NIST Technical Note 1476

Performance of Physical Structures in Hurricane Katrina and Hurricane Rita: A Reconnaissance Report

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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U.S. DEPARTMENT OF COMMERCE
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AASHTO	American Association of State Highway and Transportation Officials
ADCIRC	Advanced Circulation Model
AEI	Architectural Engineering Institute
AOML	Atlantic Oceanographic and Meteorological Laboratory
API	American Petroleum Institute
APTA	American Public Transportation Association
ARA	Applied Research Associates
AREMA	American Railroad & Engineering & Maintenance of Way Association
ASTM	American Society for Testing and Materials
ASCE	American Society of Civil Engineers
ASOS	Automated Surface Observing Stations
ATC	Applied Technology Council
BFRL	Building and Fire Research Laboratory, NIST
CDC	Centers for Disease Control
CDBG	Community Development Block Grant
CDR	Council on Disaster Reduction
C-MAN	Coastal-Marine Automated Network
COPRI	Coasts, Oceans, Ports, & Rivers Institute
DOT	U.S. Department of Transportation
DHS	Department of Homeland Security
EIFS	Exterior Insulation and Finish System
EPRI	Electric Power Research Institute
EYD	Energy Division
EWRI	Environmental & Water Resources Institute
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FCMP	Florida Coastal Monitoring Program
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration

FTA	Federal Transit Administration
GAO	Government Accountability Office
GI	GeoInstitute, ASCE
GIS	Geographic Information System
GIWW	Gulf Intracoastal Waterway
GSA	U.S. General Services Administration
HRD	Hurricane Research Division, NOAA
HUD	U.S. Department of Housing and Urban Development
IBHS	Institute for Business & Home Safety
IHNC	Inner Harbor Navigation Canal
ILA	International Longshoremen's Association
IPET	Interagency Performance Evaluation Task Force
LHA	Louisiana Hospital Association
LIDAR	Light Detection and Ranging
LRFD	Load and Resistance Factor Design
LSU	Louisiana State University
MHI	Manufactured Housing Institute
MCEER	Multidisciplinary Center for Earthquake Engineering Research
MRGO	Mississippi River Gulf Outlet
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NAHB	National Association of Home Builders
NAVFAC	Naval Facilities Engineering Command
NCDC	National Climatic Data Center, NOAA
NCSBCS	National Conference of States on Building Codes & Standards
NHC	National Hurricane Center
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NMSA	National Maritime Safety Association
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWS	National Weather Service
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy

PHMSA	Pipeline and Hazardous Materials Safety Administration
SEI	Structural Engineering Institute
SEAOCC	Structural Engineers Association of Central California
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
TCFE	Technical Council on Forensic Engineering
TCLEE	Technical Council on Lifeline Earthquake Engineering
TISP	The Infrastructure Security Partnership
T&DI	Transportation & Development Institute
TTU	Texas Tech University
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WEMITE	Wind Engineering Mobile Instrumented Tower Experiment

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Abstract

This is the final report on the National Institute of Standards and Technology (NIST) led-reconnaissance to assess the performance of physical structures during Hurricane Katrina and Hurricane Rita. The report describes the environmental conditions (wind speed, storm surge, and flooding) that were present during the hurricanes in regions that were affected by the hurricanes. The report further documents the NIST-led team's observations of damage to major buildings, infrastructure, and residential structures resulting from wind and wind-borne debris, storm surge, surge-borne debris, and surge-induced flooding.

Following Hurricane Katrina's landfall on August 29, 2005, NIST began planning for a two-phase reconnaissance to study and document damage to major buildings, infrastructure, and residential structures. In phase 1, NIST deployed a roofing expert with a team assembled by the Roofing Industry Committee on Weathering Issues (RICOWI) during the week of September 6, 2005 to study damage to roofing systems in Mississippi Gulf Coast region. NIST deployed four structural engineers in cooperation with the FEMA Mitigation Assessment Team (MAT) during the week of September 26, 2005 to study damage in the Mississippi Gulf Coast region. Two NIST members of this team also inspected the breaches in the floodwalls and levees, as well as damage to major buildings, in New Orleans. These phase 1 deployments provided input that was used to plan a broader phase 2 reconnaissance to study damage in the Mississippi coastal area, New Orleans, and Southeast Texas (the area affected by Hurricane Rita). In the phase 2 reconnaissance, 26 experts from the private sector, universities, and federal agencies (including 6 from NIST) deployed during the weeks of October 10, 2005 and October 17, 2005. This report documents the observations made during these deployments and subsequent analysis of damage data and environmental actions. It also outlines the major findings of the NIST-led reconnaissance team.

The report concludes with 23 recommendations for: (1) improvements to practice that will have an immediate impact on the rebuilding of structures damaged or destroyed by the hurricanes; (2) improvements to standards, codes, and practice; and (3) further study or research and development.

Keywords: Hurricane, wind, wind-borne debris, storm surge, surge-borne debris, flooding, major buildings, physical infrastructure, residential structures, building codes and standards, building practices.

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Executive Summary

Introduction

This report documents the findings and recommendations resulting from a multi-organizational reconnaissance of the performance and damage to physical structures due to Hurricanes Katrina and Rita in 2005. The reconnaissance was organized and led by the U.S. Commerce Department's National Institute of Standards and Technology's (NIST)[1].

The NIST-led reconnaissance was a cooperative effort from its very launch. NIST and other participating federal agencies and private sector organizations have openly shared data and information from the beginning to plan for and conduct the reconnaissance, and to develop the findings and recommendations. NIST technical experts have participated on other Katrina-Rita studies (e.g., Federal Emergency Management Agency's Mitigation Assessment Team, the U.S. Army Corps of Engineers' Interagency Performance Evaluation Task Force, and the Roofing Industry Committee on Weathering Issues). Similarly, the NIST-led reconnaissance that is the subject of this report has benefited from the participation of technical experts from other federal agencies and the private sector. While the findings and recommendations are NIST's, the report and its recommendations have been reviewed by the participating organizations. The interagency cooperation is continuing as agencies plan and carry out follow-up actions in response to the recommendations of this report.

This work complements other completed and ongoing studies of the performance of structures in the Gulf region during the hurricanes. It is the only study to take a broad look at damage to physical structures and its implications for the Gulf Coast and other hurricane-prone regions.

Disasters such as Hurricane Katrina and Hurricane Rita provide an unfortunate but important opportunity to learn from the performance of structures exposed to catastrophic events and to derive lessons that can lead to improvements in standards, codes, and practice that will reduce losses in future events. NIST chose to undertake a broad-based reconnaissance effort rather than a detailed investigation since much already has been learned from past hurricanes. The reconnaissance was intended to identify new technical issues that need to be addressed in the rebuilding effort, in the improvement of building standards and model codes, or in future research studies. In the process, the team identified opportunities for improvement in standards, codes, and practices that require no additional study.

The reconnaissance identified three key areas where detailed technical studies are essential: (1) to evaluate the performance of the New Orleans flood protection system and provide credible scientific and engineering information for guiding the immediate repair and future upgrade of the system; (2) to develop risk-based storm surge maps for use in flood-resistant design of structures, and (3) to evaluate and, if necessary, modify the Saffir-Simpson hurricane scale's treatment of storm surge effects due to hurricanes.

The findings of the reconnaissance highlight the critical importance of state and local entities adopting and then rigorously enforcing building standards, model codes, and practices.

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[1] The National Institute of Standards and Technology (NIST) is a non-regulatory agency of the Department of Commerce. NIST's Building and Fire Research Laboratory (BFRL) supports U.S. industry and public safety by providing critical tools – metrics, models, and knowledge – and the technical basis for standards, codes, and practices.

First, at the time of the hurricanes, there was no statewide building code in Louisiana, Mississippi, Alabama, or Texas[2], although some local jurisdictions within those states had adopted model building codes. The City of New Orleans had adopted the 2000 edition of the model building and residential codes issued by the International Code Council in January 2004. Second, the team observed significant damage in many instances where the winds were lower than those levels cited in codes and standards—suggesting that the structures did not perform as required. Third, older structures—only required to meet building codes in effect when they were built—were particularly vulnerable to wind damage. Current model building codes and standards contain provisions for the design of structures subject to high wind, flood, and storm surge; adoption and enforcement of such codes and standards in hurricane prone regions can greatly improve the performance of structures.

Federal agencies, state and local governments, and the private sector already have taken actions consistent with NIST's recommendations to facilitate rebuilding and mitigate the potential for damage in future storms—in many cases even as the findings were being analyzed and recommendations were being formulated. The U.S. Army Corps of Engineers (USACE) promptly took action to repair damage to the flood protection system in New Orleans as well as to determine the factors that contributed to the failures and make improvements. The Federal Emergency Management Agency (FEMA), in conjunction with USACE, is providing updated base flood information to guide rebuilding. The Federal Highway Administration (FHWA) is developing a plan of action for studies and research for coastal bridges.

NIST Response and Scope of Reconnaissance

On August 29, 2005, Hurricane Katrina first made landfall near Buras, Louisiana[3]. Less than one month later, Hurricane Rita made landfall near the Texas-Louisiana border. NIST began preparation for conducting reconnaissance in the hurricane affected areas on August 29, 2005. NIST coordinated with FEMA, USACE, and other agencies to begin planning for an initial deployment to the region. NIST technical experts deployed to the field twice during September 2005: first during the week of September 6th as part of a team assembled by the Roofing Industry Committee on Weathering Issues (RICOWI), and again, during the week of September 26th in cooperation the FEMA Mitigation Assessment Team (MAT). Two NIST team members also inspected damage to the levees and floodwalls in New Orleans during this deployment. These initial deployments provided valuable input to NIST in planning a comprehensive reconnaissance effort.

NIST, working with the Applied Technology Council (ATC) under a contract, assembled a team of 26 experts to conduct reconnaissance in the areas affected by Hurricane Katrina and Hurricane Rita. The team consisted of a diverse and balanced group of private sector, academic, and government experts from 16 organizations, including NIST, FHWA, and USACE. Based upon the earlier reconnaissance efforts and other available data, the team was deployed to the Mississippi Gulf Coast, New Orleans, and Southeast Texas-Southwest Louisiana areas to conduct reconnaissance and collect perishable data.

The scope of the reconnaissance was broad-based in light of the breadth and scope of damage from the hurricanes and it included major buildings[4], physical infrastructure[5], and residential structures. In

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[2] The Texas Department of Insurance put into effect the 2000 International Building Code and International Residential Code with Texas revisions on February 1, 2003 for the 14 counties located on the Gulf Coast. The 2003 editions of these codes were put into effect on January 1, 2005 for these counties. To be eligible for windstorm insurance, homeowners were required to comply with the Windstorm Code (which is based on these model codes) published by the Texas Department of Insurance.

[3] Cities in southern Florida were hit by Hurricane Katrina on August 25, more than three days before it made landfall in Louisiana on August 29, 2005.

[4] Major buildings are defined herein as buildings that are a result of engineering design or have special occupancy classifications. See Chapter 3 for further detail.

addition to collecting perishable data in the field, the team analyzed environmental data (e.g., wind speeds and storm surge heights) and analyzed observations made by other teams working in the affected areas. The findings contained in this report are consistent with a broad-based field reconnaissance effort covering a large geographic region, rather than an in-depth scientific investigation of a limited set of technical issues. Further, the findings are based on physical evidence that was not completely destroyed by the hurricane.

The Hazard Context

Hurricane Katrina struck the Gulf Coast region as a Category 3 hurricane on the Saffir-Simpson hurricane scale. However, due to the large horizontal size of the hurricane, the accompanying storm surge was observed to be as high as 28 ft at some locations along the Mississippi Gulf Coast. Hurricane Katrina reached Category 5 intensity while in the Gulf of Mexico, with maximum sustained winds of 150 kt (approximately 175 mph). The storm began weakening about 18 hours before making landfall as a Category 3 hurricane with maximum sustained winds of 110 kt (approximately 125 mph).

Hurricane Rita made landfall near the Texas-Louisiana border as a Category 3 hurricane and generated storm surge as high as 15 ft (Cameron, Louisiana). Although the National Hurricane Center (NHC) has officially classified Hurricane Rita as a Category 3 hurricane, Category 3 intensity winds were confined to a small area on the coast in extreme Southwest Louisiana. Most of the affected areas experienced wind speeds consistent with Category 1 or 2 hurricane intensity. Like Hurricane Katrina, Hurricane Rita reached Category 5 intensity over the Gulf of Mexico, with maximum sustained winds of 155 kt (180 mph. Hurricane Rita began weakening 48 hours before landfall.

Principal Findings

Based upon data collected in the field during the reconnaissance, analysis of observations made by other teams, analysis of environmental data, and engineering judgment[6], NIST has identified key findings described below.

In coastal areas and in New Orleans, storm surge was the dominant cause of damage. Storm surge heights, in general, exceeded the levels defined by existing flood hazard maps as well as historical records. While design provisions exist to address storm surge and flooding, existing flood hazard maps – which provide the basis for design of structures – are outdated and not consistent with the risks posed by storm surge in these coastal areas. Better definition of the storm surge hazard is required to appropriately apply existing design provisions and elevation levels to mitigate the effects of storm surge on buildings and residences.

The Saffir-Simpson hurricane scale—which is used in part by emergency managers for evacuation planning and making evacuation decisions—specifies hurricane wind speeds and indicates storm surge heights associated with each hurricane category. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf and the shape of the coastline, in the landfall region. Hurricane Katrina and Hurricane Rita showed that it is possible for storm surge heights to substantially exceed heights associated with a specified category on the Saffir-Simpson hurricane scale. The National Oceanic and Atmospheric Administration (NOAA) does not rely on the storm surge ranges associated with the Saffir-Simpson hurricane scale in its hurricane advisories. Instead, NOAA includes in its advisories storm surge forecasts based upon use of storm surge simulation models.

[5] Physical infrastructure includes: levees and floodwalls, bridges and roadways, seaport structures, utilities (e.g., electric power, water and wastewater, communications, gas distribution), and industrial facilities such as petrochemical plants.
[6] Analytical, numerical, and statistical calculations were outside the scope of this reconnaissance study.

NOAA, in their advisories prior to landfall of Hurricane Katrina, predicted "coastal storm surge flooding of 18 to 22 ft above normal tide levels…locally as high as 28 ft along with large and dangerous battering waves…can be expected near and to the east of where the center makes landfall", and "storm surge flooding of 10 to 15 ft near the tops of the levees is possible in the greater New Orleans area." These storm-surge related advisories were consistent with observed high water marks along the Mississippi coast where the hurricane made landfall and the greater New Orleans area.

Storm surge and associated wave action led to breaches in the flood protection system in New Orleans, resulting in significant structural damage to residences in the immediate vicinity of breaches due to high-velocity water and flooding in approximately 75 percent of the city. The NIST-led team observed failures of the levees and floodwalls in New Orleans by three different mechanisms: rotational failure of the floodwall-sheet pile system triggered by soil erosion due to overtopping; massive erosion and scour of the earthen levee at the levee/floodwall junction (with water overtopping); and sliding instability of the floodwall-levee system due to foundation failure (without water overtopping). The foundation failures due to sliding instability at the above breaches could have been possibly caused either by underseepage erosion and piping or by shear failure within the clay in the foundation beneath the levee and the floodwall.

Houses in New Orleans were constructed at grade level or slightly elevated on the presumption that the flood protection system would remain intact and that flooding in low lying areas would be the result of precipitation only. Many houses located in the immediate vicinity of levee breaches were severely damaged or destroyed as a result of high velocity water flow and flooding. It is important for building codes and standards to better define the hazards and design requirements in coastal flood prone regions in a risk-consistent manner.

Many bridges in the coastal areas were damaged due to the uplift and lateral loads imparted by storm surge and associated wave action. A number of simple span bridges lost spans or had spans displaced as a result of these actions. Some bridges, both highway and railway, exposed to these actions remained in place due to design features that prevented displacement of decks. Swing span bridges exposed to storm surge were in many cases rendered inoperable due to inundation of mechanical and electrical equipment. Failures of precast parking-garage structures were similar to those of simple span bridges, where uplift and wave forces dislodged first floor decks from their connections to columns.

In coastal Mississippi, storm surge, wave action, and surge-borne debris caused extensive damage to casino barges that either sank in place or broke free of moorings and floated inland. Mooring requirements, based on wind speeds of 155 mph and 15 ft storm surge heights were inadequate for the storm surge heights generated by Hurricane Katrina. There are no national standards for the design of mooring systems used to secure permanently moored facilities such as casino barges.

Many industrial facilities, such as seaports, petrochemical facilities, and utilities sustained damage due to storm surge and flooding. One of the major ports in the region sustained significant structural damage to piers and warehouses due to storm surge and wave loading. Inundation due to storm surge and waves caused damage to electrical and mechanical equipment on the port's cargo crane, rendering the crane inoperable. Also, the hurricane tie-down for this crane was damaged.

Current model codes and standards contain provisions for design of structures and location of equipment to account for flooding and storm surge. However, several buildings were rendered inoperable because critical equipment, such as backup electrical generators, electrical equipment, and chiller plants were located at or below grade and damaged due to inundation by floodwaters. In addition, some utilities such as electrical generation plants and substations, and water and wastewater treatment plants, became inoperable because they sustained damage to electrical and mechanical equipment.

Away from the immediate coastal areas, wind and wind-borne debris were the dominant causes of damage to structures. In general, wind speeds were below levels required by codes and standards. Wind also caused damage to roofing and rooftop equipment, providing paths for water ingress into buildings. Wind-driven rain through walls and around intact windows also was responsible for water damage to the interiors of buildings.

Major buildings suffered wind-induced damage to glazing (window glass) as a result of debris impact from aggregate surface roofs on adjacent buildings, debris from damaged equipment screens on top of buildings, and debris from the damaged façade or structure of adjacent buildings. In many cases, buildings that suffered structural damage due to wind were built before current model building codes were available. Design wind speeds in current codes and standards provide a sufficient level of safety if provisions are properly implemented and enforced.

Roofing failures on buildings and residential structures were observed throughout the region. Typical damage to building roofs included failure of roof coverings and finishing details, loss of the roof deck, and in some cases the supporting structure. Failure of shingles on residential structures was observed throughout the region, and the team documented many cases of improper installation of shingles[7].

Industrial facilities outside the surge and flood zones also sustained damage due to wind loads. In another major port in the region, failures of hurricane tie-downs due to wind loads caused significant damage to three large cranes. As many as one million timber electric power distribution poles were lost in the two hurricanes, as well as a number of high voltage transmission towers. Petrochemical plants in the region experienced damage that was generally limited to cooling tower shrouds, and insulation on oil storage tanks and flare towers, due to wind. Some structural failures of oil storage tanks were observed at plants near Hurricane Katrina's landfall.

Recommendations

As a part of its reconnaissance, NIST is making 23 recommendations for specific improvements in the way that buildings, physical infrastructure, and residential structures are designed, constructed, maintained, and operated in hurricane prone regions. It is important to note that these recommendations may apply to other hurricane-prone regions of the country. These recommendations are grouped as follows:

Group 1: Immediate impact on practice for rebuilding: These recommendations (1 through 5) have immediate implications for the repair and reconstruction of buildings, physical structures, and associated equipment damaged or destroyed by Hurricanes Katrina and Rita.

Group 2: Standards, codes, and practices: These recommendations (6 through 14) address the need for development or modification of codes, standards, and practices with a view toward improving the performance of buildings, physical structures, and associated equipment in future hurricanes based upon the observed damage due to Hurricanes Katrina and Rita.

[7] A statistically-based analysis of roofing performance, damage, and installation practices was beyond the scope of this reconnaissance study.

Group 3: Further study of specific structures or research and development: These recommendations (15 through 23) identify the need for detailed performance assessments of structures or classes of structures to determine the factors that influenced their performance during the hurricanes or the need for research and development on specific technical issues.

The recommendations call for action by specific entities regarding standards, codes, and regulations, as well as their adoption and enforcement; professional practice, education and training; and research and development.

The recommendations do not prescribe specific systems, materials, or technologies. Instead, NIST encourages competition among alternatives that can meet performance requirements. The recommendations also do not prescribe threshold levels; NIST believes that this responsibility properly falls within the purview of the public policy setting process, in which the standards and codes development process plays a key role.

NIST believes that the recommendations are realistic, appropriate, and achievable within a reasonable period of time.

Most of the recommendations deal with adopting and enforcing current requirements or with making improvements to existing requirements and practice. Some of the recommendations address developing a risk-consistent basis for consideration of storm surge as a design load for coastal buildings and structures.

NIST strongly urges state and local agencies to adopt and enforce building codes and standards since such enforcement is critical to ensure the expected level of safety. In many cases, the reconnaissance clearly found that building codes, standards, and practice are adequate to mitigate the types of damage that resulted from the hurricanes. *Following good building practices also is critical to better performance of structures during extreme events like hurricanes.* Relatively straightforward changes to practice could have reduced the damage that occurred. The best codes and standards cannot protect occupants or buildings unless they are strictly followed. Examples include:

- Masonry wall failures observed during the reconnaissance may have been prevented had they been properly anchored and reinforced as required by the model codes.

- Many roofing shingle failures resulted from installers using an inadequate number of fasteners or installing fasteners in the wrong locations. NIST is recommending that states and localities consider licensing roofing contractors, providing continuing education for contractors, and putting in place field inspection programs to monitor roofs being constructed. A licensing program instituted by the state of Florida for roofing contractors may serve as a model for other states to implement licensing programs.

- Wind-borne gravel from building rooftops caused a great deal of damage to nearby structures. Model building codes do not permit aggregate surface roofs in high wind zones to ensure that the aggregate does not become wind-borne debris and cause damage to windows on nearby buildings.

- In many instances backup electrical generators, electrical equipment, chillers, and other critical equipment were not placed above the expected flood levels. Model code provisions address the location of critical building equipment to avoid this kind of damage due to flooding. This would not have protected all buildings that lost equipment due to the high storm surge, but it would have made a large difference for many critical structures.

Federal agencies, state and local governments, and the private sector already have taken actions that are consistent with NIST's recommendations—in many cases even as the findings were being analyzed and recommendations were being formulated. NIST encourages other organizations with responsibility for implementation to take similar actions. Some of the actions that are already underway include:

Levees and Floodwalls:

- USACE immediately began a major project (Project Guardian) to rebuild the levees and floodwalls where breaches occurred before the start of the hurricane season on June 1, 2006.

- USACE initiated the Interagency Performance Evaluation Task Force (IPET) to assess the performance of the New Orleans flood protection system, understand the factors that contributed to failures during Hurricane Katrina, and make recommendations for improvements.

Building Code Adoption and Other Actions:

- Louisiana has adopted the International Building Code (IBC) in the 11 parishes hardest hit by Hurricane Katrina effective immediately for reconstruction. The IBC will become effective statewide for all new construction in 2007.

- The Mississippi Legislature (House Bill 45) amended the Mississippi Code of 1972 to allow the gaming portions of Gulf Coast casinos to be built on land within 800 feet of the high water line or in some cases, as far inland as the southern boundary of the US-90 right-of-way.

- The Department of Housing and Urban Development (HUD) requires that community development block disaster recovery grants not be used for any activity in special flood hazard areas delineated in FEMA's most current flood advisory maps unless it also ensures that the action is designed or modified to minimize development-related harm to or within the flood plain.

Flood Map Modernization and Storm Surge Mapping:

- FEMA, leading the effort, in cooperation with the USACE, has undertaken a project to update the Flood Insurance Rate Maps for New Orleans and the Gulf Coast areas affected by Hurricane Katrina and Hurricane Rita. Both NOAA and FEMA already are conducting studies to document and assess the storm surge risks posed by Hurricane Katrina in the Gulf Coast region. FEMA has also published a Coastal Construction Manual which provides guidance on building standards and techniques to resist both wind and waves.

- The Federal Coordinator for Gulf Coast Rebuilding, FEMA, and USACE have issued guidelines for rebuilding in New Orleans and surrounding areas based on updated advisory base flood elevations.

- The U.S. Geological Survey (USGS) has initiated a project to map the changes in the coastline due to the effects of storm surge. The agency also plans to study the effects of natural and restored land in mitigating the effects of storm surge.

- NIST has funded a project to develop the methodology for risk-based structural design criteria for coastal structures subjected to both hurricane winds and storm surge that will consider different methods for predicting input hurricane parameters for storm surge and wave models, different storm surge models, and coupling of storm surge models with different wave models. NIST is facilitating coordination and collaboration among relevant federal agencies (e.g., FEMA, USACE, NOAA, USGS, and FHWA) and key private sector organizations in support of FEMA's overall flood map modernization program and under FEMA leadership to ensure that the needs for structural design are adequately met.

Highway Bridges:

- FHWA issued an initial guidance document on "Coastal Bridges and Design Storm Frequency." This document provides a regulatory and engineering rationale for considering both storm surge and wave forces, specifically for those coastal states affected by Hurricane Katrina.

- FHWA is developing a plan of action that will be used to coordinate with the American Association of State Highway and Transportation Officials (AASHTO) and other stakeholders in performing studies and research for coastal bridges vulnerable to scour and hydrodynamic forces.

