating outward and downward from the top fiber. If on the other hand it were the weight of water on top of the deck that caused failure, one would expect to see the opposite: concrete spalling at the top fiber at midspan and diagonal cracks radiating outward and upward from the bottom fiber.

The damage observed here supports the negative bending hypothesis: spalling of concrete at the bottom fiber rather than the top (Figure 4-14) and diagonal cracks radiating outward and downward from the top fiber (Figure 4-15). In Figure 4-15, note the damage to the deck flange every three feet or so at the points where angle clips (visible on the right-hand side of Figure 4-8 as well) connected to the spandrel beam: the concrete cover spalled downward

Figure 4-14. Spalling of concrete at the bottom fiber of deck beams.

rather than upward, particularly at the midspan, implying that the midspan of the deck moved up relative to the spandrel beam.

This review of fairly widespread damage to precast concrete garage structures in Biloxi, MS, and Gulfport, MS, caused by Hurricane Katrina is based on limited information: brief (1 to 2 hr) visual examination of only five structures, no material testing, examination of structural drawings, mathematical modeling of the structures, nor analysis of the imposed hydrodynamic forces. We did not search for or examine precast concrete structures where collapse did not occur but that were similarly exposed to storm surge and wave action (we didn't see any). We therefore draw no firm conclusions about the safety of other, similar structures that could be exposed to storm surge, nor do we offer any advice for mitigating potential risk. Because this was a quick reconnaissance study, a thorough literature review was not performed to check whether this phenomenon has already been observed elsewhere and addressed by standards-writing authorities such as the Precast Concrete Institute, American Concrete Institute, International Code Council, or American Society of Civil Engineers. Such additional steps would be required before firm, general conclusions about safety and risk mitigation could be made.

Figure 4-15. Concrete cover at deck-to-spandrel connections spalled downward, implying that the midspan of the deck moved up.

5.0 Lifelines

Lifeline performance other than highway bridges was not a focus of MCEER's reconnaissance. However, some observations can be provided on the hurricane performance and post-hurricane impacts of power, water, wastewater, telecommunications, emergency facilities and airports in Mississippi and New Orleans. All were impacted to varying degrees.

5.1 Electric Power

Electric power was lost to much of coastal Mississippi and the New Orleans areas. Damage to electric power distribution lines was observed throughout the affected area, with poles apparently downed both because of tree limbs or other debris (Figure 5-1), and because of wind or water pressure causing overturning of poles whose foundation soils or embedment depth were apparently inadequate. According to electric-utility workers in Biloxi MS and employees of the US government General Services Administration in Gulfport MS, flooding at electric substations caused damage to equipment requiring the replacement of the equipment. According to the electric-utility workers in Biloxi MS, flooded substation equipment was rapidly replaced because mutual-aid agreements and other emergency plans allowed the local electric power utility to have replacement equipment staged a day's drive north of the coast, the day before the hurricane struck, and trucked in as soon as it the storm had passed. As a consequence, electric power was available to 95% of Biloxi customers able to receive it within 10 days of the hurricane.

Figure 5-1. Downed power pole with poletop transformer; exposed substation equipment in Biloxi, MS, replaced by October 7.

5.2 Water Supply

5.2.1 New Orleans Water Supply

Potable water in New Orleans was made available to parts of the city beginning on October 6, 2005. MCEER researchers visited the Carrolton Water Works in Orleans Parish, the main drinking water treatment facility for the City of New Orleans (Jensen and Ram, 2007). The plant treats 122 million gallons per day (mgd) and serves 440,000 people. The source water is the Mississippi River. On October 6, 2005, a boil-water order was lifted for about 269,000 people. The boil water order for the remaining customers was lifted on October 7, 2005. At the time of MCEER's visit, the facility was operating with a highly reduced staff.