- FHWA has issued a solicitation for a pooled funds project to develop retrofit strategies and options to mitigate damage to highway bridges subject to coastal storm hydrodynamic factors and recommend improvements for bridges in coastal environments. The objective of this project is to develop solutions that can be immediately implemented by states and bridge owners and adopted into AASHTO standards as appropriate.

Recommendation	Affected Standards/Codes/ Guidance	Primary Interested Government Entities	Interested Entities
Group 1: Immediate impact on practice for rebuilding			
Recommendation 1. Improve the design, construction, and performance of the New Orleans levees and floodwalls by: (1) conducting a comprehensive review and upgrade of the design hazard, criteria, and manuals for levees and floodwalls to develop a risk-based approach to design for storm surge that is similar to the current risk-based approach to design for wind; (2) performing a systematic review of the existing, as-constructed levees and floodwalls relative to design requirements in USACE design manuals; and (3) developing methodologies for levee and floodwall design, construction, and repair that allow for overtopping without subsequent failure of the floodwall or levee structures. Major steps are already underway that will fulfill this recommendation. USACE promptly took action (a) to repair damage to the New Orleans flood protection system and (b) to conduct a detailed performance evaluation that will provide credible scientific and engineering information for guiding the immediate repair and future upgrade of the system.	*USACE Engineer Manuals governing the design, construction, and maintenance of levees and floodwalls.*	USACE	Local levee districts, FEMA, ASCE-COPRI
Recommendation 2. Install mechanical, electrical, and plumbing components, equipment, and systems—including alternative/backup electric power supplies—required for the continued operation of existing critical facilities at a level that is above the design flood elevation by a specified minimum threshold.	*FEMA Flood Insurance Rate Maps, International Building Code, NFPA 5000*	FEMA	ICC, NFPA, BOMA, ASHRAE
Recommendation 3. Adopt and enforce model building codes for masonry wall construction to ensure that: (1) load-bearing masonry walls are adequately anchored and reinforced to resist lateral forces; (2) non-load-bearing masonry walls are adequately anchored to the supporting structure; and (3) exterior masonry walls are flood-proofed to the design flood elevation.	*IBC, IRC, NFPA 5000, ASCE 24, ACI 530 (also published as ASCE 5 and TMS 402), ACI 530.1 (also published as ASCE 6 and TMS 602), and ACI 318, FEMA Technical Bulletin 11-01*	FEMA	TMS, ASCE, ACI, ICC, NFPA, state and local building authorities

Recommendation	Affected Standards/Codes/ Guidance	Primary Interested Government Entities	Interested Entities
Recommendation 4. Adopt and enforce model building codes and the latest standards for roofing systems to: (1) prohibit the use of aggregate surface roofs when re-roofing existing aggregate surface roofs in hurricane-prone regions; and (2) ensure that roofing systems are designed and installed according to standards for roofing in high wind zones. This includes residential steep-sloped asphalt shingle roofs, commercial low-sloped roofs, and mechanically attached metal roofs. Model building codes should be modified to incorporate ASTM D7158, "Wind Resistance of Sealed Asphalt Shingles (Uplift Force/Resistance Method)."	*International Building Code, NFPA 5000, ASTM D 7158*	State and local building authorities (especially in Mississippi, Louisiana, Texas, and Alabama)	Roofing Industry Committee on Weathering Issues (RICOWI), Asphalt Roofing Manufacturers Association (ARMA), the National Roofing Contractors Association (NRCA), and the Roof Consultants Institute (RCI), ASTM, ICC, NFPA
Recommendation 5. States and local jurisdictions should consider (1) licensing of roofing contractors; (2) continuing education of roofing contractors; and (3) field inspection programs to monitor roofs under construction for proper installation, in order to ensure acceptable roofing application.		State and local building authorities	RICOWI

Recommendation	Affected Standards/Codes/ Guidance	Primary Interested Government Entities	Interested Entities
Group 2: Standards, codes, and practices			
Recommendation 6. Evaluate and upgrade mooring system design criteria for floating structures (e.g., casino barges) to be consistent with the wind and storm surge risk including dynamic wave loads.		State and local government agencies (e.g., Mississippi Gaming Commission), USACE, USCG	
Recommendation 7. Develop risk-based storm surge maps for several mean recurrence intervals, incorporating storm surge height and current velocity and the associated wave action, to provide a technical basis for the design of coastal structures in storm surge zones – including port facilities, flood protection systems, coastal highway and railroad bridges, and buildings - along the U.S. Atlantic and Gulf Coast regions. The information on storm surge heights, current velocity, and wave characteristics could be provided in separate maps at different mean recurrence intervals (e.g., 10, 50, 100, and 500-yrs)—in addition to the current flood maps which provide total inundation expected from all sources, including storm surge—for use in designing coastal structures.	*ASCE 7, ASCE 24*	FEMA, NOAA, USACE, NIST	USGS, NSF, FHWA, ASCE
Recommendation 8. Evaluate and, if necessary, modify the Saffir-Simpson hurricane scale's treatment of storm surge effects due to hurricanes. The results of the evaluation should be broadly discussed by experts before changes, if needed, are considered for implementation.		NOAA, NIST	FEMA, NSF

Recommendation	Affected Standards/Codes/ Guidance	Primary Interested Government Entities	Interested Entities
Recommendation 9. Develop design requirements for improved structural integrity of precast reinforced concrete structures subject to storm surge loadings.	*ACI 318, International Building Code, NFPA 5000*	NIST, FEMA	American Concrete Institute (ACI), Portland Cement Association (PCA), Prestressed Concrete Institute (PCI), Construction Technology Laboratories (CTL), ICC, NFPA
Recommendation 10. Establish risk-based design methodologies for: (1) coastal bridges, (2) communication systems, (3) electricity, water, and gas distribution systems, and (4) roadside signs to resist flooding, storm surge, debris impact, and wind.	*American Association of State Highway and Transportation Officials (AASHTO)'s "LRFD Bridge Design Specification" and "Standard Specifications for Structural Supports for Highway Signs, Luminaries and Traffic Signals;" ASME/ANSI B31.3; API 620 and 650; AWWA D; RUS 1742e-200 and -300; ASCE 7 and 10, Manual 72, 74, and 91, Concrete Poles; IEEE; NESC; TIA/EIA 222F and G; Bell Core.*	USACE, FHWA	FEMA, ASCE, AASHTO, EPRI, IEEE, Railroad Industry
Recommendation 11. Evaluate the adequacy of restraining systems for large cargo cranes in port facilities.		OSHA, State Port Authorities in coastal areas	American Association of Port Authorities; Port Authorities at Mobile, Pascagoula, Biloxi and New Orleans; National Maritime Satey Association (NMSA), International Longshoremen's Association (ILA)
Recommendation 12. Adopt and implement existing model code provisions for providing alternative/backup electric power supplies for all critical facilities and equipment.	*International Building Code, NFPA 5000, ASCE 24*		ICC, NFPA, APWA, AWWA, utility and telecommunication companies

Recommendation	Affected Standards/Codes/ Guidance	Primary Interested Government Entities	Interested Entities
Recommendation 13. Install isolation valves in water and gas distribution systems in areas susceptible to damage.	*AWWA Standards for Valves and Hydrants, ASME/ANSI B16.33, B16.34, B16.38*	State and local governments	NFPA, APWA, AWWA, utilities
Recommendation 14. Develop and implement special inspection requirements for connection and cladding attachments in pre-engineered metal buildings within model codes for hurricane prone regions.	*International Building Code, NFPA 5000*	NIST	ICC, NFPA
Group 3: Further study of specific structures or research and development			
Recommendation 15. Conduct detailed performance assessments of coastal highway and railroad bridges to fully understand and document the factors that contributed to their failure or survival and make recommendations for improvements to future designs. This work should include: (1) evaluation of design methods and connection details to improve the resistance to storm surge-induced uplift and lateral forces; (2) development of measures to prevent widespread loss of functionality of moveable bridges following a hurricane due to inundation of electrical and mechanical equipment; (3) development of means to mitigate the impacts of debris and massive objects carried by storm surge on the performance and functionality of bridges; and (4) development of methods for armoring bridge approaches against scour and erosion to avoid losing the use of a bridge.	*AASHTO LRFD Bridge Design Specification*	FHWA	AASHTO, AREMA, NSF, Railroad Industry
Recommendation 16. Conduct detailed studies to identify mechanisms for water ingress into buildings during hurricanes and to develop improved building envelope construction and cladding systems that are resistant to water ingress.	*International Building Code; IRC; NFPA 5000*	DOE	HUD, FEMA, ASCE, ASTM, ICC, NFPA, and state and local building authorities

Recommendation	Affected Standards/Codes/ Guidance	Primary Interested Government Entities	Interested Entities
Recommendation 17. Conduct an evaluation of the application of seismic design methods and retrofit details to improve the resistance of existing unreinforced masonry construction to extreme wind loading.	*ACI 530 (also published as ASCE 6 and TMS 402)*	FEMA	ACI, ASCE, TMS, state and local building authorities
Recommendation 18. Conduct detailed performance assessments of the wharfs in the Gulf States that were exposed to uplift and lateral forces due to storm surge to fully understand and document the factors that contributed to their performance during Hurricane Katrina or Rita and make recommendations for improvements to future designs.		State and local port authorities	ASCE-COPRI
Recommendation 19. Conduct detailed performance assessments of the portable classrooms (manufactured houses) in Port Arthur, TX, to fully understand and document the factors that contributed to their survival and make recommendations for improvements to future designs.	*HUD Manufactured Home Construction and Safety Standards*	HUD	MHI, NAHB, state and local building authorities
Recommendation 20. Conduct detailed studies of the performance of metal buildings subjected to hurricane force winds to fully understand and document the factors that contributed to their performance and make recommendations for improvements to future designs.		NIST	Metal Building Manufacturers Association (MBMA)
Recommendation 21. Conduct detailed studies of the performance of residential asphalt shingle roofing, metal roofing on both residential and commercial buildings, and low-rise membrane roofs on commercial buildings to identify factors that affected performance and provide the technical basis for improved guidance on the use of these roofing systems in high wind zones.	*ASTM D 7158, International Building Code, International Residential Code*	HUD, DOE	Asphalt Roofing Manufacturers Association (ARMA), National Roofing Contractors Association, RICOWI, Roof Consultants Institute, Metal Construction Association, Metal Building Manufacturers Association, NAHB.

Recommendation	Affected Standards/Codes/ Guidance	Primary Interested Government Entities	Interested Entities
Recommendation 22. Conduct detailed studies to: (1) evaluate and quantify the effects of corrosion, decay, and other aging factors on the service life performance of residential buildings and components; and (2) evaluate and improve performance criteria and installation practice for anchorage systems for manufactured homes.	*International Residential Code, HUD Manufactured Home Construction and Safety Standards*	HUD	NAHB, MHI, FEMA
Recommendation 23. Evaluate the effects of shielded (e.g., wooded or wooded/suburban) exposures and their potential for reducing the wind loads on nearby residential structures and better explain the variation in observed damage.	*ASCE 7*	HUD, NIST	NAHB, ASCE, AAWE

Chapter 1
INTRODUCTION

Hurricane Katrina first made landfall near Buras, Louisiana on August 29, 2005[3], and was classified at the upper end of a Saffir-Simpson Category 3 storm by the National Hurricane Center (NHC [10]). With NHC estimated sustained maximum wind speeds of 110 kt (approximately 125 mph) and storm tide (storm surge plus astronomical tide) heights up to 27 ft (at Hancock, MS, Emergency Operations Center [10]), Hurricane Katrina caused overwhelming damage to exposed communities along the coastline of Louisiana and Mississippi. Surge heights of about 10 ft were responsible for the failure of the flood protection system in New Orleans. Prior to landfall, Hurricane Katrina was classified by the NHC as a Category 5 storm with estimated maximum sustained wind speeds of 150 kt (approximately 175 mph) [10]. It now stands as the costliest, and one of the five deadliest, hurricanes to ever strike the United States.

Less than one month later, Hurricane Rita made landfall along the Texas-Louisiana border on September 24, 2005, and was classified as a Category 3 storm by the NHC. However, only a small area on the coast of extreme Southwestern Louisiana that was to the east of the eyewall experienced Category 3 wind speed according to the NHC [11]. Prior to landfall, Hurricane Rita was also classified by the NHC as a Category 5 storm with estimated maximum sustained wind speeds of 155 kt (approximately 180 mph) [11]. Wind damage was extensive in the coastal areas of southeastern Texas and southwestern Louisiana. Storm surge of up to 15 ft caused extensive damage to buildings in coastal towns and caused some of the repaired levees in New Orleans to fail again, resulting in the return of floodwaters to parts of the city.

The National Institute of Standards and Technology (NIST) is a non-regulatory agency of the U.S. Department of Commerce. On the day that Hurricane Katrina made landfall, NIST began coordinating with the Federal Emergency Management Agency (FEMA) and other Federal agencies to exchange information about the effects of the storm and to begin planning for damage reconnaissance. During the weeks immediately following Hurricane Katrina, NIST technical experts deployed in cooperation with the Roofing Industry Committee on Weather Issues (RICOWI) and the FEMA Mitigation Assessment Team (MAT) to observe damage. By September 23, 2005 NIST had contracted with the Applied Technology Council (ATC) to assemble a team of engineers and scientists to conduct a major damage reconnaissance effort. The team included six NIST technical experts, and was made up of 26 engineers and scientists from 16 separate private-sector, academic, and federal organizations.

Modern building codes, standards, and good practice measures establish improved minimum requirements for safeguarding public health, safety and general welfare [1]. To the extent that local building practices do not meet these newer minimum expectations, adoption and enforcement of current model building codes can improve safety and help reduce damage thereby minimizing the impacts of natural hazards. While the legacy of these hurricanes will likely be remembered in terms of the deaths and social and economic disruptions experienced in the days and weeks immediately following the disasters, an opportunity exists to reduce future catastrophic effects by improving design and construction practices. This is accomplished through analysis of damage observed in the aftermath of Hurricanes Katrina and Rita and conduct of research leading to the development and use of improved guidelines, codes, and standards in design, construction, operation, and maintenance of major buildings, infrastructure, and residential construction.

This report documents the findings and recommendations resulting from a multi-organizational reconnaissance of the performance and damage to physical structures due to Hurricanes Katrina and Rita in 2005. The NIST-led reconnaissance was a cooperative effort from its very launch. NIST and other participating federal agencies and private sector organizations have openly shared data and information from the beginning to plan for and conduct the reconnaissance, and to develop the findings and recommendations. NIST technical experts have participated on other Katrina-Rita studies (e.g., Federal Emergency Management Agency's Mitigation Assessment Team, the U.S. Army Corps of Engineers' Interagency Performance Evaluation Task Force, and the Roofing Industry Committee on Weathering Issues). Similarly, the NIST-led reconnaissance that is the subject of this report has benefited from the participation of technical experts from other federal agencies and the private sector. While the findings and recommendations are those of NIST, the report and its recommendations have been reviewed by the participating organizations. The interagency cooperation is continuing as agencies plan and carry out follow-up actions in response to the recommendations of this report.

This work complements other completed and ongoing studies of the performance of structures in the Gulf region during the hurricanes. It is the only study to take a broad look at damage to physical structures and its implications for the Gulf Coast and other hurricane-prone regions.

Disasters such as Hurricane Katrina and Hurricane Rita provide an unfortunate but important opportunity to learn from the performance of structures exposed to catastrophic events and to derive lessons that can lead to improvements in standards, codes, and practice that will reduce losses in future events. NIST chose to undertake a broad-based reconnaissance effort rather than a detailed investigation since much already has been learned from past hurricanes. The reconnaissance was intended to identify new technical issues that need to be addressed in the rebuilding effort, in the improvement of building standards and model codes, or in future research studies. In the process, the team also identified opportunities for improvement in standards, codes, and practices that require no additional study.

The reconnaissance identified three key areas where detailed technical studies are essential: (1) to evaluate the performance of the New Orleans flood protection system and provide credible scientific and engineering information for guiding the immediate repair and future upgrade of the system, (2) to develop risk-based storm surge maps for use in flood-resistant design of structures, and (3) to evaluate and, if necessary, modify the Saffir-Simpson hurricane scale's treatment of storm surge effects due to hurricanes.

The findings of the reconnaissance highlight the critical importance of state and local entities adopting and then rigorously enforcing building standards, model codes, and practices. First, at the time of the hurricanes, there was no statewide building code in Louisiana, Mississippi, Alabama, or Texas[8], although some local jurisdictions within those states had adopted model building codes. Second, the team observed significant damage in many instances where the winds were lower than those levels cited in codes and standards—suggesting that the structures did not perform as required. Third, older structures—only required to meet building codes in effect when they were built—were particularly vulnerable to wind damage. Current model building codes and standards contain provisions for the design of structures subject to high wind, flood, and storm surge; adoption and enforcement of such codes and standards in hurricane prone regions can greatly improve the performance of structures.

Federal agencies, state and local governments, and the private sector already have taken actions consistent with NIST's recommendations to facilitate rebuilding and mitigate the potential for damage in future

[8] The Texas Department of Insurance put into effect the 2000 International Building Code and International Residential Code with Texas revisions on February 1, 2003 for the 14 counties located on the Gulf Coast. The 2003 editions of these codes were put into effect on January 1, 2005 for these counties. To be eligible for windstorm insurance, homeowners were required to comply with the Windstorm Code (which is based on these model codes) published by the Texas Department of Insurance.

storms—in many cases even as the findings were being analyzed and recommendations were being formulated. The U.S. Army Corps of Engineers (USACE) promptly took action to repair damage to the flood protection system in New Orleans as well as to determine the factors that contributed to the failures and make improvements. The Federal Emergency Management Agency (FEMA), in conjunction with USACE, is providing updated base flood information to guide rebuilding. The Federal Highway Administration (FHWA) is developing a plan of action for studies and research for coastal bridges.

Based upon data collected in the field during the reconnaissance, analysis of environmental data, and analysis of observations made by other organizations, this report includes 23 recommendations grouped as follows: (1) immediate impacts on practices for rebuilding; (2) standards, codes, and practices; and (3) further study of specific structures or research and development.

1.1 OVERVIEW OF ENVIRONMENTAL EFFECTS

Hurricanes Katrina and Rita both originated as tropical depressions in the Atlantic Ocean southeast of Florida. In both cases, as the hurricanes moved into the warm waters of the Gulf of Mexico, they gained strength, reaching Category 5 status, weakening as they approached landfall. This section provides an overview of the evolution of both storms from tropical depression through landfall, and documents the resulting environmental effects. Chapter 2 of this report details the environmental effects (wind speed, storm surge, and flooding) for both hurricanes.

1.1.1 Wind Speed

Hurricane Katrina, at its peak intensity 18 hours before landfall, was classified by NHC as a Category 5 storm on the Saffir-Simpson hurricane scale, with estimated maximum sustained wind speeds of 150 kt (approximately 175 mph) [10]. At landfall, it was categorized by the NHC as a Category 3 storm with estimated maximum sustained wind speeds of 110 kt (approximately 125 mph) and a radius of maximum winds between 29 miles and 35 miles [10]. Hurricane Katrina's large horizontal size caused significantly high storm-surge in coastal areas.

Hurricane Rita, at its peak intensity 48 hours before landfall, was categorized by the NHC as a Saffir-Simpson Category 5 storm with NHC-estimated maximum sustained winds of 155 kt (approximately 180 mph). At landfall, Hurricane Rita's maximum sustained winds were estimated by the NHC to be 100 kt (approximately 115 mph) in a small area east of the eye along the immediate coast of extreme Southwestern Louisiana. However, most of the affected area in Southwest Louisiana and Southeast Texas was exposed to wind speeds of Category 1 or 2 intensity,

1.1.2 Storm Surge

Storm surge heights varied throughout the areas of the Gulf Coast affected by Hurricanes Katrina and Rita. Reported inundation levels are based on NIST-led reconnaissance field observations, FEMA documented high water marks (HWM), and modeled storm surge hindcasts.

Hurricane Katrina resulted in storm surge heights of more than 20 ft at a number of locations along the Mississippi coast. Observations suggest that at some locations in Mississippi, storm surge reached as high as 28 ft. In New Orleans, estimated storm surge heights ranged from 9 ft to 10 ft.

Hurricane Rita resulted in observed storm surge heights of over 5 ft in Sabine Pass, Texas, 10 ft in Creole, Louisiana, and up to 15 ft in Cameron, Louisiana. In New Orleans, estimated storm surge heights were approximately 8 ft.

1.1.3 Flooding

Failure of the levees and floodwalls in New Orleans allowed floodwaters to inundate more than 75 percent of the city. Many areas of New Orleans were covered by at least 7 ft to 9 ft of water. In some areas (e.g., Lower Ninth Ward) flood depth exceeded 20 ft.

1.2 OVERVIEW OF DAMAGE AND IMPACTS

Hurricane Katrina was arguably the most costly natural catastrophe to hit the United States in the past century. The geographic region affected by high winds and storm surge from Hurricanes Katrina and Rita covers coastal areas of five states including Alabama, Florida, Louisiana, Mississippi, and Texas. Major population centers affected by the two hurricanes include: Mobile in Alabama; Lake Charles, Slidell, and New Orleans in Louisiana; Long Beach, Gulfport, Biloxi, and Pascagoula in Mississippi; and Beaumont, Orange, and Port Arthur in Texas. The total population in these cities is almost five million people. Figure 1-1 shows the areas surveyed during NIST-led reconnaissance efforts overlaid onto a map showing the variation in population density. The groups indicated in Figure 1-1 are described later in this chapter.

As of March 2006, the full extent of losses due to both Hurricanes Katrina and Rita is still not known. Some facts, however, at the time of this writing provide a measure of the total impact of these events:

- *Fatalities:* Over 1,300 [2, 3].
- *Estimated economic losses*: $70-$130 billion [4].
- *Estimated insured losses*: $45-$65 billion [4, 5, 6].
- *Disaster assistance requested*: Over 2.6 million applications for assistance have been received from victims of Hurricanes Katrina and Rita [7].
- *Federal aid provided*: Over $88 billion in federal aid has been allocated for relief, recovery, and rebuilding in the areas affected by Hurricanes Katrina and Rita, with another $20 billion requested [8].

1.2.1 Overview of Observed Damage

Damage was observed in major buildings, infrastructure, and residential construction due to high wind, storm surge, flooding, or the combined actions of one or more of these environmental effects. Storm surge and flooding prevailed as the primary source of structural and non-structural damage along the immediate coastal areas and tidal waterways. Wind damage in these areas was comparatively subdued, although failure of the weather-resistant building envelope (e.g., roofing, cladding, flashing and seals, etc.) and subsequent wind-driven rain penetration probably contributed to extensive economic damage from the events, particularly beyond the areas that were primarily affected by storm surge and flooding.

1.2.1.1 Major Buildings[9]

High winds caused damage to unreinforced masonry walls and probably caused the collapse or partial collapse of older unreinforced masonry buildings and some metal building structures. High winds also caused damage to all types of roofing and rooftop equipment. Wind-borne debris including roof aggregate, rooftop equipment, and equipment screens, caused damage to cladding and glazing (window units or glass façade) of buildings located downwind.

[9] Major buildings are defined herein as buildings that are a result of engineering design or have special occupancy classification. See Chapter 3 for further detail.

Storm surge caused failures resulting in the partial collapse of modern precast, prestressed parking structures, due to uplift forces and and poor connection details. Storm surge also resulted in extensive damage to casino barges, which broke free of their moorings, floated inland, impacted structures or sank in place.

The combination of high winds and water resulted in the loss of operation of many major buildings, including hospital facilities. Water damage to critical equipment (e.g., emergency power generators, chiller plants) located below flood elevations was responsible for extended closures of some facilities. In other cases, wind-driven water penetration through otherwise undamaged cladding and glazing systems forced closure of facilities.

1.2.1.2 Infrastructure

Storm surge caused the most damage to infrastructure systems and facilities. It caused extensive damage to port buildings, equipment, and piers along the Louisiana, Mississippi, and Alabama coastlines. Storm surge contributed to the breaching of some levees and floodwalls in New Orleans. It also caused damage to bridges through uplift and lateral displacement of bridge spans and to roads and railways through flooding and inundation.

The combination of high wind, storm surge with associated wave action, and flooding resulted in extensive damage to utilities. Wind, water, and debris caused the loss of over one million wood power distribution poles and hindered efforts to restore electric service to affected areas following the hurricanes. Both landlines and cellular telephone services were severely disrupted by damaged lines, poles, and cell towers following the storms.

Wind and storm surge also resulted in damage to storage tanks in refineries and chemical plants. Wind and debris destroyed tanks and damaged insulation cladding. Some tanks floated off their foundations when spill-containment areas became inundated with water.

1.2.1.3 Residential Construction

Nearly all residential construction exposed to storm surge was completely destroyed. Direct storm surge impacts, in which houses were swept off their foundations, extended as much as half a mile inland. Flooding as a result of storm surge extended up to several miles inland.

Wind effects were less catastrophic than storm surge effects, but were prominent in most areas of the reconnaissance outside of the storm surge areas. Nevertheless, some cases of more severe wind damage were infrequently observed relative to other types of non-structural damage to the building’s weather-resistant envelope (e.g., loss of roof sheathing, loss of sheathing on gable ends, and an infrequent loss of roof or portion of roof). Damage to foundations, structural racking of bracing systems, and other “whole building” effects were generally not observed in areas that were affected by wind only.

Roof coverings of residential construction sustained considerable damage due to blow off, and residential structures suffered damage due to fallen trees. Water penetration around windows and other components such as chimney flues was observed in a number of cases, including those houses where no identifiable envelope damage was observed.

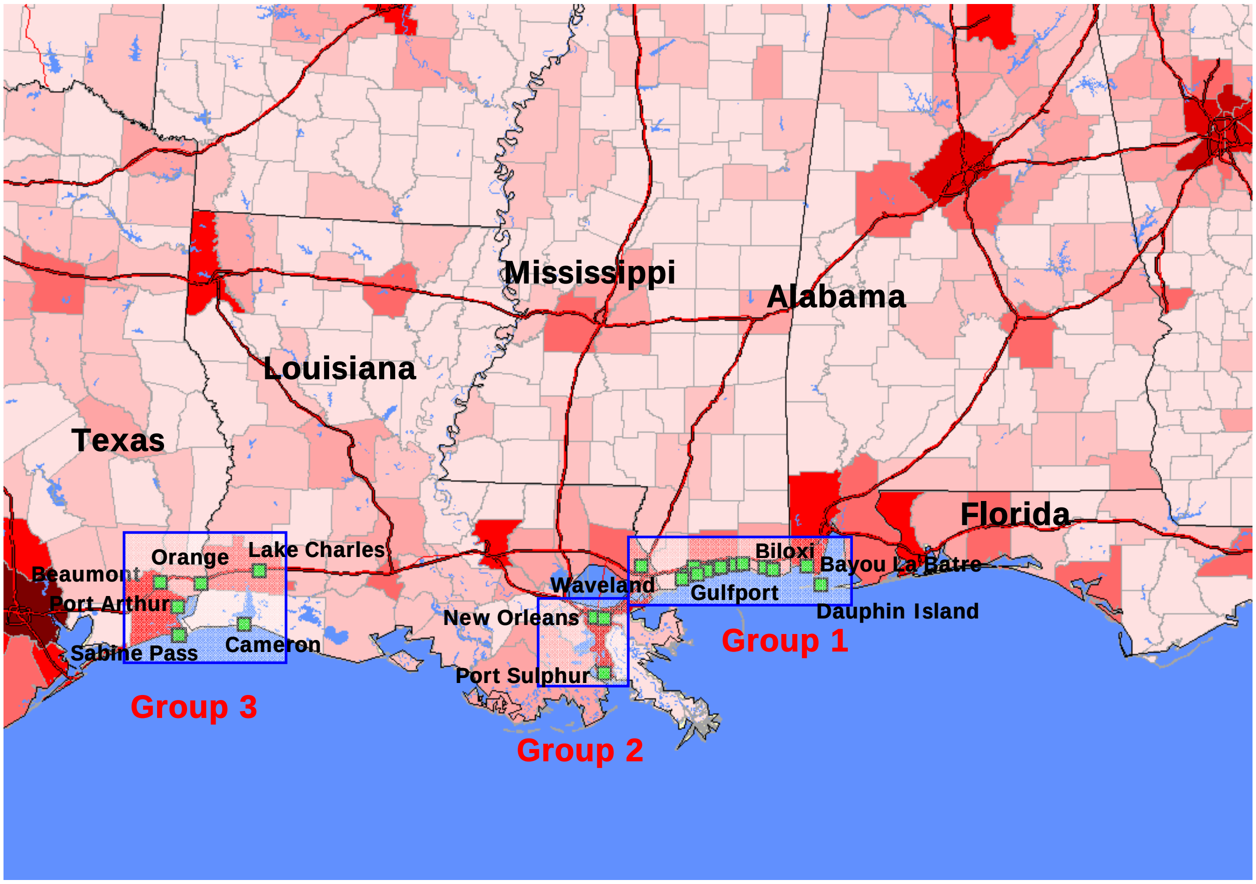

Figure 1-1 NIST-led reconnaissance locations and variation in population density. Darker areas indicate higher population density (Source: Census Bureau [9], enhanced by Ron T. Eguchi, ImageCat).

1.3 OVERVIEW OF NIST-LED RECONNAISSANCE EFFORTS

The purpose of NIST damage reconnaissance and investigations is to improve the safety and performance of constructed facilities in the United States. With a focus on fact finding, NIST investigations are used to identify factors that affect the performance of structures or classes of structures and to derive lessons that when incorporated in building codes, standards, and practices improve the safety and reliability of such structures in future events.

On the day that Hurricane Katrina made landfall, NIST began coordinating with FEMA and other Federal agencies to exchange information about the effects of the storm and to begin planning for damage reconnaissance.

Hurricanes Katrina and Rita presented an opportunity to study the effects of storms from a multi-hazard perspective by examining three hazard effects: extreme wind, storm surge and associated wave action, and flooding. The purpose of the NIST-led reconnaissance effort was to:

- Collect perishable data and information on the performance of physical structures during Hurricanes Katrina and Rita.
- Collect and review data from other sources on the performance of major buildings, infrastructure, and residential construction.

- Correlate observed damage with environmental data on measured wind speeds and recorded levels of storm surge and flooding.
- Identify immediate implications for reconstruction.
- Prepare background information for recommendations on areas of further study, either to understand the performance of specific facilities damaged in these two events or to suggest changes or modifications to existing codes and standards.

NIST conducted the reconnaissance effort in two phases. Phase 1 consisted of two field deployments of NIST technical experts. The first occurred during the week of September 6, 2005, in cooperation with the Roofing Industry Committee on Weather Issues (RICOWI), and the second occurred during the week of September 26, 2005, in cooperation with the FEMA Mitigation Assessment Team (MAT). This phase focused solely on areas in Mississippi and Louisiana damaged by Hurricane Katrina.

Based on the findings of these initial deployments, NIST contracted with the Applied Technology Council (ATC) to assemble a team of engineers and scientists to conduct a comprehensive reconnaissance effort. With input from NIST, ATC identified experts from the public and private sector with the requisite knowledge and experience to conduct field reconnaissance of damage to major buildings, infrastructure, and residential construction.

Key partners that participated in the Phase 2 NIST-led reconnaissance included the U.S. Army Corps of Engineers, Federal Highway Administration, National Oceanic and Atmospheric Administration, Federal Emergency Management Agency, Applied Technology Council, Institute for Business and Home Safety, International Code Council, National Council of Structural Engineers Associations, National Research Council of Canada, Texas Tech University, Multidisciplinary Center for Earthquake Engineering Research at the State University of New York at Buffalo, University of Puerto Rico, Amtech Roofing Consultants Inc., Applied Residential Engineering Services, ImageCat, Inc., Scawthorn-Porter Associates Inc., Shiner Moseley and Associates Inc., and Smith & Huston Inc. Individual members of the Phase 2 NIST-led reconnaissance team are listed in Appendix A.

Phase 2 consisted of field deployment of the NIST-led team consisting of NIST technical experts and experts identified by ATC. The NIST-led team subdivided into three groups and deployed between October 10, 2005 and October 21, 2005 to the areas shown in Figure 1-1. Groups 1 and 2 visited areas in Alabama, Mississippi, and Louisiana affected by Hurricane Katrina, and Group 3 visited areas in southeastern Texas and southwestern Louisiana affected by Hurricane Rita. The Phase 2 field reconnaissance collected data and documented damage to major buildings, infrastructure, and residential construction due to wind, wind-borne debris, storm surge, surge-borne debris, and flooding. The effort also included collection and analysis of environmental data and damage reports from other sources and identified building codes, standards, and construction practices used in the affected areas.

This report was prepared by the NIST-led team. While the findings and recommendations are NIST's, the report has also been reviewed by other federal agencies and by technical peer reviewers from industry and academia who have provided comments on the report, its findings and recommendations. The report draws upon data and observations from other research organizations in an effort to compile a set of recommendations that reflects the totality of the fact-finding and analysis efforts.

1.4 SCOPE

The scope of this report is defined by the following key factors:

- The NIST-led reconnaissance effort focused on two events: Hurricane Katrina and Hurricane Rita. Study areas consisted of New Orleans and the Mississippi and Alabama coastline (areas affected by

Hurricane Katrina), and southeastern Texas and southwestern Louisiana (areas impacted by Hurricane Rita).

- Observations made during Phase 1 reconnaissance in cooperation with RICOWI and FEMA were used to guide the planning of Phase 2 efforts in cooperation with ATC. As a result, reconnaissance for Hurricane Katrina focused on filling in gaps in known information on environmental effects and on collecting additional data needed to explain the performance of major buildings, infrastructure, and residential construction. For Hurricane Rita, reconnaissance focused on collecting new information.
- Because the NIST-led reconnaissance effort covered a wide variety of building types, infrastructure facilities, and systems, the reconnaissance team included multi-agency representation with significant private industry and academic involvement.
- Given the large area of devastation associated with Hurricanes Katrina and Rita, NIST-led reconnaissance studies included the mining of available data from reports of field observations prepared by other research organizations on the performance of major buildings, infrastructure, and residential construction. A survey of the activities of over 50 organizations was conducted. These organizations are listed in Appendix B, and summaries of relevant investigations are included in Appendix C.
- NIST-led reconnaissance studies included collection and analysis of data on wind speed, storm surge, and flooding, with the intent of eventually correlating the observed performance of major buildings, infrastructure, and residential structures with these environmental effects.
- NIST-led reconnaissance studies included examination of existing codes, standards, and practices in the affected areas. Information and knowledge gained from the NIST-led reconnaissance effort is being used to recommend immediate changes or modifications to existing model codes and standards in order to influence the reconstruction process in the affected areas, and to determine issues needing further research to explain the successful or unsuccessful performance of structures.
- Recommendations focus on identifying areas or topics that: (1) deserve immediate attention with respect to reconstruction; (2) could have a bearing on codes, standards, and practices; or (3) require further research to better understand the performance of major buildings, infrastructure, and residential construction.

1.5 ORGANIZATION OF THE REPORT

This report includes seven chapters and five appendices.

Chapter 1 contains general information regarding the magnitude and impact of Hurricanes Katrina and Rita, an overview of the environmental effects and damage, a description of the NIST-led reconnaissance effort, and the scope of the investigation.

Chapter 2 describes the evolution of Hurricanes Katrina and Rita from tropical depression to landfall, and the environmental effects of both events. Maps of wind speeds and storm surge heights or inundation are provided for comparison with design or risk maps for each hazard.

Chapter 3 provides observations and findings on the performance of major buildings, including highrise structures, government buildings, hospitals, and commercial construction.

Chapter 4 provides observations and findings on the performance of infrastructure systems and facilities, including ports, levees and floodwalls, highway bridges, electric power facilities, water systems, oil refineries, and chemical plants.

Chapter 5 provides observations and findings on the performance of residential construction, with special emphasis on the performance of roofing systems.

Chapter 6 summarizes the major findings and observations for each class of construction.

Chapter 7 contains recommendations that focus on topics that require immediate action with respect to the reconstruction process that is currently underway in the Gulf Coast, topics that should be addressed to assess whether codes, standards, or practices need to be changed or modified, and topics requiring further study or investigation.

Appendix A: Team Organization

Appendix B: List of Organizations Surveyed for Post-Hurricane Studies

Appendix C: Other Related Studies

Appendix D: Conversion of 1-Minute “Sustained” Wind to 3-Second Gust or “Peak Gust”

Appendix E: Design and Construction Codes in Affected Areas

1.6 REFERENCES

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[3] Harrison County, Mississippi, Civil Defense Emergency Operations posting, February 21, 2006. http://co.harrison.ms.us/assistance/confirmed/.

[4] Congressional Budget Office, 2005. Testimony by CBO Director Douglas Holtz-Eakin to House Budget Committee, October 6, 2005.

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[7] Federal Emergency Management Agency News Release, March 10, 2006. http://www.fema.gov/news/newsrelease.fema?id=24221.

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[9] http://www.census.gov/prod/cen2000/index.html.

[10] http://www.nhc.noaa.gov/pdf/TCR-AL 122005_Katrina.pdf.

[11} http://www.nhc.noaa.gov/pdf/TCR-AL 182005_Rita.pdf.

Chapter 2
WIND SPEED, STORM SURGE, AND FLOODING

This chapter documents the wind speed, storm surge, and flooding conditions that affected the Gulf Coast during Hurricanes Katrina and Rita. Environmental data from various sources, including the National Oceanic and Atmospheric Administration (NOAA), the United States Army Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), the American Society of Civil Engineers (ASCE), the Florida Coastal Monitoring Program (FCMP) and Texas Technical University (TTU), was collected and compared to provide an understanding of hurricane intensity, wind speed, and surge heights. This information was overlaid onto a series of base maps that included the locations visited in the NIST reconnaissance.

2.1 CATEGORIES OF HURRICANES

The Saffir-Simpson hurricane scale assigns a Category (1-5) to hurricanes based upon sustained wind speeds [1], [2]. The scale also gives a range of storm surge heights for hurricanes of various categories, but it is noted in [1] that “storm surges are highly dependent on the slope of the continental shelf and the shape of the coastline, in the landfall region.”

According to the ASCE 7-05 Standard Commentary [3, p. 285 and Table 6-1], “the wind speeds used in the Saffir-Simpson hurricane scale are defined in terms of a sustained wind speed with a 1-min averaging time at 33 ft (10 m) over open water” (see columns 1 and 2 of Table 2-1 below, excerpted from Table 6-1 of the ASCE 7-05 Commentary). It is shown in [4] that this definition implies that the corresponding peak 3-s gust speeds, based on the ASCE 7-05 Commentary conversion of 1-min speeds to peak 3-s gust speeds over open terrain [3, Table C6-4] have the approximate values listed in column 4 of Table 2-1, rather than those listed in the ASCE 7-05 Commentary (column 3 of Table 2-1). However, it should be noted that the Saffir-Simpson [32] scale lists only wind speed without reference to whether or not the wind speed is over open water.

Table 2-1 Saffir-Simpson hurricane scale

Category	Sustained Wind Speed Over Open Water (mph)	Approximate 3-sec Gust Wind Speed Over Open Ground (mph)		Potential Storm Surge (ft above normal)	Potential Damage to Structures
		Per ASCE 7-05 Commentary	Per [4]		
(1)	(2)	(3)	(4)	(5)	(6)
1	74-95	82-108	79-102	4-5	Minimal
2	96-110	109-130	103-118	6-8	Moderate
3	111-130	131-156	119-139	9-12	Extensive
4	131-155	157-191	140-166	13-18	Extreme
5	Over 155	Over 191	Over 166	Over 18	Catastrophic

2.2 WIND SPEED

2.2.1 Wind Speed – Hurricane Katrina

Hurricane Katrina developed as a tropical depression over the southeastern Bahamas on August 23, 2005 and strengthened into a tropical storm within 24 hours [18]. It first made landfall on August 27, 2005 in southeastern Florida as a Category 1 hurricane. After re-entering the warm waters of the Gulf of Mexico, it rapidly strengthened to a Category 3 hurricane and ultimately reached Category 5 status (155 mph) less than 12 hours later. On August 28, the hurricane reached peak intensity with maximum sustained winds of 150 kt (approximately 175 mph) about 200 miles southeast of the mouth of the Mississippi River. The central pressure fell to a low of 902 mb, which was (at the time) the fourth-lowest central pressure on record for the Atlantic basin[10]. The storm weakened significantly in the 18 hours before its second landfall. Despite this weakening, the size of the hurricane continued to expand, with hurricane-force winds (>75 mph, maximum sustained) extending more than 100 miles from the center and with tropical storm-force winds (40-75 mph, maximum sustained) extending more than 200 miles from the center, making it an exceptionally large hurricane [5].

Hurricane Katrina's second landfall occurred on August 29, 2005 near Buras, Louisiana. Initially reported to be a Category 4 hurricane at landfall in Louisiana, detailed post-storm analysis by the NHC [18] later indicated that the storm was actually a strong Category 3 at landfall, based on maximum sustained wind speeds of approximately 110 kt (approximately 125 mph) [5]. Hurricane Katrina made landfall again along the Mississippi/Louisiana border with a maximum sustained wind speed of 105 kt (approximately 120 mph). Although wind speeds diminished prior to landfall, the storm's prior strength was significant because of extraordinary storm surge and wave action. Hurricane Katrina now stands as the costliest and one of the five deadliest hurricanes to ever strike the United States [5]. The path of Hurricane Katrina is shown at various stages of development (tropical depression, tropical storm, and hurricane) in Figure 2-1.

[10] Includes the Gulf of Mexico.

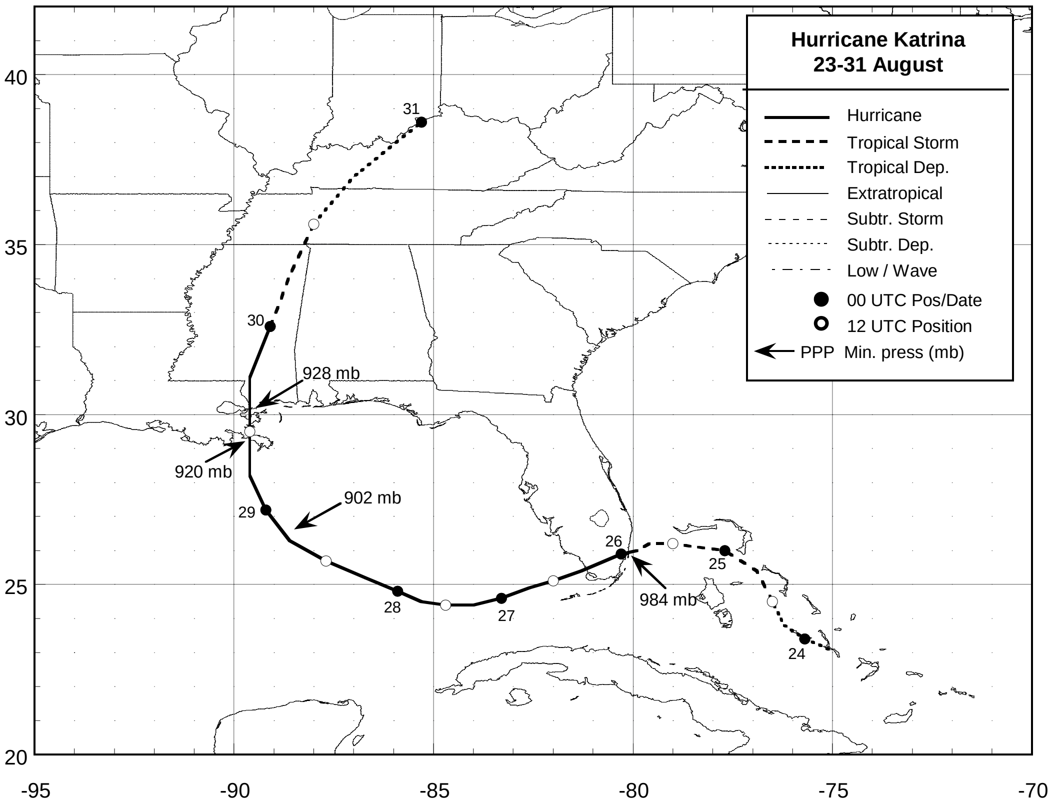


Figure 2-1 Storm development and tracks of Hurricane Katrina from Aug. 23, 2005 to Aug. 31, 2005 (Source: National Oceanic and Atmospheric Administration (NOAA) [6]).

2.2.2 Recorded and Modeled Wind Speeds, Hurricane Katrina

Wind speeds were recorded at various sites along the Gulf Coast by different organizations. A series of mobile anemometer towers were erected at strategic sites by the FCMP and TTU's Wind Engineering Mobile Instrumented Tower Experiment (WEMITE) prior to the landfall of the hurricanes. The primary objective of these tower experiments was the collection of in-situ wind speed data for use in real-time hurricane wind analysis (such as NOAA HRD's H*Wind Project) [7], in validation of measurements from reconnaissance aircraft, in validation of numerical models, and in enhanced studies of the characteristics of hurricane winds [8], [9]. Wind speed data produced by sensors operated by FCMP and the WEMITE program provided valuable information for validating regional wind speed contour maps for Hurricane Katrina. Figure 2-2 shows the locations of the FCMP [10] and WEMITE [11] sensors. Of these FCMP and WEMITE sensors, a total of six sensors reported wind speeds (See Table 2-2a).

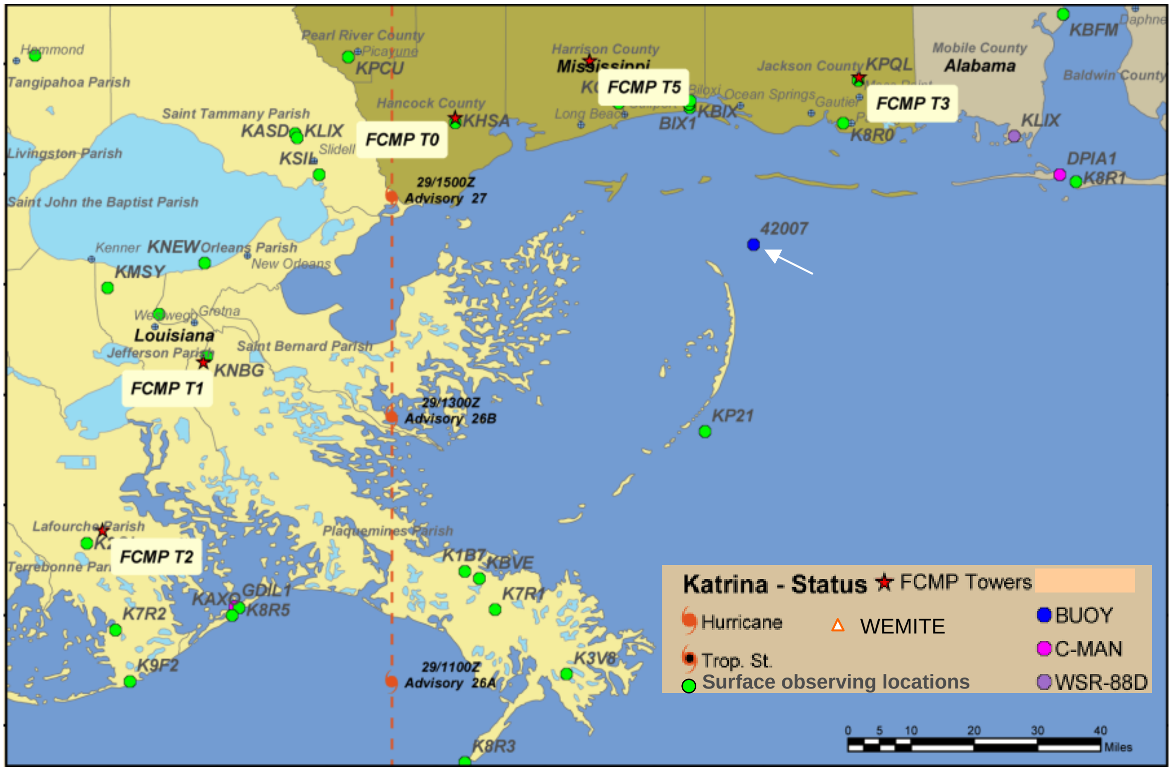


Figure 2-2 **Locations of FCMP and WEMITE measurement towers. Only buoy marked with arrow for clarity. (Source: Florida Coastal Monitoring Program (FCMP)) [10, 11]**

In addition to the FCMP and WEMITE sensors, federal surface observing stations (shown as green dots) including Federal Aviation Administration (FAA) Automated Surface Observation Stations (ASOS) located at airports, one near-shore sensor, and one offshore data buoy recorded wind data [12]. Figure 2-3 shows the locations of these additional wind speed measurement sites. In all, the FCMP and WEMITE sensors along with these seven additional sites yielded a combined total of thirteen wind speed records (Table 2-2a).

Figure 2-3 Wind speed sensors in place during Hurricane Katrina. Station names beginning with the letter "K" are ASOS stations; data buoys and C-MAN stations are all located offshore or at the coast. Solid line indicates Hurricane Katrina's path (with permission from Peter Vickery, ARA [12]).