The Water Purification Superintendent described the process required to restore water service to New Orleans. After power was restored to the facility, water was produced quickly. Initially, raw water was coagulated but not disinfected. In general, chemical addition processes (coagulation and disinfection) were not affected significantly. However, filtration was impacted severely. The pipe galleries were flooded, rendering filter controllers and instrumentation inoperative. Filters were operated manually until controller operation was reestablished. As of about October 17, 2005, the plant was maintaining about 1 mg/L free chlorine (no ammonia added).

The distribution system had been valved off in a controlled fashion, with service reestablished slowly. Large pipe breaks were repaired quickly. Distribution system problems came from numerous small breaks (perhaps hundreds) at service points, e.g., hydrants sheared off by storm-propelled vehicles and broken plumbing from homes moved in the storm. The six pipe crossings over the Industrial Canal were positively valved off to isolate the contiguous portions of the city.

The State of Louisiana set several requirements for reestablishing water service: (1) uninterrupted treatment capable of producing water meeting microbiological standards, (2) backup electrical service in place, (3) capacity to receive and store treatment chemicals, and (4) maintenance of adequate pressure in an uninterrupted fashion. A boil-water order was in effect until all requirements could be met. Plant personnel collected 300-400 samples in exploratory sampling and three days of compliance sampling. Most samples were collected at hydrants. Only eleven samples tested positive for coliforms (only one including fecal coliform-positive sample).

By October 17, two important challenges remained. The first was chlorine stability. By not adding ammonia, the plant has switched from chloramination to chlorination. As a result, staff were concerned that chlorine residuals may dissipate more rapidly than in the past. The second challenge was to reestablish water service (i.e., end the need for a boil-water order) in Orleans Parish East and the South Shore.

The impact on the operation of commercial and institutional buildings in downtown New Orleans was substantial. Although large numbers of New Orleans residents used the Ernest H. Morial Convention Center and the Louisiana Superdome as shelters of last resort during the hurricane and subsequent flooding, potable drinking water was unavailable from the municipal water supply system, and evacuees had to get bottled water to survive. The extended loss of potable water after residents began to return to New Orleans had serious economic impacts: building engineers at several otherwise undamaged downtown high-rise commercial buildings stated that, if potable water had been available, tenants would have been able to return to their offices and conduct business.

5.2.2 Water Supply in Walker and Jefferson Parish, LA

MCEER researchers visited the East Jefferson Water Works District #1 drinking water treatment facility in Jefferson Parish on Jefferson Highway. This is the main drinking water treatment facility for the Jefferson Parish. The plant serves 308,000 people. The source water is the Mississippi River. The boil water order was lifted on September 12, 2005. Researchers spoke briefly with the head operator, and were told that the plant never shut down during the storm. Five plant personnel stayed in the facility during Hurricane Katrina and maintained operations. The Jefferson plant also served as a water source for Orleans Parish during the time that the boil-water order was imposed in Carrollton. Tanker trucks were filled at the plant for use in institutions such as hospitals. Individuals did not receive water at the plant.

MCEER researchers also visited the Town of Walker's drinking water treatment facility in Livingston Parish. The facility comprises about ten wells and above-ground chlorination, serving approximately 14,000 people. The facility was under a boil water order from August 29 through September 10, 2005.

5.3 Wastewater

The Slidell Wastewater Treatment Plant, located at 2800 Terrace Ave, Slidell, LA, is a 6 million gallon per day (mgd) facility located in St. Tammany Parish. The plant is a high-rate-activated sludge facility. It discharges to the W14 Canal, which feeds the Salt Bayou and ultimately Lake Pontchartrain. The following information was provided by the Chief Operator. According to a rain gauge at the plant, the facility received 15 inches of rain from Hurricane Katrina, resulting in 4 feet of water on-site and 30 inches of water inside the buildings. Plant staff waded into the plant the day after Katrina struck. A generator had tripped off early in the morning of August 29. This likely protected the generator. The plant used the generator for a week until power was restored. Several motors and other pieces of small equipment were destroyed.