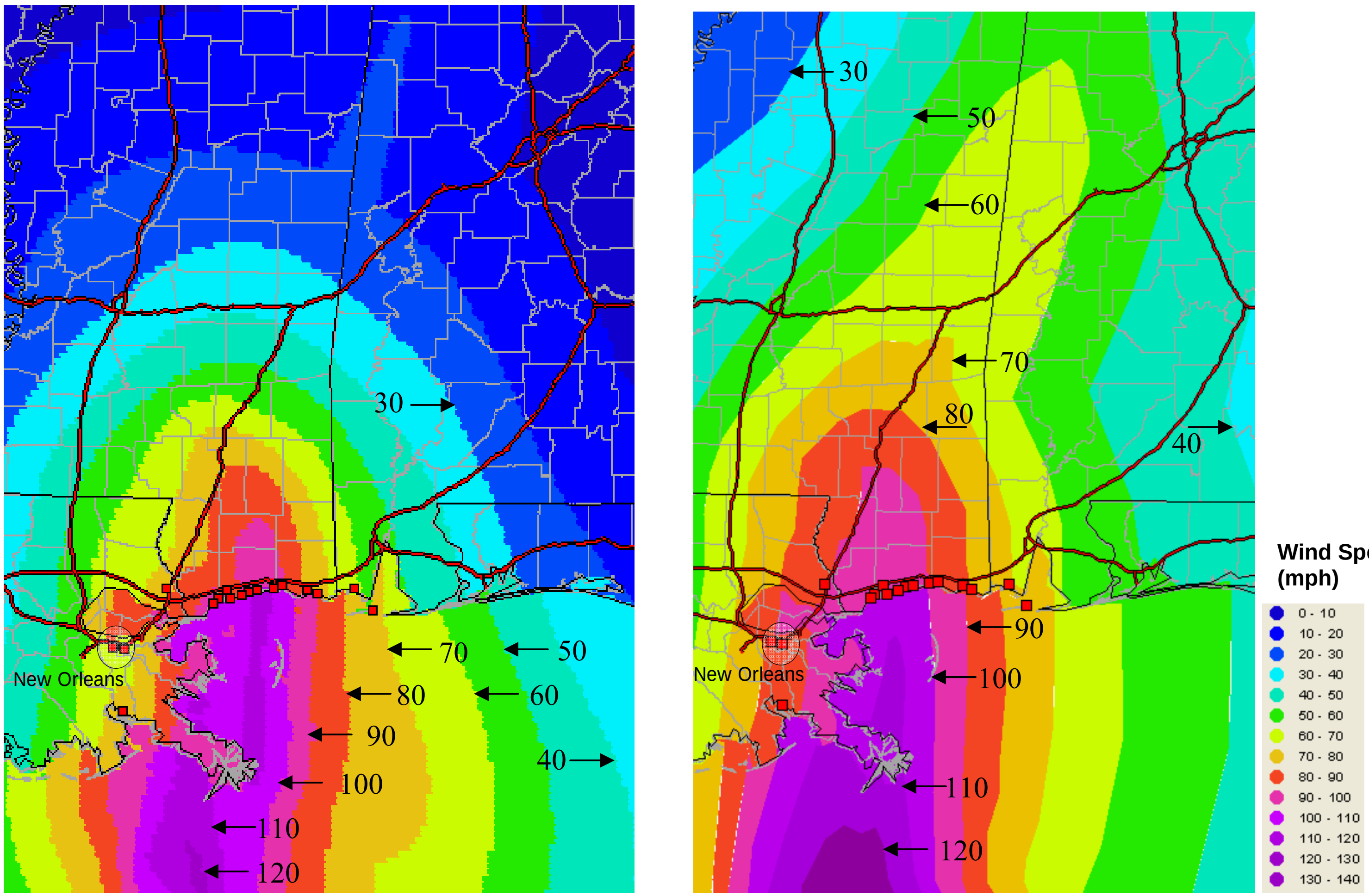
Figure 2-4 shows the estimated maximum sustained wind speeds from Hurricane Katrina for coastal Louisiana and Mississippi, including experimental (preliminary) data from NOAA HRD[11] [7] and final data from ARA [13]. Sustained wind speeds are averaged over a period of 1 minute and are reported at a height of 10 m above the surface. The NOAA's preliminary maximum sustained wind contours for Hurricane Katrina, as shown in Figure 2-4a, are based on the August 29, 2005 1132 UTC (Universal Time Coordinated, same as Greenwich Mean Time) landfall analysis [14]. Figure 2-4b shows the final ARA estimated (modeled) maximum sustained wind speeds for Hurricane Katrina. The analysis of maximum sustained wind speeds is based on the ARA hurricane wind field model [12] and key hurricane parameters obtained by ARA from the National Hurricane Center.

[11] The NOAA HRD data shown in Figure 2-4 is preliminary based on experimental real time analysis. NOAA has since revised the individual wind field analysis "snapshots" and posted these on http://www.aoml.noaa.gov/hrd/Storm_pages/katrina2005/wind.html.

Both Figs. 2-4a and 2-4b indicate that the maximum open-country equivalent sustained wind speed at landfall for Hurricane Katrina was between 110 mph and 120 mph. The ARA map, however, shows open-country equivalent sustained high winds (e.g., 80 mph or greater) extending over larger areas than in the NOAA's preliminary wind map. While the NOAA preliminary contour map shows only three counties affected by wind speeds higher than 90 mph at landfall, the ARA map shows at least six counties affected by winds of 90 mph or greater. In New Orleans, the ARA maps suggest that open-country equivalent sustained wind speeds reached as high as 90 mph, while NOAA's preliminary maps indicate that the sustained winds were 80 mph or less. One possible reason for differences in the NOAA and ARA maps is the use of different inland wind-speed decay models [26]. Other reasons may include differences in the formulation of the models. The NOAA H* wind product is created by translating all upper level and surface data into functions to create an overall wind field model. The ARA model is based on an analytical formulation that uses key parameters such as central pressure, maximum wind translation speed, and radius to generate the wind field. The two models generally have predicted similar estimates of peak wind speeds (within a few mph) for all storms analyzed over the past two years, but typically produce different geographic distributions of the winds.

For comparison, ASCE 7-05 maps recommend a basic design wind speed (peak 3-sec gust at 33 ft (10 m) above ground for exposure C) of 135 mph for the New Orleans region. According to the ASCE 7 Commentary (Fig. C6-4), this is nominally equivalent to a 1-min sustained wind speed of 135 mph x 1.25 / 1.52 = 111 mph (ASCE 7-05, Fig. C6-2). This corresponds to the lowest value for Category 3 in the Saffir-Simpson hurricane scale.

Note that the ASCE 7-05 Commentary (Table C6-4) conversion factors between wind speeds with various averaging times are nominal values used for structural engineering purposes, and that those factors are currently regarded by some experts as being inadequate. The conversion factors are reasonable approximations for engineering purposes even though they are not deterministic and exhibit random variability around a mean value.



(a) NOAA's preliminary wind speed contours (in mph) **(b) ARA wind speed contours (in mph)**

Figure 2-4 **Estimated maximum sustained wind speeds (mph) at 10 m above surface for Hurricane Katrina (using the August 29, 1132 UTC landfall analysis). NIST reconnaissance sites are shown as red squares (Source: (a) NOAA; (b) with permission from Peter Vickery, ARA. Enhanced by Ron T. Eguchi, ImageCat)**

2.2.3 Wind Speed – Hurricane Rita

Hurricane Rita developed on September 18, 2005 from a tropical depression that started in the Atlantic Basin. It brushed the Florida Keys as a Category 2 hurricane on September 20 and subsequently strengthened into an extremely intense Category 5 hurricane on September 21 with sustained winds of 155 kt (approximately 180 mph) [15]. The 2005 hurricane season thus became the first season on record in which more than one hurricane reached Category 5 strength in the Gulf of Mexico. At peak intensity, Hurricane Rita's minimum central pressure reached 897 mb, which, at the time, was the lowest pressure[12] ever recorded for a hurricane in the Gulf of Mexico. Hurricane Rita weakened significantly during the 48 hours preceding landfall, and finally made landfall near the Texas-Louisiana border on September 24, 2005. At landfall, Hurricane Rita's maximum sustained winds were estimated by the NHC [28] to be 100 kt (approximately 115 mph) in a small area east of the eye along the immediate coast of extreme Southwestern Louisiana. However, most of the affected area in Southwest Louisiana and Southeast Texas was exposed to wind speeds of Category 1 or 2 intensity. The NHC reports the strongest sustained wind from an official surface observing site to be 71 kt (approximately 82 mph), with a gust speed of 86 kt (approximately 99 mph), at Sabine River Pass, Texas, near the Louisiana border. The path of Hurricane Rita is shown in Figure 2-5 along with various stages of development (tropical depression, tropical storm, and hurricane).

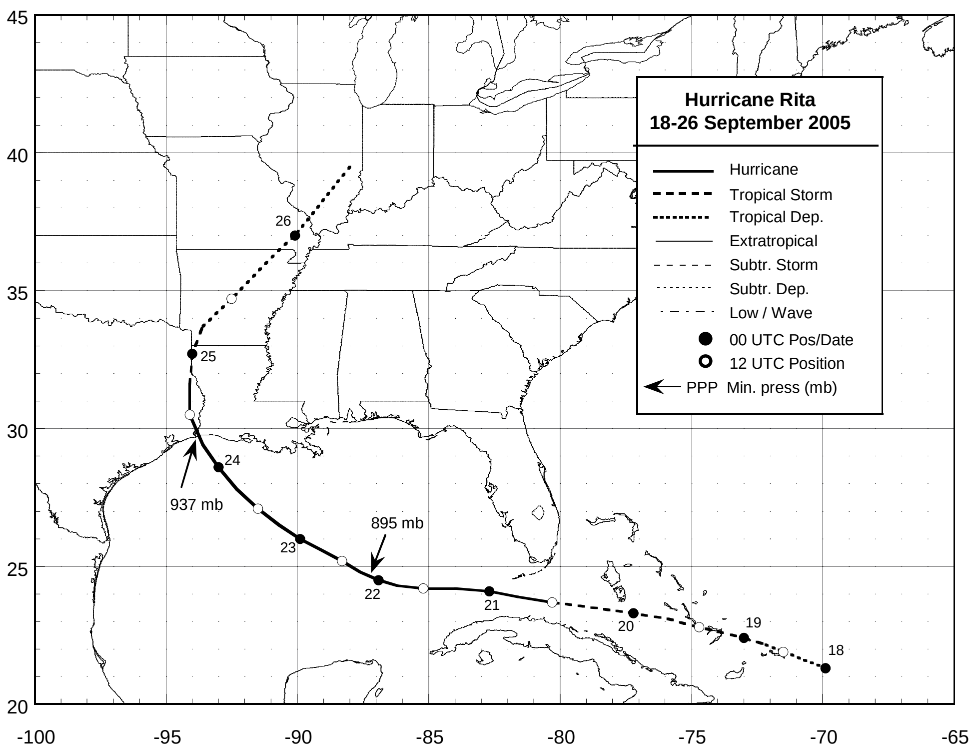


Figure 2-5 Storm development and tracks of Hurricane Rita from September 17, 2005 to September 24, 2005. (Source: NOAA [6]).

[12] Hurricane Wilma had the lowest pressure on record which occurred in the Caribbean (882 mb); Hurricane Rita had the fourth-lowest pressure recorded in the overall Atlantic basin and the lowest pressure in the Gulf of Mexico (897 mb)

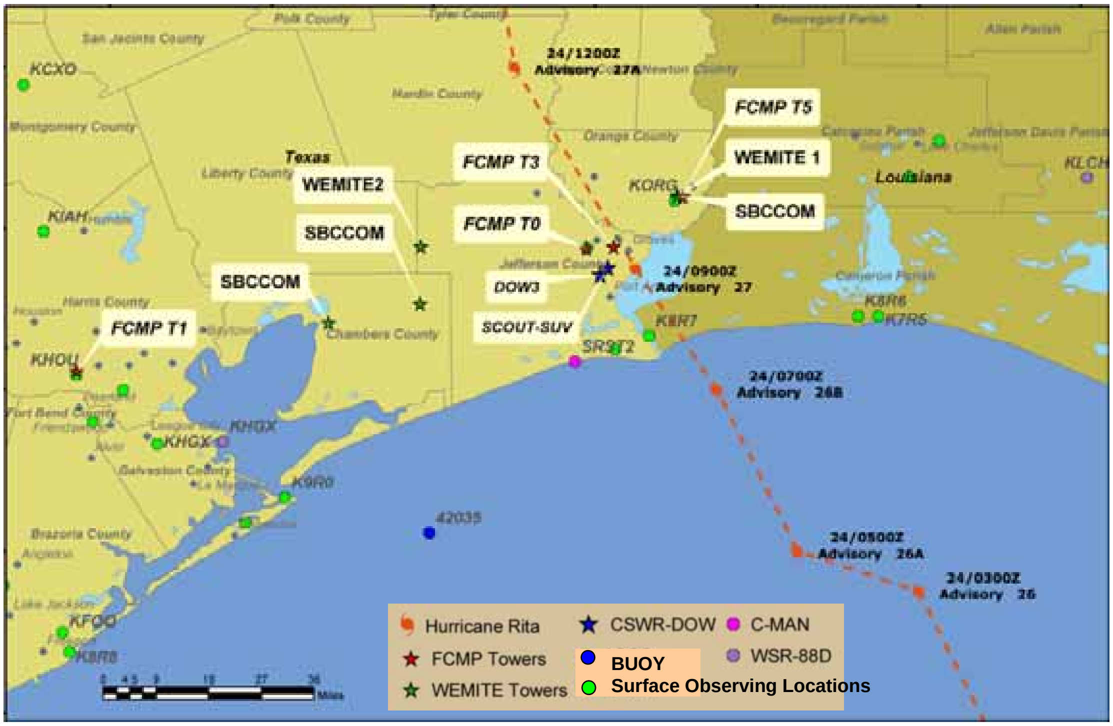


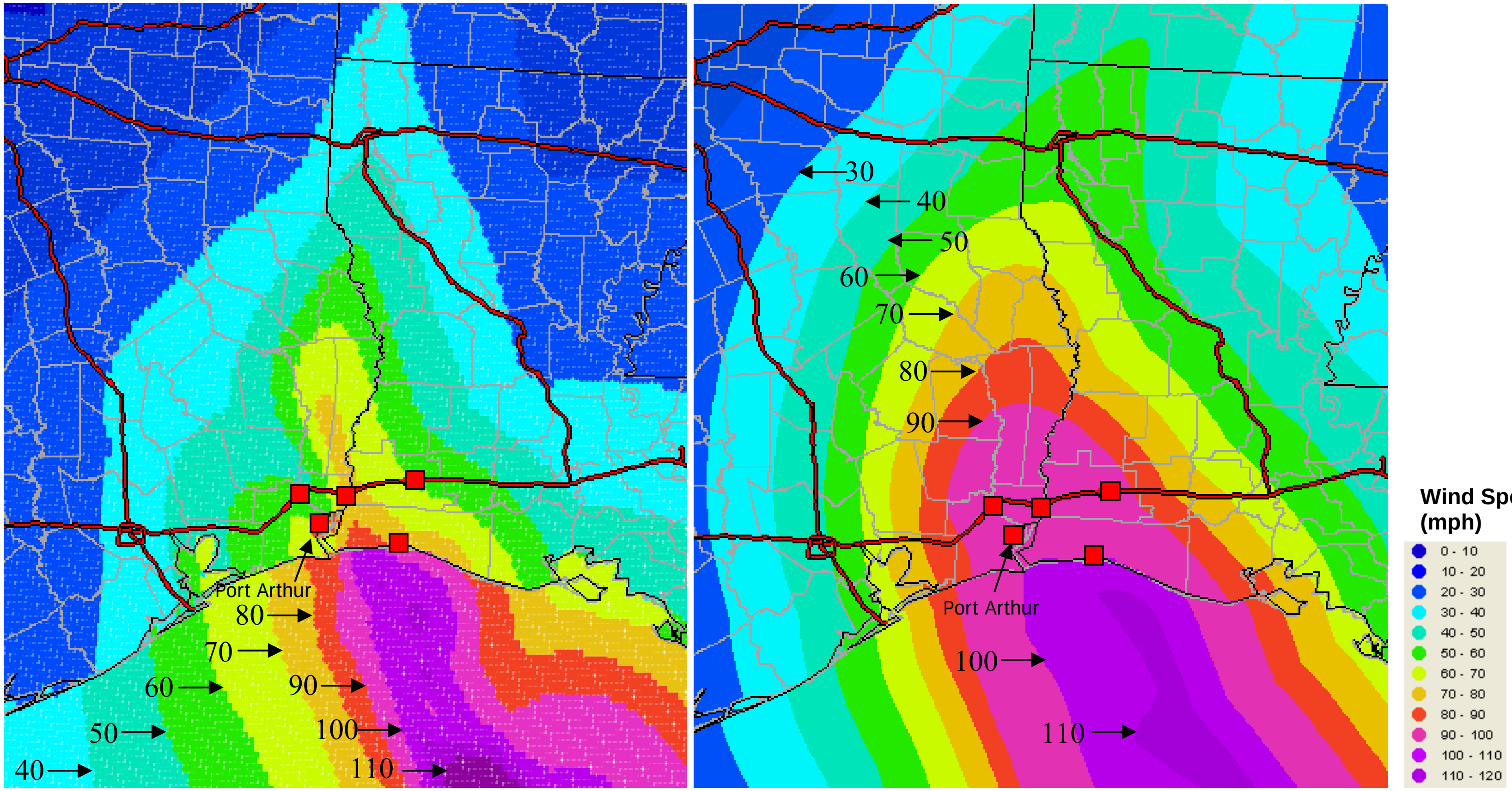
Figure 2-6 Locations of FCMP and WEMITE measurement towers (Source: FCMP [10,11]).

2.2.4 Recorded and Modeled Wind Speeds, Hurricane Rita

Figure 2-6 shows the locations of the FCMP [10] and WEMITE [11] sensors. Of these FCMP and WEMITE sensors, a total of 8 sensors reported wind speeds (See Table 2-2b) for Hurricane Rita.

Figures 2-7a and 2-7b show the estimated maximum sustained wind speeds for Hurricane Rita, as developed from NOAA and ARA data. The NOAA's preliminary maximum sustained wind contours for Hurricane Rita, as shown in Figure 2-7a, are based on the 24 September 1030 UTC landfall analysis [17]. Figure 2-7b shows the ARA modeled maximum sustained wind speeds for Hurricane Rita developed from wind gust contours.

NOAA's National Weather Service (NWS) estimated Rita's maximum sustained wind speed at landfall to be near 115 mph. Figs. 2-7a and 2-7b show the preliminary wind swath analyses which indicate that the maximum sustained wind speed at landfall for Hurricane Rita was approximately 100 mph at the coast. Note that the wind swath analyses do not estimate wind speeds higher than observed or implied at the widely spaced observation sites. NWS maximum wind speed estimates are often higher than those derived from the observing sites and are based on an understanding of the horizontal variability of winds in the core eyewall-region of hurricanes that is usually under sampled by the available observing sites. The ARA map shows high sustained wind speeds (over 80 mph) extending over larger areas than for the NOAA map. While the NOAA's preliminary contour maps show few counties in Texas affected by wind speeds higher than 80 mph at landfall, the ARA maps show a large swath encompassing multiple counties affected by winds of 80 mph or greater.



(a) NOAA's preliminary wind speed contours (in mph)

(b) ARA wind speed contours (in mph)

Figure 2-7 Estimated maximum sustained wind speeds (mph) at 10 m above surface for Hurricane Rita (using the September 24, 2005 1030 UTC landfall analysis). NIST reconnaissance sites shown as red squares (Source: (a) NOAA; (b) with permission from Peter Vickery, ARA. Enhanced by Ron T. Eguchi, ImageCat).

2.2.5 Comparison of Recorded Versus Modeled Wind Speeds

Tables 2-2a and 2-2b present a comparison of recorded wind measurements (from FCMP towers, WEMITE towers, ASOS towers, NOAA's C-MAN stations and data buoys) and modeled wind measurements (3-second peak gust and maximum sustained mean) for several locations. In addition, Tables 2-2a,b provides the basic 3-sec peak-gust wind speeds from ASCE 7-05. Discussion of the design peak-gust and comparison with recorded and modeled values is presented in Section 2.2.6.

NOAA-modeled wind measurements were extracted from a GIS-based (Geographic Information System) grid of maximum sustained wind speeds for Louisiana/Mississippi for the 29 August 1132 UTC landfall analysis and projections of the peak sustained winds at 10-minute intervals using the HRD inland decay model [7]. ARA wind speed estimates are based on cross-referencing a digitized version of the maximum sustained mean wind speed map produced by ARA [13] and are also based on data collected from different sensors.

Peak wind speeds are generally 20 percent to 25 percent higher than sustained wind speeds when a hurricane moves inland [15]. An analysis of wind speed measurements in Hurricane Rita showed that observed peak wind gusts were 23 percent higher than the observed sustained winds (average of 11 stations) [15]. In Tables 2-2a and 2-2b, the NOAA modeled maximum sustained wind speeds have been converted to peak 3-sec gusts using a factor of 1.52/1.25=1.21 for comparison with the recorded values and for comparison with the basic wind speeds of ASCE 7-05 (for the conversion factor see end of Section 2.2.2 and Appendix D).

Table 2-2a shows that the maximum modeled sustained wind speed for Hurricane Katrina at landfall was 115 mph at Gulfport, Mississippi (equating to a 139 mph gust), which makes it a Category 3 hurricane on the Saffir-Simpson scale by the over-land values (Table 2.1) presented by both the ASCE 7-05 Commentary [3] and Simiu et al.[4]. This assignment is consistent with the sensor data that was collected after the hurricane (FCMP, WEMITE, ASOS towers, C-MAN stations, and data buoys) as well as with estimates of wind speed made by other investigators [18].

For the sensors listed in Table 2-2b, the highest peak-gust speed recorded for Hurricane Rita was 116 mph at Port Arthur, Texas. This speed would correspond to a Category 2 hurricane at this tower location (T0), according to the ASCE 7-05 Commentary [3], and a borderline Category2/Category 3 according to [4].

Table 2-2a. Comparison of observed and modeled wind speeds for selected sensor locations affected by Hurricane Katrina

Sensors	Location/GPS	Basic 3-sec Peak Gust from ASCE 7-05 (mph)	3-Second Peak Gust			Maximum Sustained	
			Recorded and Terrain Adjusted[b] (mph)	Modeled: NOAA[c] (mph)	Modeled: ARA[d] (mph)	Modeled: NOAA (mph)	Modeled: ARA (mph)
KMOB (ASOS)	Mobile, AL	130-140	91	70	90	58	74
KBTR (ASOS)	Baton Rouge, LA	100-110	61	46	63	38	52
KPNS (ASOS)	Pensacola, FL	130-140	72	67	66	55	55
KDTS (ASOS)	Destin-Ft. Walton Beach, FL	130-140	55	51	57	42	47
C-MAN DPIA1	Dauphin Island, AL	140-150	101	92	91	76	75
Buoy 42040	Marine data buoy	-	92	-	97	-	80
T0 (FCMP)	Bay St. Louis, MS	130-140	-	116	120	96	**110**
T1 (FCMP)	Belle Chasse, LA	140-150	102 [99]	91	109	75	90
T2 (FCMP)	Galliano, LA	140-150	98 [96]	85	102	70	80
T3 (FCMP)	Pascagoula, MS	140-150	93 [95]	117	100	97	80
T5 (FCMP)	Gulfport, MS	130-140	-	**139**	121	**115**	**110**
WEMITE #1	Vacherie, LA	110-120	70	64	84	53	70
SBCCOM Clear	Slidell, LA	120-130	86	98	109	81	90
SBCCOM White	Stennis International, MS	130-140	**105**	116	**133**	96	**110**
Max. Map Value	-		**-**	-	**-**	110-120	110-120

Note:

a. Numbers in bold represent the maximum wind speed for that category.

b. Terrain-adjusted values for FCMP towers given by [12].

c. NOAA modeled sustained mean speeds have been converted to 3-sec peak gusts using a multiplier of 1.21 (Appendix D).

d. ARA modeled 3-sec peak gusts given by [12]. Modeled values for FCMP towers given by [12]. Other values obtained from Figure 2-4b.

Table 2-2b. Comparison of observed and modeled wind speeds for Hurricane Rita

Sensors	Location/GPS	Basic 3-sec Peak Gust from ASCE 7-05 (mph)	3-Second Peak Gust			Maximum Sustained	
			Recorded (mph)	Modeled: NOAA[b] (mph)	Modeled: ARA[b] (mph)	Modeled: NOAA (mph)	Modeled: ARA (mph)
T0 (FCMP)	Port Arthur, TX	110-120	**116**	**91**	120	75	**100**
T1 (FCMP)	Houston, TX	100-110	59	39	60	32	50
T3 (FCMP)	Nederland, TX	110-120	93	71	110	59	90
T5 (FCMP)	Orange, TX	110-120	98	88	120	73	**100**
WEMITE #2	Port Arthur, TX	110-120	**116**	91	120	75	**100**
SBCCOM Black	Orange, TX	110-120	88	88	120	73	**100**
SBCCOM White	Anahuac, TX	110-120	85	59	90	49	75
SBCCOM Clear	Winnie, TX	110-120	86	67	100	55	85
Max. Map Value	-	-	-	-	**>120**	**~100**	**~ 100**

Note:

a. Numbers in bold represent the maximum wind speed for that category.

b. Modeled sustained mean speeds have been converted to 3-sec peak gusts using a multiplier of 1.21

2.2.6 Structural Design for Wind

Since this reconnaissance focused on damage to physical structures, it is important to compare the wind speeds inflicted by Katrina and Rita with the design wind speeds for the affected regions. The basic wind speed map in the ASCE 7-05 standard [3] sets model criteria for designing buildings and other structures. Figure 2-8 shows the ASCE 7-05 basic wind speed map for the Gulf Coast. This map shows contours of basic 3-sec-peak-gust wind speeds along the hurricane coast. These basic wind speeds are specified for open-country terrain at a height of 33 ft (10 m) above ground. Linear interpolation between wind contours is permitted by ASCE 7. Use of these basic wind speeds results in *nominal* wind loads having a mean recurrence interval of approximately 50 years to 100 years, depending on location. In the strength-design methodology of ASCE 7, the nominal wind loads are multiplied by a wind load factor of 1.6 to achieve *ultimate strength* design wind loads having a recurrence interval of at least 500 years [3].

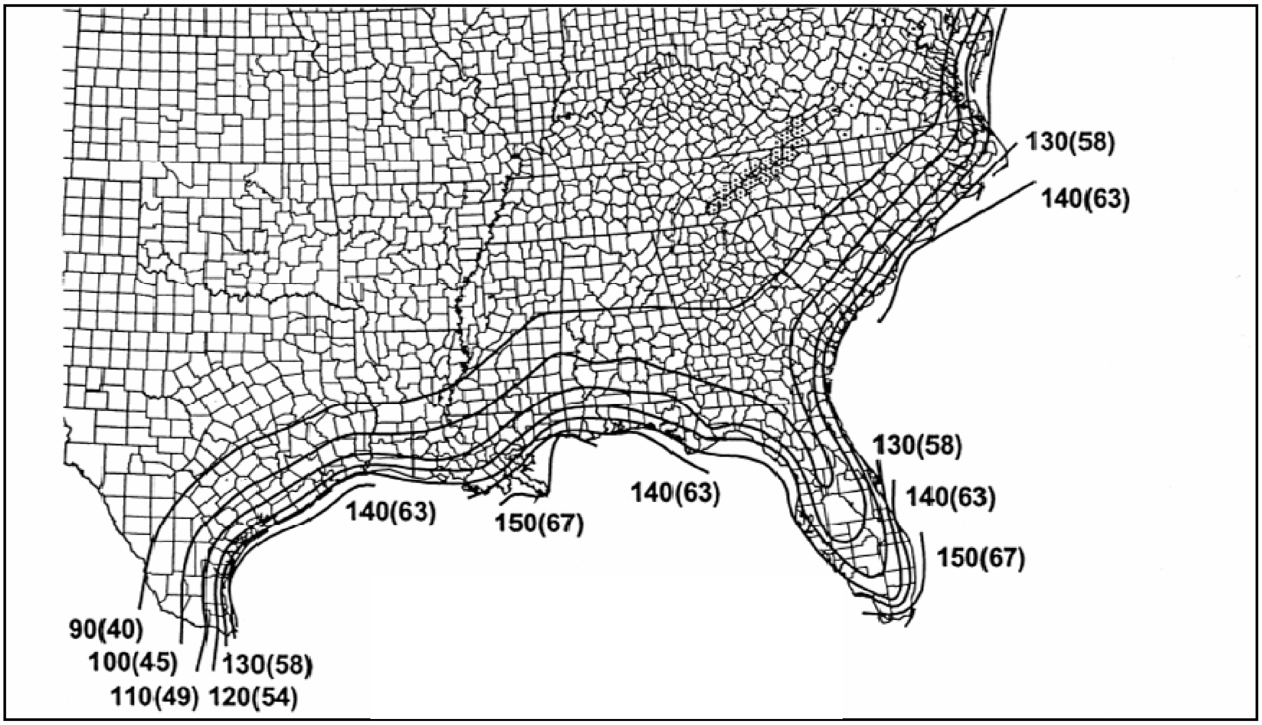


Figure 2-8 ASCE 7-2005 basic wind speed map for the southeastern U.S. hurricane coast. Units are mph or (m/s). (With permission from ASCE [3])

The third columns of Table 2-2a and 2-2b provide the design peak-gust wind speeds from ASCE 7-05, which can be compared with those recorded at sensor stations and those derived from the wind speed contour maps shown in Figure 2-4 (Hurricane Katrina) and Figure 2-8 (Hurricane Rita). Tables 2-2a and 2-2b show that in all locations, the recorded and modeled wind speeds in the two hurricanes were at or below the basic (nominal) wind speeds presented in ASCE 7-05. For example, peak-gust winds of 91 mph were recorded in Mobile, Alabama, and 93 mph in Pascagoula, Mississippi (Hurricane Katrina); whereas, the ASCE 7-05 basic wind speeds are 130 mph-140 mph for Mobile and 140 mph-150 mph for Pascagoula. Gust speeds for Gulfport, MS., were estimated to be between 121 mph to 139 mph (Hurricane Katrina), compared to ASCE 7-05 basic wind speeds of 130 mph to 140 mph. A peak gust of 116 mph was reported at Port Arthur, Texas (Hurricane Rita), which is consistent with the nominal wind speed set forth by ASCE 7 (110-120 mph).

2.3 STORM SURGE

The National Hurricane Center defines storm surge as *"An abnormal rise in sea level accompanying a hurricane or other intense storm, and whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone. Storm surge is usually estimated by subtracting the normal or astronomic high tide from the observed storm tide."* On top of storm surge and astronomical tide, pounding waves generated by powerful storm winds add to the destructive potential. Preliminary numerical studies by USACE's Interagency Performance Evaluation Task Force (IPET) [27] indicate that "peak significant wave height along the south shore of Lake Pontchartrain reached at least 9.4 ft, exceeding design values by about 1.0 ft to 1.5 ft. Estimated wave periods were about equal to design values… In south Plaquemines Parish, design wave height conditions were exceeded by 2 to 4 ft and design wave periods were exceeded by a factor of two to three." Since this report documents observations by the reconnaissance team, it does not contain computer hydrodynamic studies, but it recognizes that storm driven waves may have contributed significantly to the destruction. This section discusses the data and methodologies employed to assess the extent of storm surge hazard for Hurricane Katrina. Storm surge data for Hurricane Rita was limited, and is therefore included only to the extent that direct measurements or observations made by the NIST reconnaissance team were available.

2.3.1 Hurricane Katrina

2.3.1.1 Storm Surge Mapping with NOAA Aerial Imagery

High-resolution aerial photography captured by NOAA in the days following Hurricane Katrina provided a dataset to map the effects of storm surge in Alabama, Mississippi, and Louisiana. Interpretation of the NOAA imagery by researchers from the Multidisciplinary Center for Earthquake Engineering Research (MCEER) [19] was used to delineate Hurricane Katrina's debris line, which reflects maximum inland penetration of water from combined surge, waves, tide and rainfall runoff, along the Gulf Coast and to classify neighborhoods by severity of damage from coastal storm surge effects. An estimated surge height of 27 ft was reported by the Hancock, Mississippi Emergency Operation Center [18,20]. Some of the hardest hit areas in this hurricane were located along the Mississippi coastline between Biloxi and Bay St. Louis. Figure 2-9 shows a sample of the NOAA coverage for an area located in western Biloxi, with the debris line delineated, indicating the possible extent of surge-induced inundation.

Figure 2-9 NOAA aerial imagery for an area over western Biloxi. Yellow line denotes interpreted debris line. Storm surge heights of between 20 and 24 feet were reported in this area. (Source: NOAA [21]. Enhanced by Ron T. Eguchi, ImageCat).

2.3.1.2 Estimated Storm Surge Contours in Mississippi and Louisiana

FEMA mapped coastal surge in 1-foot intervals using documented coastal High Water Marks (HWMs) data (caused by storm surge and other processes). Field personnel deployed by FEMA collected detailed information about each HWM, including the physical basis of the mark, e.g., a mud line inside a building, a mud line on the outside of a building, or debris [15]. Figure 2-10 shows these contours for Mississippi with the key reconnaissance sites identified on the map (red dots). The surge height contours are generally based on the coastal HWM elevation data recorded by the FEMA field teams. A brief description of the methodology used to develop the contours (maximum surge elevation) is discussed in Table 2-3.

Table 2-3. FEMA methodology for developing storm surge contours from HWM data (source: http://www.fema.gov/hazards/floods/recoverydata/katrina_index.htm)

"The Hurricane Katrina surge elevation contours are based upon the surveyed coastal HWM elevations, which were used to find patterns in the coastal storm surge as it pushed against the open coast and into the inland bays. The known path and landfall location of Hurricane Katrina, together with the knowledge of how storm surge propagates inland, allowed surge contours to be drawn across the areas where the coastal HWMs indicate a change in storm surge elevation.

Assumptions are made in some locations to allow the surge elevation contours to "step" up or down at 1-foot intervals. Because of the inherent uncertainty in and the random and irregular spacing of coastal HWMs, the surge contours represent a generalized maximum storm surge elevation, and required professional judgment in their creation. Within certain surge contours, coastal HWMs may be higher or lower than the contours if they did not fit the overall pattern."

A storm surge contour map was also created for the New Orleans area of southeastern Louisiana. The spatial coverage of these contours included Tammany, Tangipahoa, St. John the Baptist, St. Charles, Jefferson, and Orleans Parishes. Figure 2-11 depicts surge elevation contours calculated from post-Katrina HWMs collected along the Gulf of Mexico, Lake Borgne, and Lake Pontchartrain coastlines of Louisiana.

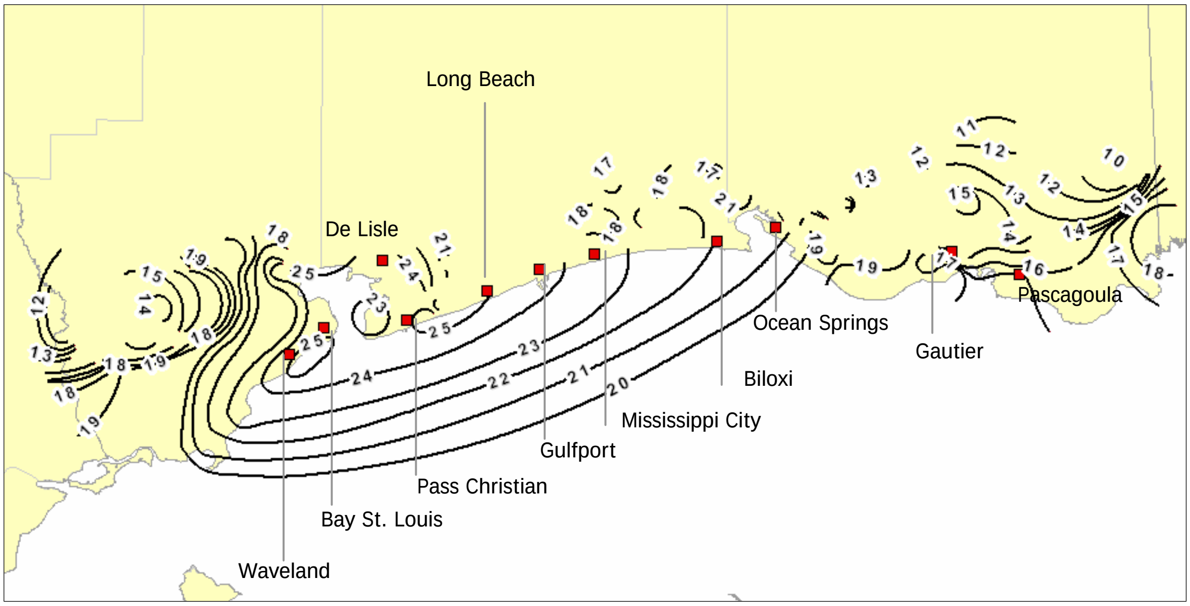


Figure 2-10 Storm Surge contours for Mississippi, as mapped by FEMA (heights measured in feet). Note: red squares indicate sites inspected by NIST-led reconnaissance team (Source: FEMA, enhanced by Ron T. Eguchi, ImageCat)

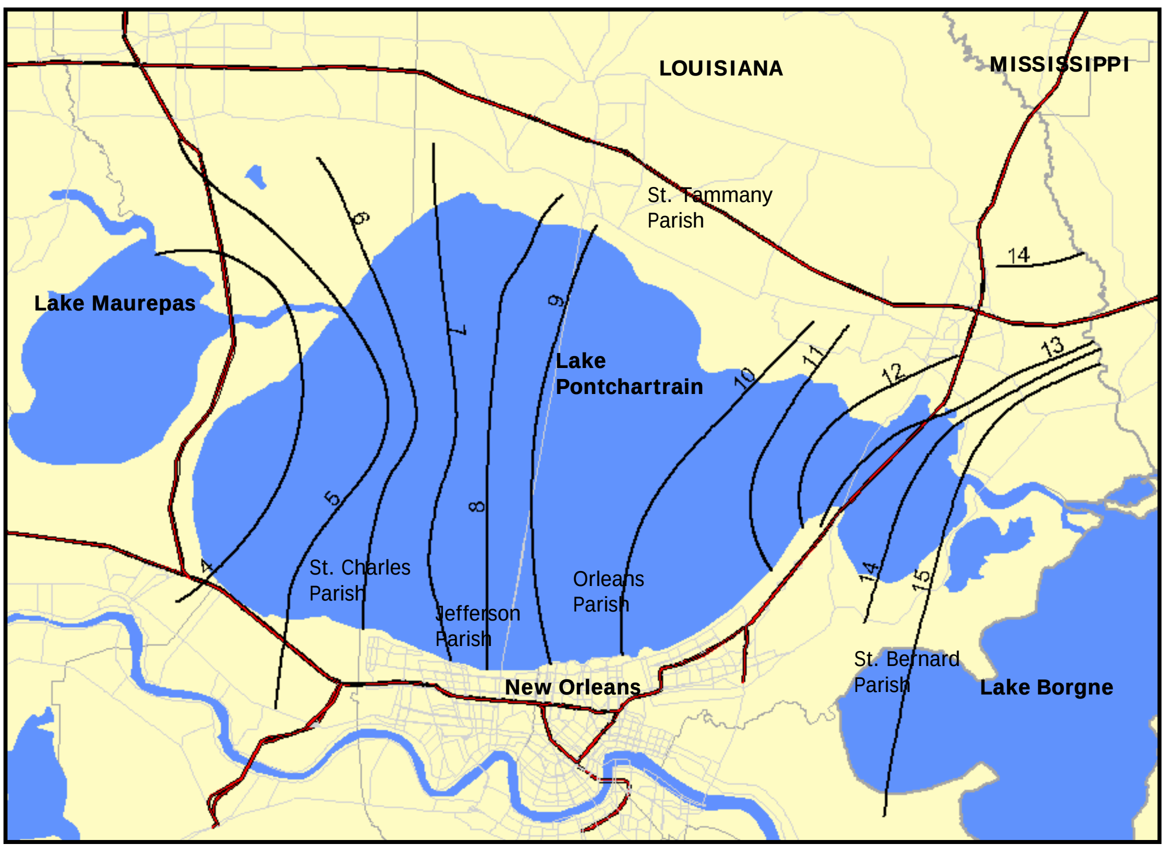


Figure 2-11 Storm surge contours (heights measured in feet) for the New Orleans area of southeastern Louisiana, as mapped by FEMA (Source: FEMA, enhanced by Ron T. Eguchi, ImageCat)

2.3.1.3 Preliminary Storm Surge Modeling

NOAA conducts real-time forecasts of potential storm surge from approaching hurricanes using SLOSH (Sea, Lake, and Overland Surges from Hurricanes) [31] and includes these forecasts in periodic hurricane advisories. NOAA forecasts, evacuation plans and real-time decisions of the emergency management community for storm surge are based on SLOSH. NOAA/FEMA has trained more than 1000 coastal emergency managers and other decision makers in week-long courses over the past 15 years on the use of NOAA forecasts products, including storm surge data. Emergency managers are provided composite products based on 5000+ SLOSH runs to define their local flood plain. In real-time, NOAA runs storm surge simulations and considers the associated output in its operational text and graphical products.

For hurricane Katrina, NOAA, in their advisories prior to landfall, predicted "coastal storm surge flooding of 18 to 22 ft above normal tide levels…locally as high as 28 ft along with large and dangerous battering waves…can be expected near and to the east of where the center makes landfall." (Advisory number 24 4PM CDT August 28, 2005), and "storm surge flooding of 10 to 15 ft near the tops of the levees is possible in the greater New Orleans area." (Advisory number 26B 8AM CDT August 29, 2005).

Preliminary storm surge hindcasts were performed by NOAA using SLOSH [31] and the Louisiana State University (LSU) Hurricane Center using the Advanced Circulation Model (ADCIRC-2DDI). The highest storm surge levels predicted by SLOSH and ADCIRC for the Gulf of Mexico are presented in Figures 2-12 (a) to (d). The SLOSH model estimated surge heights of up to 28.1 ft depending on location along the Mississippi coast. The ADCIRC model estimated surge heights of 25 feet-30 feet along the same coast. For New Orleans, the SLOSH and ADCIRC models estimated surge heights of 5 feet-10 feet in the canals (Figures 2-12 (b) and (d)). Figure 2-12 (c) shows that storm surge hindcasts using SLOSH are in agreement with the observed high water marks obtained by FEMA. The IPET study [27] reports that "observed peak water levels along the south shore of Lake Pontchartrain were 10.7 ft to 11.7 ft, which were less than or right at the design peak water levels of 11.8 ft. In the Inner Harbor Navigation Canal (IHNC), north of the intersection of IHNC with the Intracoastal Waterway (IWW) / Mississippi River Gulf Outlet (MRGO), there is large gradient in peak water level, from 15.2 ft just south of the intersection to 11.7 ft at the IHNC entrance to Lake Pontchartrain… Along the east-west oriented IWW/MRGO channel section, peak water levels exceeded the design value of 13.2 ft by 1 to 5 ft. Along the MRGO adjacent to the St. Bernard Parish hurricane protection system, peak water levels were over 18 ft, which exceeded the design levels by 5 to 6 ft." The IPET study uses ADCIRC to model storm surge, but also models waves with WAM and STWAVE.

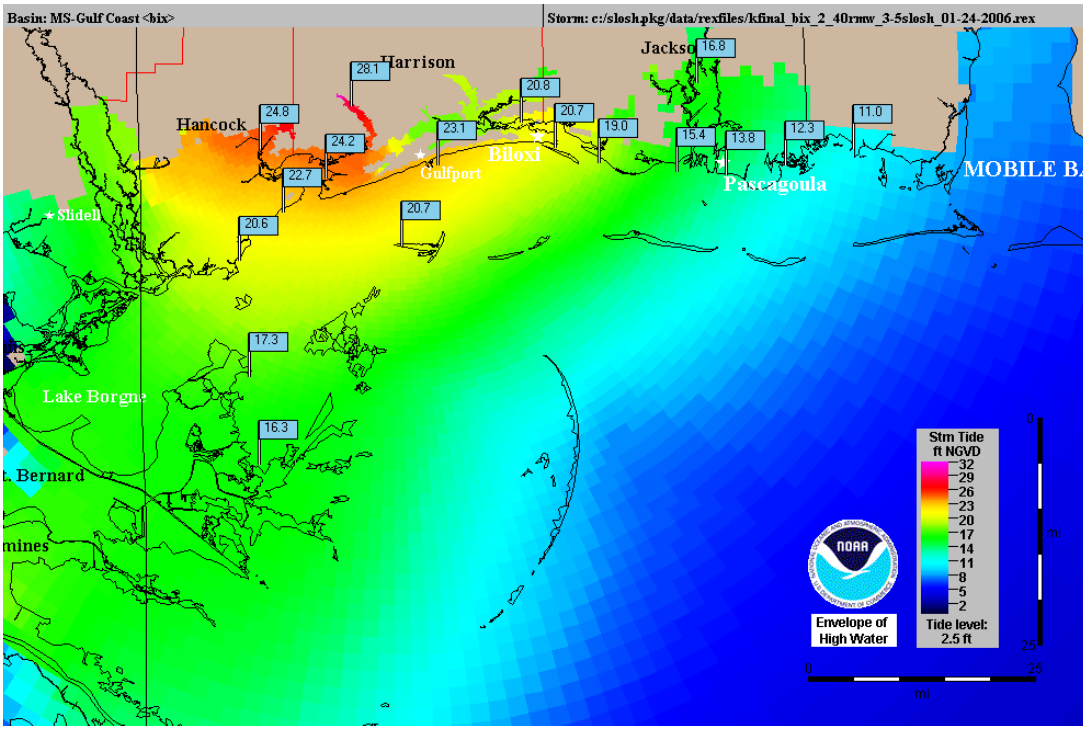


Figure 2-12 (a) **Preliminary storm surge hindcast results for Mississppi Gulf coast for Hurricane Katrina using SLOSH (Source: NOAA)**

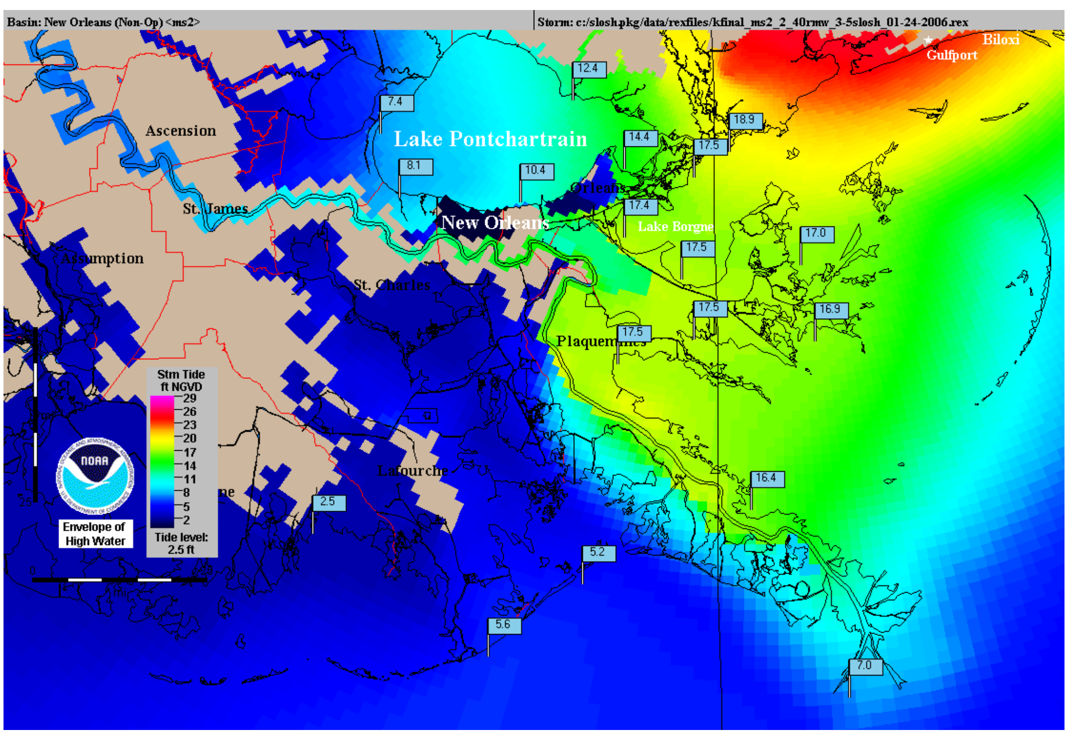


Figure 2-12 (b) **Preliminary storm surge hindcast results for Southeast Louisiana for Hurricane Katrina using SLOSH (Source: NOAA)**

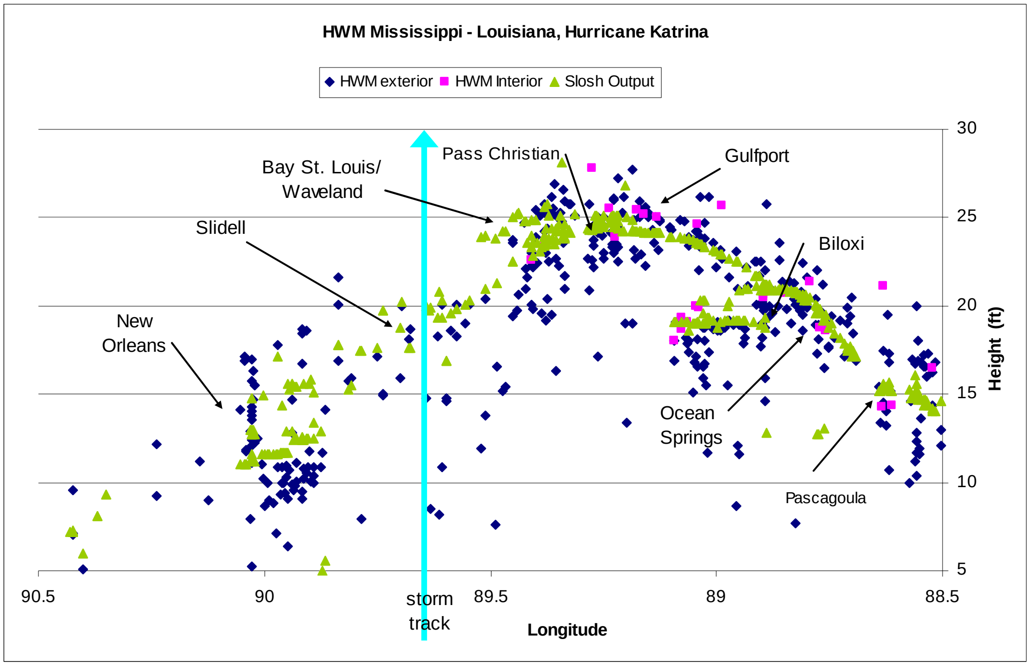


Figure 2-12 (c) **Comparison of storm surge predictions using SLOSH with preliminary high water marks observed by FEMA in Mississippi and Louisiana (Source: NOAA)**