Wastewater began entering the facility five days after the storm, at which time the plant was restarted. Flow to the plant was delayed because power was not available to the 90 lift stations in the collection system. The staff believes that the biomass was killed off by insufficient oxygen. After restart, water quality, as measured in terms of biochemical oxygen demand (BOD) and total suspended solids (TSS), has been good. Compounding the challenges, the plant has had to treat high strength wastewater from portable toilets and trailers. In addition, low rainfall (approximately ¾ inch between the passing of Hurricane Rita and mid-October) affected settleability.

The staff anticipates that some corrosion may occur because of brackish water deposited on site (although Mississippi received much more brackish water, as evidenced by the death of plant life in the affected areas). Another challenge is that the City of Slidell lost about 25 workers (out of a workforce of about 330) due to attrition after Hurricanes Katrina and Rita. Finally, repairs are being hampered because of the shortage of electrical contractors.

5.4 Telecommunications

By the time the reconnaissance team arrived in Mississippi on September 4, 2005, wireless telephone service was available throughout the affected area.

5.5 New Orleans Police and Fire Stations

Damage to police and fire facilities in New Orleans was substantial. The New Orleans Police Department has eight district stations and a number of support facilities. The first through seventh district police stations all experienced flooding, damage to architectural and mechanical, electrical, and plumbing components, and subsequent mold infestation that rendered them unsafe to occupy. The same is true of the crime lab, carpenter shop, facility support complex, and Special Operations Division complex. Of these facilities, only the carpenter shop, a century-old single-story warehouse building of unreinforced masonry, experienced significant structural damage, with heavy roof damage causing minor loss of bricks near roof-wall connections. By October 17, none of these police facilities were operational, and the New Orleans Police Department had relocated its headquarters temporarily to a French Quarter hotel. Fire stations throughout New Orleans were also flooded and infested with mold, damaged by wind pressure, storm surge, or a combination of these effects.

6.0 Conclusions

MCEER researchers have collected a substantial amount of data from field investigations in areas affected by Hurricane Katrina. The catastrophic level of damage to buildings and infrastructure was caused by a combination of hurricane driven winds, storm surge and flooding in the Gulf Coast. Investigators observed that the majority of multistory commercial buildings constructed of steel or reinforced concrete framing performed well structurally during Hurricane Katrina. However, extensive losses were incurred from nonstructural damage to cladding, windows, and roof-mounted equipment. In many of these cases, wind, water and wind-born debris infiltrated the interior of the building causing additional water damage to property.

The observed damage indicates the important role of architectural finishes in protecting the building interior and minimizing losses. In storm surge regions such as the Mississippi coast, structural damage was observed in buildings and parking structures exposed to extreme loads, mainly storm surge and impact from large storm surge debris such as barges. In evaluating the performance of parking structures in the Biloxi and Gulfport, Mississippi coast, it was found that while none of the cast-in-place structures that were investigated suffered any structural damage (with the exception of one that partially collapse from impact by a casino barge carried by storm surge), all of the precast concrete structures examined suffered partial collapse of the second-floor deck.

The information presented here and in other reports in this series will expand on multi-hazard studies to better understand the similarities and differences between various potential hazards such as hurricanes, earthquakes and terrorist attacks. Potential results from this work include the use of seismic design details to mitigate hurricane induced damage on precast concrete construction. Along the Mississippi Coast, many precast/prestressed concrete decks of parking structures fell from their support. Based on the survivability of cast-in-place concrete construction, pre-cast parking structures could benefit from improved continuity in their connections and possibly from measures to reduce buoyancy, such as new air vents drilled through second-floor decks and fitted with grilles. Similar failures have been observed after earthquakes, but the vulnerability of this type of construction to seismic loading has been improved by modern connection details developed and tested through research. Similar advancements are needed for precast construction in storm surge regions and seismic detailing could potentially minimize damage to these types of structures.

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