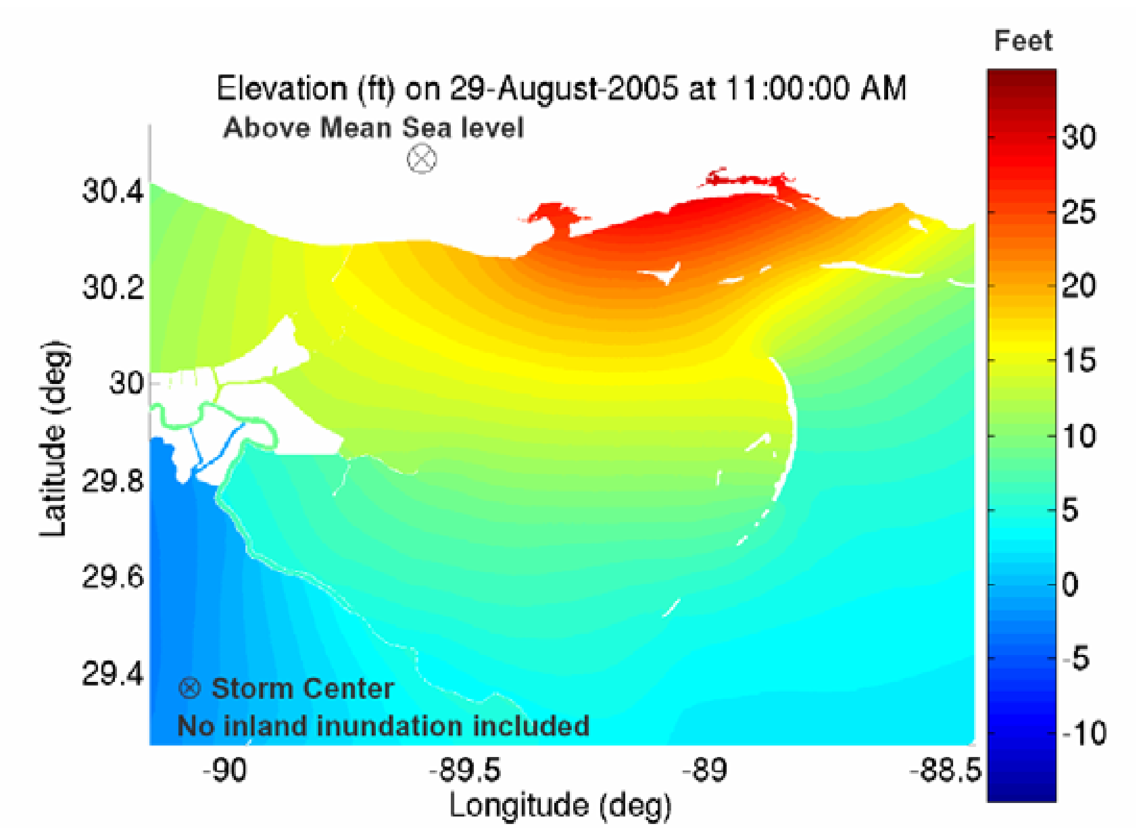


Figure 2-12(d) **Preliminary storm surge hindcast results for Hurricane Katrina; inland inundation not included (Source: Commander, Naval Meteorology and Oceanography Command at Stennis Space Center [30])**

2.3.1.4 Comparison of Recorded and Estimated/Modeled Storm Surge Heights

Modeled values of post-hurricane storm surge height from FEMA's contour maps and those from the ADCIRC model were compared with surge heights observed by the NIST-led team at only two locations where comparisons can be made listed in Table 2-4.

Table 2-4 shows that a number of locations experienced storm tide (storm surge plus astronomical tide) heights in excess of 20 feet above mean sea level. Observations by the NIST reconnaissance suggest that in some locations between Biloxi and Long Beach, Mississippi, for example in the area around Gulfport, the surge reached 28 feet.

Surge heights in the canals in New Orleans have been estimated to be less than 13 ft 9 inches based on observations at the London Avenue and 17th Street Outfall Canal. A research team sponsored by the National Science Foundation (NSF) [23] reports that lakefront storm surges along Lake Pontchartrain were about 11 feet, which was below the crest of the lakefront levees (see also Appendix C). The surge contours mapped by FEMA show similar surge levels along the lakefront (Figure 2-10).

Table 2-4 Comparison of recorded and modeled storm surge heights for Hurricane Katrina.*

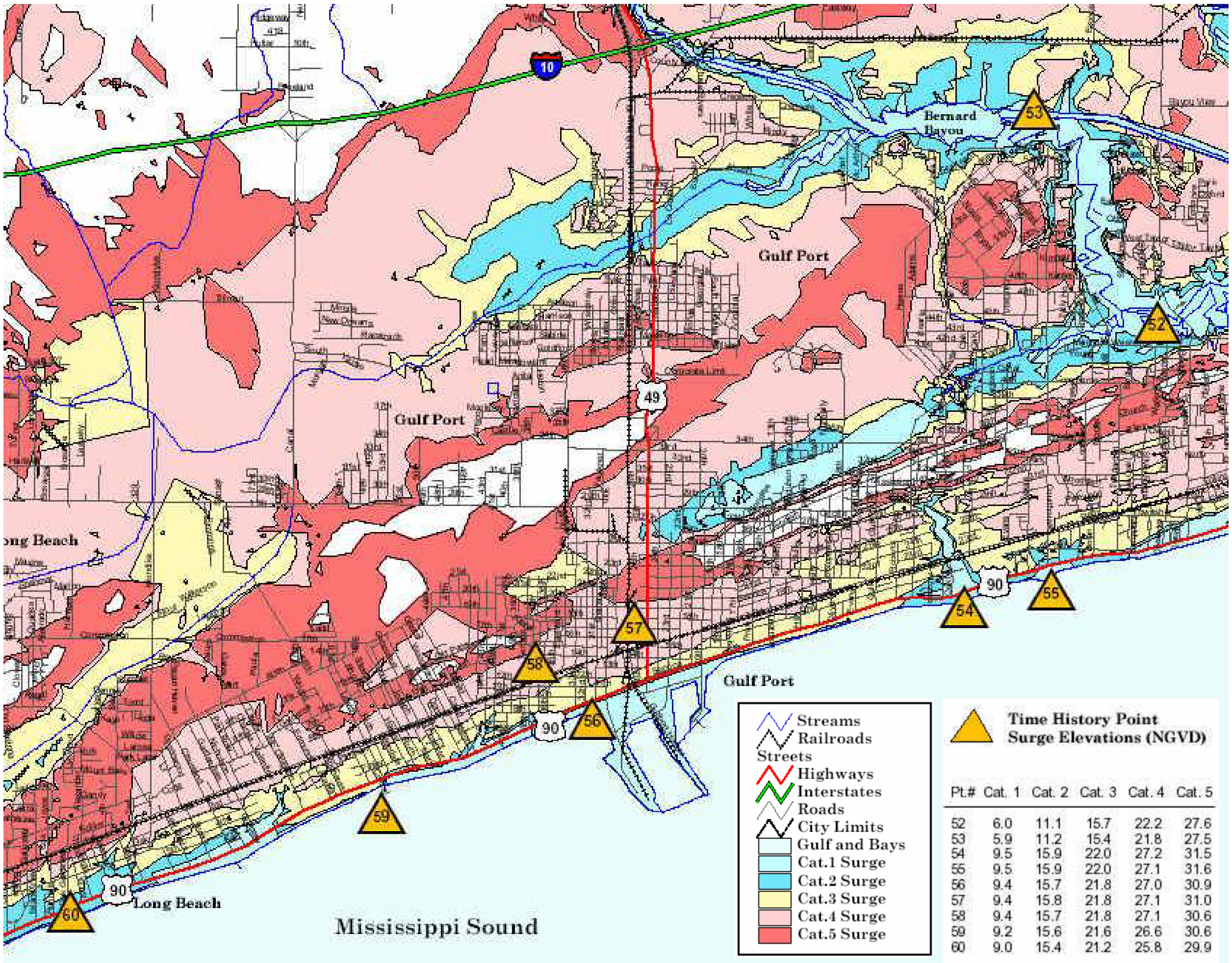
Location of Key Sites	Storm Surge Height (ft)			
	NIST Reconnaissance Observed HWM relative to ground level (ft)	Estimated: FEMA Storm Surge Contour (ft)	Modeled: Storm Surge Hindcast (ft)	
			ADCIRC	SLOSH
Hurricane Katrina				
The Alabama State Docks/Port of Mobile, AL	13			
Jackson County Port Authority/Port of Pascagoula, MS	20	15-17		
Port of Gulfport, MS	**26- 28**	**24-25**		23
Eastbank Wastewater Treatment Facility, New Orleans, LA		9-10		
Entergy's Michoud Power Generating Facility, New Orleans, LA	>14	9-10		
Lake Pontchartrain Causeway, New Orleans, LA		8-9		8-11
Lake Pontchartrain I-10 bridge, New Orleans, LA	14			14
Watson Electric Power Plant, Gulfport, MS		**24-25**		
Waveland City Hall, MS		**24-25**	23	24-25
Bay St. Louis City Hall, MS		**23-25**	25	
Bay St. Louis Bridge, US 90, MS		**23-25**	26	24-25
Biloxi Bay Bridge, US 90, MS	22			
Pass Christian City Hall, MS		**23-25**	26	24
Long Beach Harbor, MS		**24-25**	**28**	
Gulfport City Hall, MS		**24-25**	**28**	**24-25**
Biloxi City Hall, MS		21-22	**28**	**21-22**
Ocean Springs City Hall, MS		21-22	26	19-21

*Surge heights estimated by FEMA for inland sites are lakefront surge levels (Lake Pontchartrain) at the mouth of the canals and not within the canals themselves. Bold numbers indicate maximum surge height in that category.

2.3.1.5 Storm Surge Hazard: USACE Hurricane Storm Surge Maps

Hurricane storm surge maps prepared by the USACE in cooperation with Mississippi Emergency Management Agency and FEMA provide information on areas vulnerable to storm surge for the five hurricane categories (e.g.[24]). These maps are used to determine the limits of hurricane evacuation zones using a "worst-case" scenario of hurricane storm surge flooding for each storm category. The SLOSH Model (1999) [31] and hypothetical storm data form the basis of the surge heights summarized in these maps. Figure 2-13 is a portion of a Hurricane Surge Map from USACE for Harrison County in Mississippi. The surge information described in the Hurricane Surge Map reflects only still water flooding; local effects of current, waves, rainfall, or flooding from overflowing rivers were not considered in the development of the USACE Hurricane Surge Maps.

An important item for future study would be to compare the mapped storm surge inundation areas (e.g., Figure 2-9) with the surge heights delineated in Figure 2-13. This analysis would help to determine whether local evacuation maps need to be revised in order to incorporate the effects from an actual event.



Pt.#	Cat. 1	Cat. 2	Cat. 3	Cat. 4	Cat. 5
52	6.0	11.1	15.7	22.2	27.6
53	5.9	11.2	15.4	21.8	27.5
54	9.5	15.9	22.0	27.2	31.5
55	9.5	15.9	22.0	27.1	31.6
56	9.4	15.7	21.8	27.0	30.9
57	9.4	15.8	21.8	27.1	31.0
58	9.4	15.7	21.8	27.1	30.6
59	9.2	15.6	21.6	26.6	30.6
60	9.0	15.4	21.2	25.8	29.9

Figure 2-13 Harrison County, Mississippi hurricane surge map (Source: USACE [24]).

2.3.2 Hurricane Rita

With respect to Hurricane Rita, only a few direct observations of HWMs were available for this report. These were obtained by NIST-led reconnaissance team members during their deployment in October 2005 (Table 2-5). The maximum HWMs observed by NIST team members were in Cameron Parish, Louisiana, which were between 12 feet and 15 feet. The NHC [28] also reports storm surge estimate of 15 ft in Cameron, based on unofficial visual observations of HWMs and debris lines. In Sabine Pass, storm surge heights of 5 feet and greater were reported [28]. A FEMA report documenting HWMs along the Louisiana coast following Hurricane Rita noted surge heights of between 6 feet and10 feet in Lake Charles (http://www.fema.gov/hazards/floods/recoverydata/rita_la_gis.shtm). The NHC [28] also reports that "flood waters in downtown Lake Charles were as deep as about six feet in some places. Farther east, most or all of Vermillion, Iberia, and St. Mary Parishes south of Highway 14 and U.S. 90 (several miles inland) were inundated by the storm surge, visually estimated at 8-12 ft in some of these areas."

Table 2-5 Observed HWMs for Hurricane Rita.

Location of Key Sites	Storm Surge Height (ft)	
	NIST reconnaissance observed HWM relative to ground level (ft)	FEMA HWM (ft)
Port of Sabine Pass, TX	> 5	-
Cameron, LA	12-15	
Creole, LA	>10	
Lake Charles, LA		6-10

2.4 FLOODING IN NEW ORLEANS

The failure of the flood control system in New Orleans resulted in more than 75 percent of New Orleans being flooded [5]. In some areas of the city, flood depths of 20 feet were observed. This section discusses the data sources used to quantify the extent of flooding in New Orleans.

A determination of flood extent for a larger area of New Orleans, including sections of Jefferson and St. Bernard Parishes, was made by MCEER researchers using high-resolution QuickBird satellite imagery from DigitalGlobe [19]. The resulting flood extent boundary is shown in Figure 2-14.

The flood boundary in Figure 2-14 was visually compared with an automatically-generated spectral classification of the inundated area, obtained from moderate resolution (30m) Landsat 5 coverage. The Landsat coverage was captured on August 30, 2005 and posted by the USGS on September 3, 2005. From Figure 2-14, the Landsat image corresponds with QuickBird™ coverage for metropolitan New Orleans. Although a comparison is precluded in some areas due to cloud cover, the degree of correspondence between the QuickBird™ flood line and the classified flood extent is generally high.

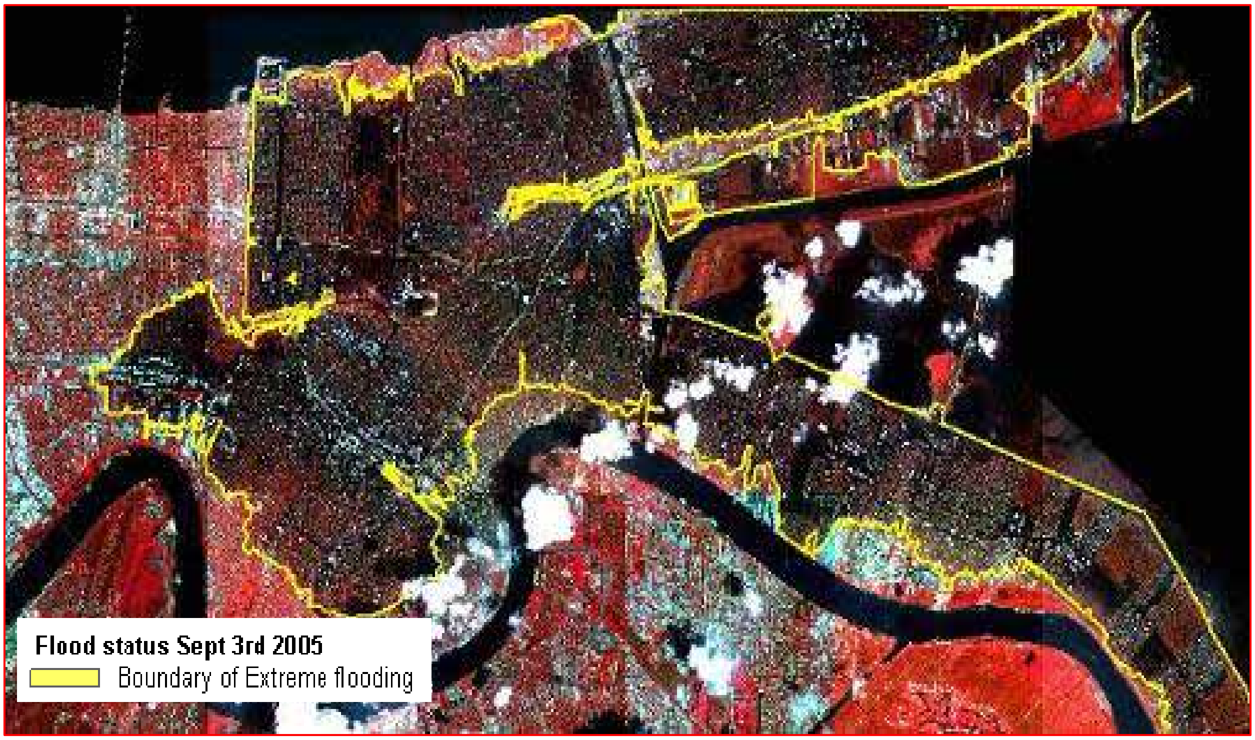


Figure 2-14 Expert interpretation of flood limit (yellow lines) overlaid onto DigitalGlobe QuickBird "false color" composite image of New Orleans (September 3, 2005). (Photo courtesy of DigitalGlobe, enhanced by Ron T. Eguchi, ImageCat)

Flood depths in New Orleans and in areas along coastal Mississippi were estimated using: (1) flood depth maps produced by NOAA; and (2) field observations by the NIST reconnaissance team.

(1) Flood depth maps produced by NOAA: NOAA's flood depth map for August 31, 2005 was developed using a combination of satellite imagery from the National Geospatial Intelligence Agency and LIDAR (Light Detection and Ranging) data from Louisiana State University and the State of Louisiana. This map (Figure 2-15) shows that many areas of New Orleans were covered by at least 7 feet to 9 feet of water, with some areas exceeding 20 feet. The extent of flooding (surface-wise) shown in Figure 2-15 corresponds well with the flood boundary delineations made in Figure 2-14. In both cases, independent data sources (i.e., high-resolution optical imagery and LIDAR) were used to determine the flood extent boundaries.

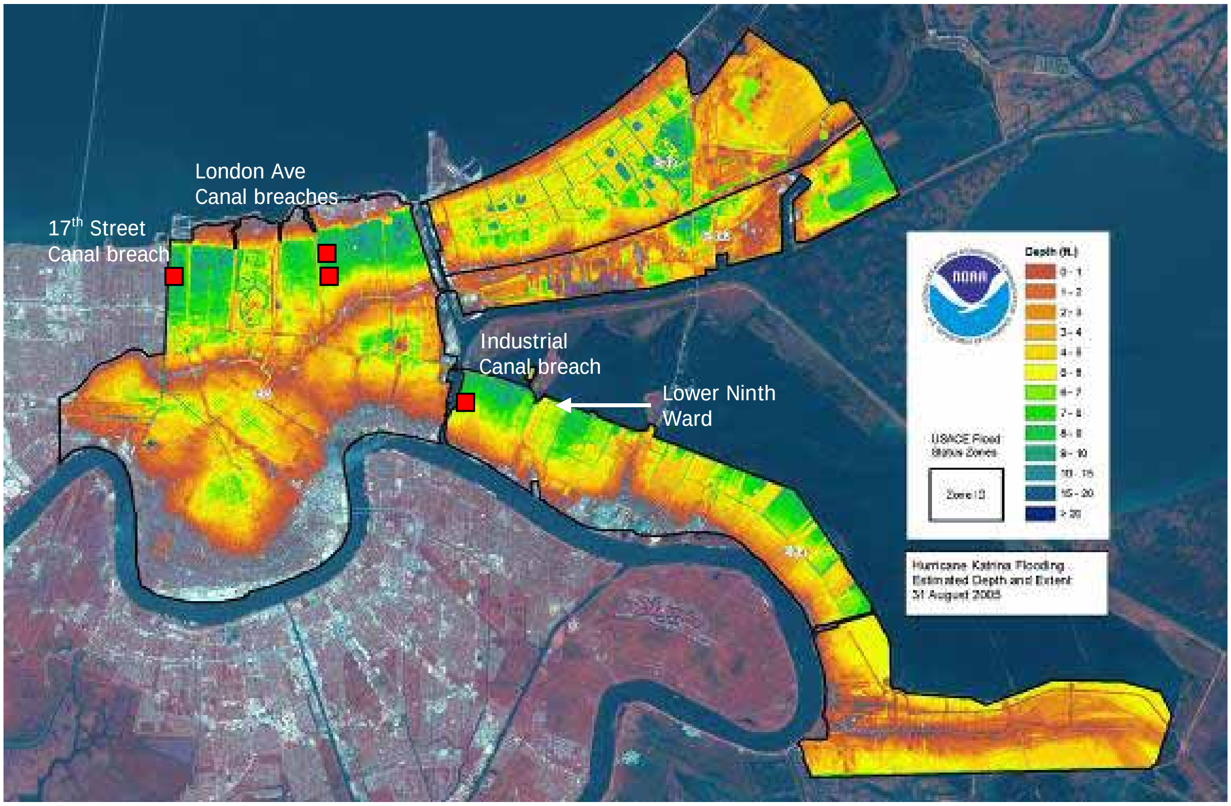


Figure 2-15 Flood depth estimation for New Orleans by NOAA, 31 August 2005 (Source: NOAA [25], enhanced by Ron T. Eguchi, ImageCat).

(2) Field observations by the NIST reconnaissance: The NIST reconnaissance effort also collected approximate observations on HWMs at key locations throughout the reconnaissance areas. Wherever possible, team members noted the GPS coordinates of these key sites in order to reference the observed and modeled water levels. Comparison between observed HWMs and depth of flooding in Mississippi and Louisiana is presented in the next section.

Table 2-6 compares flood depths after Hurricane Katrina using observations by the NIST reconnaissance team and by NOAA. Observations made by the NIST reconnaissance at the various locations in New Orleans generally agree with the estimated NOAA values where available. The greatest depth of flooding was observed by the NIST reconnaissance team in the Lower Ninth Ward area of the western St. Bernard Parish and residential areas adjacent to the Industrial Canal Breach, where 8 feet to 10 feet of flooding was recorded. According to the NOAA flood depth maps, the areas with the greatest depths were adjacent to major levee breaches.

Table 2-6 Comparison of recorded and estimated flood depths for several locations in New Orleans affected by Hurricane Katrina.

Key Locations	Flood Depths	
	NIST Observed HWM relative to ground level (ft)	Estimated: NOAA Flood Depth Map Aug. 31, 2005 (ft)*
Residential areas adjacent to the 17th Street Canal Breach, New Orleans, LA	8-10	10-15
Residential areas adjacent to the London Avenue Canal Breaches, New Orleans, LA	6-8	10-15
Residential areas adjacent to the Industrial Canal Breach, New Orleans, LA	8-10	10-15
University of New Orleans, New Orleans, LA	3	2-3
USDA Research Southern Regional Research Laboratory, New Orleans, LA	2	5-6
LSU Medical Center, New Orleans, LA	3	1-2
Ninth Ward and Western St. Bernard Parish, LA	8-10	7-8
Eastbank Wastewater Treatment Facility, New Orleans, LA	>16	5-6
Entergy's Michoud Power Generating Facility, New Orleans, LA	~6	2-3

*Observed depths of flooding presented in this table are approximate. NOAA flood depth values were determined by visually inspecting hard copy maps.

2.5 SUMMARY

2.5.1 Wind Speed

In general, for most locations studied in this reconnaissance report, the observed and modeled/estimated wind speeds for both hurricanes were less than the design wind speeds prescribed in the ASCE 7- 05 standard. In a couple of locations, the estimates were equal to the design values.

Hurricane Katrina

Wind speed estimates taken from two independent maps (NOAA and ARA) generated from wind speed observing stations indicate that the maximum sustained wind speed at landfall along the Mississippi coast was between 110 mph and 120 mph. In New Orleans, the ARA maps suggest that wind speeds reached 90 mph, while the NOAA maps indicate that winds were 80 mph or less. Furthermore, according to a recent NHC report (December 2005) [18], the estimated maximum 1-minute sustained wind speed produced by Hurricane Katrina was approximately 125 mph. The NHC maximum wind speed estimates are often higher than those derived from the observing sites since they are based on an understanding of the horizontal variability of winds in the core eyewall-region of hurricanes that is usually under sampled by the available observing sites. The available wind swath analyses and wind speed measurements from Hurricane Katrina are consistent with a Category 3 event.

Hurricane Rita

The NHC has reported that a small area on the coast of extreme Southwestern Louisiana to the east of the eye experienced Category 3 conditions, with estimated maximum sustained wind speed of 115 mph. Hurricane Rita has officially been classified as a Category 3 hurricane although most of the affected regions experienced only Category 1 or 2 hurricane conditions.

2.5.2 Storm Surge

Hurricane Katrina

A number of locations experienced storm surge heights greater than 20 feet. An estimated surge height of 27 ft was reported by the Hancock, Mississippi Emergency Operation Center. Observations by the NIST reconnaissance suggest that in some locations between Biloxi and Long Beach, Mississippi, the surge reached as high as 28 feet. Estimates of surge heights in New Orleans ranged from 9 feet to 10 feet. This information is based on HWM data collected by FEMA investigators as well as on other observations.

Hurricane Rita

The maximum HWMs observed by NIST team members were in Cameron Parish, Louisiana, which were between 12 feet and 15 feet. The NHC [28] reported storm surge estimates of 15 ft in Cameron, based on unofficial visual observations of HWMs and debris lines. In Sabine Pass, storm surge heights of 5 feet and greater were reported [28]. The NHC [28] also reported that "flood waters in downtown Lake Charles were as deep as about six feet in some places. Farther east, most or all of Vermillion, Iberia, and St. Mary Parishes south of Highway 14 and U.S. 90 (several miles inland) were inundated by the storm surge, visually estimated at 8-12 ft in some of these areas."

2.5.3 Flooding in New Orleans

Hurricane Katrina

The depth of flooding in New Orleans based on NOAA estimates indicates that many areas of New Orleans were covered by at least 7 feet to 9 feet of water with some areas exceeding 20 feet (as of August 31, 2005). Field observations made by members of the NIST reconnaissance team noted that flood depths of up to 10 feet were observed in three areas of New Orleans (residential neighborhoods adjacent to the 17th Street Canal and Industrial Canal breaches, and the Ninth Ward of the St. Bernard Parish).

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Chapter 3
DAMAGE TO MAJOR BUILDINGS

This chapter discusses the damage observed to major buildings from Hurricanes Katrina and Rita. Major buildings are defined as buildings that are a result of engineering design or have special occupancy classification. Specifically, major buildings refer to structures that 1) involved engineered design or were proportioned using engineering calculations of load and resistance, and/or 2) serve as critical facilities such as high-occupancy buildings, government buildings, buildings that contain emergency services or hazardous materials, and schools. Certain residential structures fit this definition; however, discussion of their performance during Hurricanes Katrina and Rita is included in Chapter 5.

Damage to major buildings during Hurricanes Katrina and Rita were a result of primarily three phenomena: (1) storm surge along the coastal regions of the Gulf; (2) wind; and (3) flooding in New Orleans. Storm surge damage from Hurricane Katrina was more devastating than wind or flooding damage – many structures located close to the shore completely collapsed while other structures located further inland partially collapsed. Wind damage was observed in most areas of the NIST reconnaissance. Winds caused damage to steel-framed warehouses, masonry walls, and various types of cladding systems. Roofing systems experienced extensive damage either directly by the wind or through failure of the flashing and coping[13]. Roofing aggregate was responsible for the majority of wind-borne debris damage to windows. Water ingress around rooftop equipment that was compromised by wind or completely removed from the roof caused extensive water damage to many buildings' interiors. Water ingress from wind driven rain around window systems was also observed.

The flooding of certain buildings, particularly in New Orleans, caused damage to critical building contents such as electrical equipment, generators, and chiller plants. These buildings would have returned to full operation after the hurricanes had the critical equipment not been rendered inoperable by flooding. Mold growth in many of these buildings after the flooding receded prevented them from reopening.

This chapter summarizes the observations of key damage to major buildings made during the NIST-led reconnaissance.

3.1 STRUCTURAL SYSTEMS

Major buildings in the hurricane regions are constructed with steel, reinforced concrete, and masonry (brick, concrete masonry unit). The most severe, catastrophic damage to these structural systems was caused by storm surge and associated wave action along the Mississippi and Alabama coasts. In some instances, storm surge alone was implicated in the collapse or partial collapse of structural systems, while in other instances, damage due to strong winds was evident at higher elevations. In areas not exposed to storm surge or flooding, winds were responsible for damage to masonry wall and metal buildings.

This section focuses on observations of damage to selected structural systems that exhibited vulnerability to collapse or partial collapse as a result of high wind, storm surge, or flood loading associated with Hurricanes Katrina and Rita. In particular, the following systems are addressed:

[13] Flashing is the component of the roof system used to seal edges of roof coverings at walls, chimneys, expansion joints, drains, gravel stops, and other places where the covering is interrupted or terminated. A coping is a covering on top of a wall exposed to the weather; it is usually sloped to carry off water.

- precast and prestressed concrete parking structures,
- masonry walls,
- metal buildings,
- Mississippi casino barge structures and mooring.

3.1.1 Precast and Pres-stressed Concrete Parking Structures

The NIST-led reconnaissance team observed partial collapse of the second floor decks of six reinforced concrete parking structures in Biloxi and Gulfport, Mississippi as a result of Hurricane Katrina. These multiple-level structures were constructed of all precast structural components and were located along the shore of the Gulf of Mexico. The floor beams comprising the driving/parking decks are pretensioned, double-tee beams topped with thin cast-in-place slabs. All floor beams that collapsed were subjected to storm surge (estimated to be at least 20 feet high based on the elevation of debris deposited on the structures), which appeared to have pushed or lifted the floor beams or spandrels from their seats. Connections between the floor beams and support girders or support girders and columns were such that only a small lateral displacement was needed to off-seat the supported member; these relatively light gravity load connections had little to no lateral load capacity. The pre-tensioned double-tee beams were also susceptible to failure under their own pre-tension loads when subjected to uplift forces caused by storm surge. Pictures of failed parking structures are provided in Figure 3-1. Note the missing support girders on the first level in Figure 3-1a, the missing floor beams from the first level and the concrete beam seats located on the columns for the support girders in Figure 3-1b and Figure 3-1c, and the spandrel in the foreground that was lifted or pushed off of its steel beam seat located on the column in Figure 3-1d. Note that the reinforced concrete frames suffered no observable effects from the storm surge event.

Figure 3-1 Partial, first-level collapse of precast, prestressed double-tee deck parking structures in (a) Gulfport, MS and (b,c,d) Biloxi, MS (Photo credit: NIST).

Two reinforced concrete parking structures located on the beach in Biloxi, MS, experienced storm surge that was about 20 ft to 30 ft in depth. These structures had cast-in-place columns with post-tensioned deck slabs and framing beams. One of the garages, a five-story parking structure located in the eastern-most part of Biloxi, experienced no apparent structural collapse from storm surge directly, but did experience partial collapse of the southwest corner due to the rocking motion of the floating barge moored alongside it. All five levels of the southwest corner collapsed from the barge impact. (This failure due to a floating barge is discussed in Section 3.1.4.) A nearby single-story parking structure of similar construction appeared to have sustained no structural damage (Figure 3-2). The difference in performance between these two parking structures and those in Figure 3-1 is likely[14] attributable to the connection details of the beams/girders and columns.

[14] The terms *possible, apparently,* and *likely* refer to increasing levels of supporting observations or technical certainty in the findings. These determinations are made based on visual observations and engineering judgment, and not on the basis of analytical, numerical, or statistical calculations.

Figure 3-2 Successful performance of a single-story parking structure in Biloxi, MS (Photo credit: NIST).

The inherent weakness of prestressed flexural members against uplift forces from storm surge was observed at a cast-in-place, post-tensioned parking garage in Biloxi, MS. Almost all the bays of the south side of the structure, which was directly exposed to the storm surge, were damaged in the manner seen in Figure 3-3. The damage was most severe in the middle bays where the broken-up slab was found to hang like a catenary with portions of the concrete slab broken cleanly from the reinforcement. The adjacent bays were damaged to a lesser extent; slabs were still largely intact, but bottom reinforcement (note that the bottom reinforcement was epoxy-coated, while the top was not) had pulled out of the concrete. The concrete cover for this bottom reinforcement appeared thinner than usual, and it seems likely[15] that the storm surge exerted a "buoyancy" effect causing, in combination with the prestressing forces, a sufficient negative bending moment in the midspan to cause bending failure of the slab.

Figure 3-3 Failure of post-tensioned concrete slab exposed to uplift forces due to storm surge (Photo credit: Jack Hayes, USACE)

The response of these reinforced concrete parking structures, and in pre- and post-tensioned structures in general, to storm surge loadings is an issue that needs further investigation. Since no real structural requirement for storm-surge loading exists for their designs, existing codes and standards could be modified to improve performance of such structures in areas susceptible to storm surge.

3.1.2 Masonry Walls

Masonry walls include brick and concrete masonry unit (CMU), e.g., CMU infill walls between the steel frames of a structure. Masonry veneer is addressed in Section 3.4.2. Masonry walls suffered extensive damage due to storm surge and associated wave action and damage due to wind.

The Venetian Isles Fire Station in New Orleans is a single-story building with steel columns, concrete masonry infill walls, and brick veneer. Storm surge collapsed the ungrouted and unreinforced CMU walls of the building but left the columns and roof standing (Figure 3-4).

Figure 3-4 Storm-surge-induced collapse of CMU walls at the Venetian Isles Fire Station in New Orleans (Photo credit: Keith Porter, Scawthorn Porter Associates).

Figure 3-5 shows the effects of storm surge on a similarly constructed building, but with reinforced CMU walls. This retail store is located on US 90 west of Gulfport and fronts almost immediately on the Gulf. The storm surge here would have been approximately 30 ft above mean sea level. The lower portion of the walls around most of the entire building's perimeter was destroyed by the surge, but the upper portion stayed in place owing to the reinforcement in the CMU walls.

Figure 3-5 Storm-surge-induced collapse of the lower portions to a reinforced CMU wall in Gulfport, MS (Photo credit: Habib Rahman, National Research Council of Canada).

The NIST-led reconnaissance observed the contrast of the storm surge damage and the wind damage in Gulfport, MS. At the Department of Veterans Affairs (DVA) hospital campus, which fronts on the Gulf and US 90, every one of the approximately dozen large buildings on the campus suffered severe damage from the storm surge on the lower two stories (most buildings in the campus were either two or three stories tall). The buildings were typically reinforced concrete frames with brick cladding on thick backup walls. In most instances, the massive exterior walls survived the water flow. In Figure 3-6a, a reinforced concrete frame building that was located toward the rear of the campus (with respect to the Gulf) is shown. The storm surge devastated the first story level, while most of the windows in the second story remained intact. The contrast between storm surge and wind damage was also evident at the First Baptist Church near the intersection of US 90 and US 49 (Figure 3-6b). The church steeple survived largely intact, with much of its cladding in place. The south wall (front wall in photo) and north wall of the building were almost completely destroyed. Based on impact marks on the church's columns that were on the brick annex, it is estimated that approximately 9 ft of storm surge water flowed through the church. The surge apparently[15] destroyed the lower segments of the walls (CMU faced with brick); when the lower portions were destroyed, no support for the upper portions existed, leading to complete wall collapses.

(a)

(b)

Figure 3-6 Damage due to storm surge at (a) the Department of Veterans Affairs hospital, and (b) First Baptist Church, in Gulfport, MS (Photo credit: (a) Habib Rahman, National Research Council of Canada, (b) Jack Hayes, USACE).

A one-story building in Long Beach, MS, made of solid, unreinforced masonry wall failed during Hurricane Katrina from high winds and likely[15] exposure to storm surge (Figure 3-7). The southern masonry wall collapsed along with half of the eastern wall. The corrugated metal deck roof supported by light-weight steel trusses was missing from half of the structure. Storm surge could have been the cause of failure because the shore area of an inlet is located behind barriers across the street to the south, but storm surge levels were not apparent. Debris from the building failure had been removed at the time of the reconnaissance as shown in the figure.

[15] The terms *possible, apparently,* and *likely* refer to increasing levels of supporting observations or technical certainty in the findings. These determinations are made based on visual observations and engineering judgment, and not on the basis of analytical, numerical, or statistical calculations.

Figure 3-7 Collapse of solid, unreinforced masonry walls in Long Beach, MS (Photo credit: NIST).

In New Orleans, a metal-framed aircraft hangar at the Lakefront Airport partially collapsed apparently[15] as a consequence of a reinforced, infill masonry wall collapsed into the structural steel frame. This building had a reinforced CMU wall with fully grouted cores. The wall along the north face of the building was 8 in thick with a 12 in. foundation wall and was reinforced with #5 vertical bars at 16 in. centers. However, the vertical bars in the wall and the foundation only overlapped each other by as little as 3 inches, a length that would not satisfy Masonry Standards Joint Committee reference standards for a lap splice (Ref. [2] sec. 2.1.10.3). This wall was within 20 ft of a sea wall that was overtopped by storm surge during Hurricane Katrina. The wall failed in large sections along the horizontal joint at the short lap splice near the base of the wall and collapsed into the steel frame, causing the columns to buckle. The two-story steel frame along the north face collapsed almost completely, and the northeast portion of the primary hangar framing also collapsed (Figure 3-8).

(a) **(b)**

Figure 3-8 (a): Partial collapse of aircraft hangar apparently[15] as a result of the collapse of a CMU infill wall. (b): 3 in lap splice at base of collapsed CMU wall (Photo credit: Ed Huston, Smith and Huston, Inc.)

Strong winds in areas of the NIST-led reconnaissance not exposed to storm surge also induced damage to masonry walls. A two-story, steel framed warehouse in Beaumont, TX, with unreinforced and ungrouted masonry block wall infill failed due to wind loads acting on the roof parapet wall (Figure 3-9). The winds apparently[15] blew the parapet wall over, causing failure of the entire masonry block wall on the second floor. Similar failures of masonry parking deck wind screens were observed in New Orleans: one of the three walls that failed showed evidence that adequate reinforcement and grouting of cells had not been followed, thus likely[15] contributing to the collapse. These types of failures of masonry block walls exemplify the need for adequate reinforcement and anchoring of the walls to the steel structure or roof diaphragm.

Figure 3-9   Failure of a non-load bearing masonry wall in Beaumont, TX (Photo credit: NIST).

The Gaston Hewes Recreation Center in Gulfport, MS, stands about 0.6 miles from the coast (Figure 3-10). This 1974-built single-bay, single-story metal-framed building had CMU exterior walls backed by perimeter reinforced concrete columns anchored to a concrete slab foundation with four anchor bolts. The NIST-led reconnaissance team observed severe damage due solely to wind, with collapse of the windward masonry exterior wall, partial collapse of the leeward wall and the supporting reinforced concrete columns, and damage to the curtain wall frame near the entrance.

Figure 3-10   Damage to Gaston Hewes Recreation Center in Gulfport, Mississippi (Photo credit: NIST).

The Port Arthur YMCA experienced a unique failure of a masonry wall. The building consists of a metal frame with in-fill masonry block wall. It was unknown if the wall was grouted or not. A glass double door opening into the swimming pool area at the northeast corner of the building failed, allowing the room to pressurize, which buckled the end wall of the building outward about 18 in.

The NIST-led reconnaissance team observed several old (pre-1930s) unreinforced brick masonry wall buildings that had partially collapsed in New Orleans, LA, and Port Arthur, TX. Failure likely[15] initiated at the rooftop parapets, which were pushed outward by the wind taking large portions of the exterior wall with them. Most of these buildings were unoccupied, but their collapse posed a risk to other property. For example, the debris from the partial collapse of a building in New Orleans, LA, (Figure 3-11) crushed three cars.

Figure 3-11 Partial failure of a load-bearing masonry wall in New Orleans, LA (Photo credit: NIST).

In Port Arthur, TX, high winds toppled several unreinforced brick parapet walls, causing failure of the unreinforced brick masonry facades (Figure 3-12). The complete collapse of an unreinforced masonry building in Gulfport, MS, was apparently[15] due to winds during Hurricane Katrina (Figure 3-13).

(a) **(b)**

Figure 3-12 Failure of masonry parapet walls along the roof of buildings in Port Arthur, TX, (a) subsequent partial failure of exterior wall, (b) subsequent collapse (Photo credit: Jon Heintz, Applied Technology Council).

Figure 3-13 Collapsed unreinforced masonry building in downtown Gulfport, MS (Photo credit: NIST).

Collapse or partial collapse of masonry walls and masonry buildings is commonly observed in earthquakes. Remediation measures employed in seismic regions (e.g., parapet braces, wall reinforcement, addition of wall anchors, etc.) may mitigate the risk posed by this type of construction in hurricane-prone regions. Typical seismic remediation measures could potentially address failures related to flexural demands on unreinforced masonry walls and separation between roof or floor diaphragms and the walls. Although wind, storm surge, and seismic loads and the structural response they induce have important fundamental differences, the application of seismic design methods and details to improve the resistance of existing unreinforced masonry construction to extreme wind loading and possibly storm surge should be evaluated.

3.1.3 Metal Buildings

The NIST-led reconnaissance team observed damage to a few metal buildings in the study region ranging from minimal damage to partial collapse due to high winds. These buildings were typically 20 ft to 40 ft in height, constructed with steel frames spaced between 20 ft and 30 ft on center on a concrete slab, had steel Z-channel purlins spaced about 5 ft to 6 ft on center to support a corrugated metal roof, and had the same type of corrugated metal hung on girts for the walls. Damaged buildings of this construction type experienced buckled roof purlins from wind uplift on the roof and wind pressure on the windward wall.

Wind effects at the Port Bienville Industrial Park in Jackson Landing, MS, caused permanent damage to the windward wall and the metal roof (Figure 3-14). Two large bay doors were missing, the windward wall was bent inward, and buckled purlins were observed, which suggests the roofing material (corrugated metal) was missing in the buckled area.

Figure 3-14 Permanent deformation of the windward wall inward and buckled purlins observed at the Port Bienville Industrial Park (Photo credit: NIST).

The NIST-led reconnaissance team observed collapse of an end bay between frames due to wind effects on two structures. The first structure was a storage warehouse located between Cuevas and Long Beach, MS. The intermediate columns that supported the end frame had only two 5/8 in. diameter bolts at the base connections to the concrete slab. The columns along the windward wall had failed inward due to loss of lateral support resulting from either the buckling of the purlins or the failure of the column base connections. Most of the corrugated metal walls had detached from the girts and columns (Figure 3-15).

Figure 3-15 Collapse of the entire end bay of a steel-frame warehouse from wind pressure near Long Beach, MS (Photo credit: NIST).

The second partial building collapse observed was at the Gulfco Machine and Supply Co. in Beaumont, TX (Figure 3-16). The roof purlins had buckled upward, and the windward wall collapsed inward even though angle bracing was provided between the purlins and the bay frames for added vertical support. A 3 in. by 3 in. steel angle was still securely attached to the floor slab near the corner column's base connection. The failed portion of the building had been removed, so it was unclear if the column to slab connection detail contributed to the column failure. A larger moment resisting frame warehouse at the same facility but about two hundred yards to the east lost the metal roof on the windward bay and had no evidence of buckled purlins or end bay frame failure. Round metal bar cross braces (about ¾ in diameter) were observed just under the purlins in the end bay, spanning between the frames.

Figure 3-16 Buckled purlins and collapse of a portion of the end bay of a steel-frame warehouse from wind pressure in Beaumont, TX (Photo credit: NIST).

The American Legion post in Gulfport, Mississippi, is a two-story, metal building that suffered partial collapse and the complete loss of all interior and exterior finishes at the first story. It was located within a few hundred feet of the Gulf shore, suggesting that storm surge caused much of the damage. However, damage to exterior soffits and roofing, and observed corrosion to the base plate of a partially collapsed portion of the building suggests that high winds and maintenance issues may have also contributed to the failure (Figure 3-17).

Figure 3-17 Damage to a metal building in Gulfport, Mississippi (Photo credit: Keith Porter, Scawthorn Porter Associates).

3.1.4 Casino Barge Structures

Mississippi casinos are permanently moored facilities, rather than vessels in service, erected on one or more barges along the coastal waterways. While their installations are subject to permitting by the U.S. Army Corps of Engineers and limited oversight by the U.S. Coast Guard, neither agency has specific design requirements for the mooring systems. The Mississippi Gaming Commission did, however, require that the mooring system be designed to withstand 155 mph winds and a storm surge height of 15 ft. Thirteen casino-barge structures (including two under construction on the eastern waterline of Biloxi) were in place along the Mississippi coast before Hurricane Katrina. These structures were steel-hulled barges (plan areas ranging from roughly 20 ft by 50 ft to over 200 ft by 600 ft) with a two- to five-story steel frame superstructure clad with exterior insulation and finish systems (EIFS) on metal stud framing. The barges were connected via walkways to high-rise hotel buildings. Severe damage to the EIFS was observed on most of these structures.

Seven of the thirteen casino barges broke completely free from their moorings and were deposited at various distances, mostly inland, by Hurricane Katrina. Three casino barges broke partially free from their moorings but stayed in place and damaged adjoining structures by rocking and jostling. One barge partly broke free with the broken-free part landing inland, one barge sank, and only one barge survived the storm surge without losing its moorings or sinking.

Eleven of the thirteen casino barges were located in Biloxi, MS. Two of these barge structures, moored between a hotel structure and a 5-level, precast parking garage to the east (Figure 3-18), broke partially free of their moorings, but were confined to their surroundings. Rocking action and movement of both barges caused extensive damage to the structures on land. The smaller of the two barges, whose inboard edge rested on the piers of the parking structure at the time of observation, appeared to have pushed one or more columns of the parking structure inward, causing partial collapse of a 5-level by 1-bay segment adjacent to the barge. The precast, reinforced concrete parking garage experienced no other discernable damage from storm surge or wind (discussed previously in Section 3.1.1). Observation of the steel reinforcing of the fractured columns showed little confining steel. However, it is not known whether ductile detailing could have prevented the collapse.

Figure 3-18 Partial collapse of a precast reinforced concrete garage due to impact by a Biloxi, Mississippi casino barge (Photo credit: NIST).

Barges that broke completely free of their moorings were lifted inland by storm surge and caused extensive damage. Figure 3-19 depicts the distances traveled by three of the barges. The barge at the right of Figure 3-19 (furthest east) floated about one-quarter mile inland before coming to rest in an open area next to a circular church structure (see also Figure 3-20). The two other casino barges in Figure 3-19 were moored parallel to one another on the southern side of a hotel. The hulls of both casino barges were filling with water while they were floating inland, as evidenced by large gashes observed alongside the hulls caused by the moorings and by testimony of local contractors hired to dismantle the barges for scrap metal. The longer barge destroyed a house before coming to rest, and the smaller barge to the west collided with a five-story building just north of coastal U.S. Route 90 (see also Figure 3-21a). The building experienced partial collapse of the southeast corner of the lower four stories. The top story at this corner did not collapse, likely[15] because of a redundant load path that transferred gravity loads to bays in both directions. Another, four-story hotel structure was impacted by a casino barge that floated more than half a mile from its original location (Figure 3-21b). Figure 3-22 shows a barge in Biloxi, MS, that did not break free from its moorings but rather sank in place.

Figure 3-19 Movement of three casino barges that broke completely free from their moorings and were deposited inland (Photo credit: NOAA).

Figure 3-20 Casino barge (arrow) in Biloxi, MS, broke free of its mooring and floated about one-quarter mile inland (Photo credit: NIST).

(a) (b)

Figure 3-21 Partial collapse of (a) a historic, cast-in-place, reinforced concrete hotel, and (b) a four-story hotel structure caused by two separate casino barges (arrow) that floated inland in Biloxi, MS (Photo credit: NIST).

Figure 3-22 A casino barge in Biloxi, Mississippi, that sank in place (Photo credit: Keith Porter, Scawthorn Porter Associates).

3.2 ROOFING

A wide variety of roofing systems, typical of those used in the United States for commercial and industrial roofing including those on schools, hospitals, and apartments, was observed on major buildings in all areas visited by the NIST reconnaissance. This section of the report provides an overview of these observations which included the following roofing systems:

- Bituminous built-up membrane roofing (BUR) with aggregate surfacing,
- Atactic polypropylene (APP) modified bitumen (MB) membranes (generally with granule surfacing),
- Styrene-butadiene-styrene (SBS) modified bitumen (MB) membranes (generally with granule surfacing),

- Synthetic single-ply membranes including gravel ballasted loose-laid, mechanically attached, and totally adhered systems,
- Metal roofing (including standing seam), and
- Sprayed polyurethane foam (SPF) roofing.

Performance of the major-building roofs during Hurricanes Katrina and Rita was wide-ranging with some showing little, if any, damage even when located along the coast, whereas others sustained considerable damage. Overall, it was roughly estimated that about 20 percent to 30 percent of the commercial and industrial roofing observed during the reconnaissance was damaged in some fashion. It is noted that this extent of damage occurred even though the wind speeds were generally below design levels (see tables 2-2a and 2-2b). For individual buildings (or wings of large buildings), the extent of damage ranged from less than 5 percent of the roof area to greater than 50 percent or more of the roof area. For a small number of buildings, the roof was essentially totally stripped of its covering. A notable example was a multi-family apartment building that lost its low-sloped membrane system. Overall, the main damage to the roofs of major buildings included failure of flashings, puncturing of roof coverings or the total roof system, blow-off of the roof coverings often accompanied by loss of insulation, blow-off of the insulation and covering accompanied by loss of deck, failure of metal roof panels with and without damage to structural members, and combinations of these types of damage.

3.2.1 Membrane Roofing Systems

Conventional built-up bituminous roofing with and without aggregate surfacing and polymer-modified bituminous roofing generally with granule surfacing were the predominant major building roof systems in the Hurricanes Katrina and Rita damage zones. The predominant damage to this membrane roofing was blow-off of some portion of the membrane. Such damage was typically, although not universally, initiated at the perimeter flashing. In general, these membrane roofing failures were attributed to one or more of the following reasons: (1) poor performance of perimeter metal flashing, (2) inadequate inter-laminar strength of insulation and inadequate adhesion between membranes and insulation, and (3) non-standard attachment of bituminous base sheets to decks and other substrates. These three modes of damaged roofing have commonly been observed in past hurricanes and other high wind events. They are associated with selection of a membrane roofing system that does not have adequate resistance to the winds expected for the given geographic location, or misapplication of the roofing including inadequate fastening and insufficient heating of bituminous roofing, particularly polymer-modified systems.

In this regard, where detailed observations of roofing damage on major buildings were made, the NIST reconnaissance team often observed that the installation was not consistent with currently accepted practice as given in manufacturers' literature and trade association guidelines. For example, in many cases, 20 percent to 40 percent of the expected total number of fasteners was omitted. A specific example is given in Figure 3-23 showing a lack of fasteners in the bottom ply of a mechanically attached bituminous membrane. In other cases, asphaltic materials were not sufficiently heated during installation as illustrated in Figure 3-24, which shows the bottom ply of a blown-off, heat-applied, polymer-modified bituminous membrane.

Figure 3-23 Irregularly spaced nailing on this failed hot-applied built-up roofing membrane had approximately 40 percent fewer nails than specified by a typical manufacturer (Photo credit: Robb Smith, Amtech Roofing Consultants).

Figure 3-24 Had this failed heat bonded polymer-modified bitumen membrane been heated in accordance with acceptable practice, the plastic film and white markings would not be present (Photo credit: Robb Smith, Amtech Roofing Consultants).

The paragraphs that follow provide selected examples of both well-performing and damaged membrane roofing. They demonstrate that (1) acceptable membrane roofing performance in winds such as those experienced in Hurricanes Katrina and Rita, which were, as mentioned, generally below design levels, can be accomplished, and (2) inadequate design, materials, and installation all contribute to unacceptable performance under such wind speeds.

An example of a successfully performing roof was that on the New Orleans Arena (Figure 3-25). As observed from ground level, this SBS modified bitumen membrane system, which was about 6 years old, was in good condition without evidence of wind induced damage. In contrast to this example, within the New Orleans area, a number of roofs on major buildings sustained considerable damage. For example, note in the right background of Figure 3-25 the New Orleans Superdome, which lost its flexible membrane during Hurricane Katrina (see below).

Figure 3-25 The New Orleans Arena, which has an SBS modified bitumen membrane, withstood the Hurricane Katrina winds without damage. (Photo credit: Robb Smith, Amtech Roofing Consultants).

An example of damage to a modified bituminous membrane wherein the perimeter metal flashing in all likelihood first failed and peeled up and away from the edge of the building with subsequent loss of the membrane is given in Figure 3-26. This 10-year to 15-year old roof, which was inaccessible, was on an elementary school roof in Port Arthur, TX. No debris that could be examined for evidence of failure initiation was found on the windward side of the building. Nevertheless, observations made of the building and the debris pile found along the downwind side of the building suggested that the roof system consisted of a concrete deck on which at least one layer of perlite insulation had been adhered with hot asphalt. A bituminous membrane with a polymer modified cap sheet was installed on the insulation using hot asphalt. At the location where the membrane blew over the edge of the building, the damaged perimeter metal flashing was observed to have been inadequately fastened in place; for example, no fascia cleats were present, and the screws installed through the fascia metal into wooden nailers were too few (about one every 0.6 m (2 ft)). The membrane system blew-off through peeling within the perlite insulation (i.e., cohesive failure) near the top of the insulation board.

Figure 3-26 Blow-off of a bituminous roofing membrane where failure was precipitated at the edge metal flashing, Port Arthur, TX (Photo credit: NIST).

In contrast to the school shown in Figure 3-26, two wings of a hospital in Pascagoula, MS, had a built-up bituminous membrane roofing systems estimated to be 5 years to 10 years old. This roofing system on both wings was damaged at a windward corner apparently[15] due to lack of adequate interlaminar adhesion strength of the membrane and insulation components to resist the wind-imposed uplift forces. For both wings, the perimeter metal flashing in the area of the damaged membrane did not fail. The membrane had been adhered in place to a layer of perlite insulation, which was adhered to a layer of felt-faced polyisocyanurate insulation board (i.e., iso-board), which was adhered to the roof deck. Hot asphalt was the adhesive in all cases. The membrane blow-off occurred primarily within the perlite insulation near its top surface, although there were some areas that delaminated either at the interface of the membrane with the perlite insulation, or at the interface of the felt-facer and the iso-board, or at the interface of the iso-board and the roof deck. In contrast to these two wings of the hospital, another wing sustained damage to perimeter metal flashing along a windward edge. In this case, the outer fascia was bent up and back from the building; however, the damaged perimeter flashing remained in place, and the bituminous membrane of the wing was also intact.

Observations of damaged perimeter metal flashing that was bent up and back from the building by the wind but remained in place without damage to the membrane were seen often throughout the Hurricanes Katrina and Rita damage zones. An example is given in Figure 3-27, which was taken at a school in Port Arthur, TX. Note that there is no perimeter cleat or other type of fascia metal attachment present in this photo.

Figure 3-27 Example of perimeter metal flashing that was bent up and back from the building but without damage to the membrane, Port Arthur, TX (Photo credit: NIST).

A small commercial building in New Orleans totally lost its bituminous roofing membrane. As shown in Figure 3-28a, this low-sloped roof system had a roof deck (which was also the membrane substrate) consisting of wood fiber cementitious panels that were held in place on the structural support only by their own weight. Note in the foreground of Fig 3-28a that one of these panels was lifted from its support at a roof overhang that was open to the walkway below. Such lifting of unattached wood fiber cementitious panel decks at roof overhangs was seen at a number of other buildings in the hurricane damage zones. For the roof in Figure 3-28a, the blow-off of the membrane likely[15] occurred due to uplift and tearing of the membrane base sheet from around the fasteners that secured the membrane to the wood fiber cementitious panels. A number of fasteners were found embedded in the wood fiber cementitious panels (Figure 3-28b); however, the number found was insufficient for proper attachment. Note, for example, in Figure 3-28b that the center of the wood fiber cementitious panel shown is essentially devoid of fasteners. Assuming that the fasteners shown at the left and right edges of Figure 3-28b are those that attached the edges of a membrane base sheet, then according to current guidelines two additional staggered rows of fasteners (for securing the center of the base sheet) would have been found embedded in the deck panel, instead of the single fastener shown. No evidence was seen that additional fasteners had ever been in place.

Figure 3-28 Blow-off of a bituminous roofing membrane from a wood fiber cementitious panel deck in New Orleans (a), precipitated by uplift and tearing of the membrane base sheet from around the fasteners (arrows) (b). An insufficient number of fasteners had been installed (Photo credit: Robb Smith, Amtech Roofing Consultants).

A small commercial metal building in New Orleans sustained significant damage to its modified bituminous membrane system (Figure 3-29). Although the roof and the interior of the building could not be accessed, damage to the perimeter metal flashing on the downwind side of the building was observed from the parking lot (Figure 3-29a). The damage to this flashing likely[15] occurred when the membrane blew over the edge of the building, as evidenced by a debris pile adjacent to the building and which contained damaged membrane in addition to water soaked materials that were seemingly removed from the building (Figure 3-29b). Although the type of deck, and consequently the exact mode of fastening of the membrane, was not known, examination of the debris pile showed that an insufficient number of fasteners were used to secure the membrane to the deck.

Figure 3-29 A commercial metal building in New Orleans that suffered damage to its modified bituminous membrane roof likely[15] as a result of insufficient fastening to the deck. Note in (a) damage to the edge detail (arrows). Note in (b) the debris pile, found below the damaged edge detail, containing sections of a modified bituminous membrane (Photo credit: Robb Smith, Amtech Roofing Consultants).

Few flexible synthetic single-ply membranes were seen in the Hurricanes Katrina and Rita damage zones. One such roof is shown in Figure 3-30, which shows an adhered EPDM (ethylene propylene diene terpolymer) membrane system (of unknown age) that was installed on a commercial building in New Orleans. The small pieces of rubber on the membrane surface are patches that were made to repair punctures (i.e., leaks) in the EPDM sheet that were caused by wind-borne debris. Note the lighter colored EPDM surface in the vicinity of the patches. This was due to the solvent-cleaning/priming of the punctured EPDM surface that was performed before application of the patches. Although not visible in Figure 3-30, there were some small pieces of broken window glazing on sections of this EPDM roof. This broken glazing was attributed to wind-borne debris also breaking window glazing of a nearby building.

Figure 3-30 Adhered EPDM membrane system in New Orleans. The membrane was punctured by unknown wind-borne debris (Photo credit: Robb Smith, Amtech Roofing Consultants).

The Louisiana Superdome also had an adhered EPDM membrane roofing system (Figure 3-31); much of this membrane was lost during Hurricane Katrina. As described to reconnaissance team members by engineers familiar with the renovation, the entire Superdome roofing system consisted of a metal deck topped with sprayed polyurethane foam (SPF) and an elastomeric coating. Rigid polyisocyanurate board (i.e., iso-board) insulation having a facer sheet was mechanically fastened through the SPF and into the metal deck. An EPDM single ply membrane with white coating was fully adhered to the iso-board insulation. Most of the EPDM was observed to have been blown off by Hurricane Katrina. In those areas of the roof where the EPDM membrane was not adequately adhered to the iso-board insulation, the EPDM membrane blew off the structure with the insulation facer undamaged.

Figure 3-32 shows a section of EPDM membrane that was found on the roof of a building downwind from the Superdome. Note the tan colored surface representing the adhesive used to bond the EPDM sheets to the mechanically attached iso-boards. The hexagonal-shaped areas in the adhesive layer are spots where the adhesive was applied on top of the mechanical fasteners used to attach the iso-boards to the Superdome deck. The roof of the building on which the section of EPDM was found also contained small pieces of broken window glazing. A few pieces are visible in Figure 3-32 (arrow). A nearby building down-wind of the Superdome had considerable glazing breakage that was attributed to wind-borne debris. Note that no aggregate typical of that used to surface built-up roofing was found on the roof that contained the damaged EPDM from the Superdome and pieces of broken glazing.

Figure 3-31 Louisiana Superdome. Gray areas are remaining polyisocyanurate insulation with a gray/black facer. Rust color is the original sprayed polyurethane foam (SPF). Tan is new SPF. The white area is a small section of white coated EPDM membrane that was not blown off. Before Hurricane Katrina, only the white coated EPDM membrane would have been visible on the roof (Photo credit: NIST).

Figure 3-32 Section of damaged EPDM membrane found on the roof of a building downwind from the Superdome. The tan color represents adhesive used to attach the EPDM to the insulation on the Superdome. The white specs (arrow) are pieces of broken glazing from windows of a nearby building that was also downwind from the Superdome (Photo credit: Robb Smith, Amtech Roofing Consultants).

3.2.2 Metal Roofing Systems

Many metal roofs throughout the Hurricanes Katrina and Rita damage zones performed well, particularly standing seam metal roofs installed on commercial and industrial buildings and schools. A clear example is the standing seam metal roof of the Pass Christian High School (Figure 3-33), which was located less than 1.5 km (1 mi) from the coast. Although this building was located near the coast east of Bay St. Louis where some of Hurricane Katrina's highest winds, yet still below design levels, may have been experienced (Table 2-2a), the roof sustained the winds without damage. In contrast, the first floor of the school sustained considerable due to storm surge and accompanying wave action and/or flooding.

In many cases where damage to metal roofing occurred, it was limited to a small portion of the roof area whereby some panels on the given structure were bent away or blown off. Often such damage occurred near a windward edge of the roof where the attachment of the perimeter metal flashing was likely[15] insufficient. Three examples are given in Figs. 3-34a, 3-34b, and 3-34c. The first shows limited damage to a peak on the library of the Orange Texas campus of Lamar State University; the second shows the windward gable end of the roof on a wing of Gulfview Elementary School near Waveland, MS; and the third shows similar damage at Hancock High School in Kiln, MS.

Figure 3-33 Standing seam metal roof in the coastal region of Pass Christian, MS, that sustained Hurricane Katrina without damage (Photo credit: NIST).

Figure 3-34 Limited damage to standing seam metal roofs at (a) Lamar State University in Orange, TX (Photo credit: Dominic Sims), (b) at Gulfview Elementary School near Waveland, MS (Photo credit: NIST), and at (c) Hancock High School in Kiln, MS . Damage occurred at the edge of the roofs along the windward sides of the buildings (Photo credit: Robb Smith, Amtech Roofing Consultants).

The following paragraphs provide further examples of typical observations of metal roofing made by the NIST reconnaissance team. At Anderson Elementary School in Orange, TX, five 18 in. deep steel roof trusses and the attached metal-paneled roof panels had been removed from the single-sloped, second story roof of the main building. The removed trusses were stored in the parking lot at the time of observation and showed evidence of upward buckling likely[15] due to uplift wind pressures. The roof area, approximately 25 ft by 35 ft in length, was covered by plastic at the time of the visit (Figure 3-35) and new, 24 in. deep steel trusses had been installed in the same location as the original trusses. Damage by water infiltration to the building's interior was extensive.

Figure 3-35 Loss of open-web roof trusses and metal-paneled roof deck at Anderson Elementary School in Orange, TX. Note the pictures show the replacement trusses and the temporary plastic covering (Photo credit: NIST).

Roofs on many metal buildings in the NIST reconnaissance area were comprised of corrugated metal sheets attached to purlins that spanned between the structural steel frames. These metal sheets were completely blown off from large portions of the roofs by uplift wind pressures. Examples include a three-story, open-ended steel framed boat hangar near the Pass Christian Long Beach Wastewater Treatment Plant (missing the windward roof along the full length of the structure and the top six feet of metal wall paneling, (Figure 3-36a), and a 200 ft by 100 ft hangar at the Southeast Texas Regional Airport of Port Arthur, TX, (missing an entire half of the roof and a 5 ft width up to the first purlin along the windward roof's edge, Figure 3-36b). These roof failures were likely[15] due to internal wind pressures created by openness of the boat hanger structure or by removal of the airport hanger doors.

(a) (b)

Figure 3-36 Loss of corrugated-metal roofing structures on large, metal buildings in a) Pass Christian, MS, and b) Port Arthur, TX (Photo credit: NIST).

At another building at the Southeast Texas Regional Airport of Port Arthur, TX, panels on the barrel roof at the windward end of a half-cylinder, metal airport hangar were torn off the main wind resisting structure (Figure 3-37). Wind-borne debris from this failure was observed.

Figure 3-37 Damaged metal panels on a barrel roof at the Southeast Texas Regional Airport, Port Arthur, TX (Photo credit: NIST).

A light-metal-framed aircraft hangar at Stennis International Airport near Bay St. Louis, MS, experienced roof damage wherein the roof deck and purlins bent upward and peeled off by wind pressure (see Section 4.2.5, Figure 4-56). This single-bay light steel frame hangar had Z-shape steel purlins and a light-gage metal roof.

The Third District Fire Headquarters in New Orleans is a four bay building with a single story area for the living quarters. The building was constructed with steel columns and masonry infill walls with a brick façade. Steel box section trusses support the single slope roof over the apparatus bays. The steel roof deck was supported on I-beams attached to the trusses. Four-inch (4 in.) thick insulating panels were supported on the roof deck and a metal roof over top. The metal roof consisted of sections that attached via screws 48 in. on center to hat sections and the individual, 16 in. wide panels were connected together with tabs that were attached by screws 48 in. on center. The roof continued down the side of the building on the low side of the bays. Half of the roof panels over the fire equipment bays was peeled back by winds during Hurricane Katrina, beginning at the peak of the roof and continuing down over the side of the building

(Figure 3-38). Connection to the roof diaphragm appeared to have been inconsistent. Some segments had short screws at 48-inch centers that connected the panels to the diaphragm; in others, screws were not apparent for 20 feet. The foam insulation remained in most of the exposed areas, and the roof deck also remained in place. Water marks observed in the building interior indicated that flooding to a depth of approximately 8 in. occurred due to the hurricane; the building was not in operation at the time of the NIST reconnaissance due to the flood damage.

(a) (b)

Figure 3-38 New Orleans Third District Fire Headquarters. (a): roof damage. (b): apparent lack of fasteners (Photo credit: Keith Porter, Scawthorn Porter Associates).

The extensiveness of metal roofing failures indicates that many were caused by inadequate installation or poor design. The Fairway Plaza strip mall in Port Arthur, TX, lost its entire standing-seam, metal roof (Figure 3-39a), exposing the entire interior to rain. Large quantities of metal roofing material, apparently[15] from the single-story, low-sloped roofs of many nearby commercial buildings, were observed along the road side in West Orange, TX (Figure 3-39b).

Figure 3-39 Failure of metal roofs in (a) Port Arthur, TX, and (b) West Orange, TX (Photo credit: NIST).

At the Belle Chasse Middle School in Belle Chasse, Louisiana, approximately 15 feet of a metal roof peeled back from the eave along the northeastern edge of the building. This metal roof was constructed of 24 gage, 16-inch wide standing-seam metal panels clipped to purlins with 16-gauge clips. At the time of observation, the roofing from the eaves to the peak (approximately 40-foot length) had been removed, revealing locations where clips were installed. Where the damaged metal panels had peeled back during

Hurricane Katrina, the required clips were missing from the second lowest purlin at the right eave of the building with no evidence that they had been installed (Figure 3-40). At locations on purlins higher up on the roof, the clips had been installed.

Figure 3-40 Missing roof clips (arrows) at the right eave of the Belle Chasse Middle School in Belle Chasse, LA. No evidence was seen that the clips had ever been installed (Photo credit: Robb Smith, Amtech Roofing Consultants).

The Robert A. "Bob" Bowers Civic Center in Port Arthur, Texas, had a low-sloped bituminous membrane roof with steep sloping metal panel mansards along some sides of the building (Figure 3-41a). Both the membrane roofing and mansard paneling were damaged during Hurricane Rita, although specific details were not ascertained. The low-sloped roof could not be accessed at the time of the inspection. Also, temporary repairs had been made and some debris had been removed, as evidenced by no metal panels being found in the debris piles. Nevertheless, roofing debris at the building provided evidence that the low-sloped roof construction included a lightweight concrete fill, a layer of perlite board insulation that was mechanically attached to the fill, and a bituminous membrane that was adhered with hot asphalt to the perlite board. The lightweight concrete fill apparently[15] had been damaged, because the debris pile near the building's front entrance contained broken pieces of this component (Figure 3-41b). This roof failure caused extensive water damage to the building's interior.

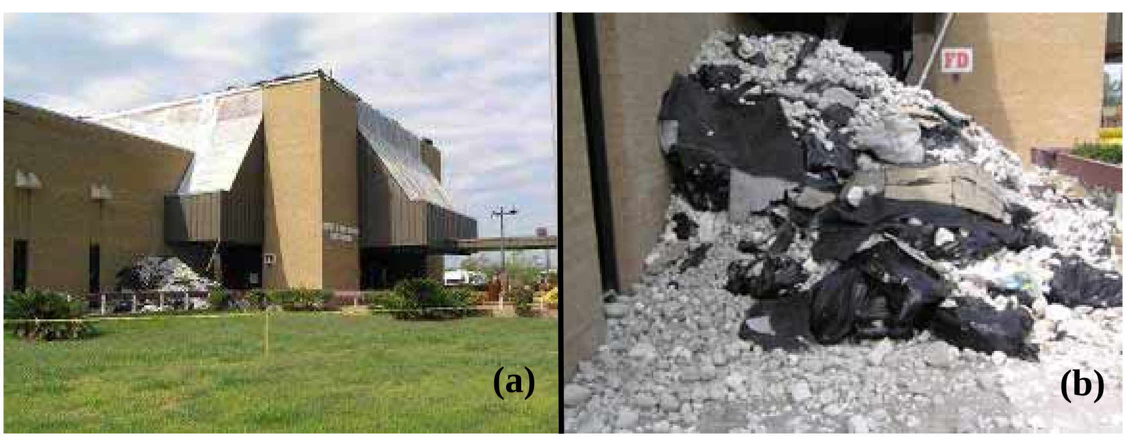

Figure 3-41 Failure of low-sloped bituminous membrane roof along with a metal panel mansard roof at Robert A. "Bob" Bowers Civic Center in Port Arthur, TX (a). The low-sloped roof construction included a lightweight concrete fill that may have been damaged during Hurricane Rita (b) (Photo credit: NIST).

3.2.3 Spray Polyurethane Foam (SPF) Roofing Systems

A number of spray polyurethane foam (SPF) roofing systems were observed in the Pascagoula, MS, area. Some of these roofs were estimated to be about 20 years old. With one minor exception, all were found to have sustained Hurricane Katrina extremely well without blow-off of the SPF or damage to flashings. In the case where damage was observed, the SPF had been applied to a wood fiber insulation that had been mechanically fastened to the metal deck with an inadequate number of fasteners. Failure likely[15] occurred when the insulation board delaminated from the deck. The area of the failure was less than 1 percent of the total roof area.

3.2.4 Other Roofing Systems

Some major buildings had steep-sloped roofs with wood-framed roof trusses that were susceptible to the strong winds of Hurricane Rita. For example, the windward wooden truss (or possibly the two end trusses) of the two-story recreation center belonging to the Lady of Guadeloupe Catholic Church in Port Arthur, TX, collapsed (Figure 3-42). The gabled, shingled roof had a ridge line parallel to the hurricane wind direction. Damage to about 20 ft of roof along the ridge line caused extensive water damage to the building's interior.

Figure 3-42 Failure of the windward, wooden truss in a recreation center in Port Arthur, TX (Photo credit: NIST).

3.2.5 Rooftop Equipment

Damage to rooftop equipment such as fans and ventilators and to architectural screens around mechanical equipment (i.e., mechanical screens) was observed in all locations included in the reconnaissance. In some cases, such equipment and sections of these mechanical screens became wind-borne, causing damage to the building itself, or to other buildings downwind. Moreover, loss of rooftop equipment created entry points for rainwater that resulted in significant water damage to the interior of the building and its contents (e.g., the Louisiana Superdome).

At the New Orleans Hyatt Regency, hoods were missing from five of six roof vents (Figure 3-43), with some damage apparent to the framing that would have connected the hoods to the vents at the point where fasteners would normally be. Looking out from the roof of the New Orleans Hyatt Regency, several high-rise buildings in the vicinity were also seen to have suffered extensive damage to rooftop mechanical equipment and mechanical screens.

Figure 3-43 Five of six vents on the roof of the New Orleans Hyatt Regency were missing their hoods. Note the remaining hood in the background (arrow) and the missing cover of the fan motor of the vent in the foreground (arrow) (Photo credit: Keith Porter, Scawthorn Porter Associates).

Two large air handling units were observed in parking areas of a building in Beaumont, TX (Figure 3-44). The units appeared to have been blown off a nearby roof (a 15-story building next to the parking garage). The bolts at the base of the units were fractured in tension.

Figure 3-44 Rooftop equipment blown off a neighboring structure in Beaumont, TX (Photo credit: NIST).

The newest building at the Memorial Hermann Baptist Hospital in Orange, TX, was constructed in 1993. The hospital had several return air ducts on the roof that were lost due to wind during Hurricane Rita. This allowed significant amounts of water to enter the hospital causing extensive damage to drywall and rendering the pharmacy, laboratory spaces, and kitchen areas unusable until complete remediation. The 40-foot high atrium was closed at the time of observation because of safety concerns over the drywall at the ceiling and on the walls. The hospital was expected to remain closed with the exception of the emergency room for one or two weeks after the NIST-led reconnaissance visit.

3.3 WINDOW SYSTEMS

Window systems include the glazing (generally observed to be ¼-inch heat-strengthened or tempered, single-pane or insulated/double pane) and the window framing. Most of the damage to window systems observed during the NIST reconnaissance was from wind-borne debris. Specifically, many buildings in areas of the NIST reconnaissance had roofs with aggregate surfaces. The aggregate typically became wind-borne during the hurricanes and caused damage to the windows of neighboring downwind buildings. A couple of the observed buildings also experienced water infiltration around the window systems.

3.3.1 Wind-Borne Debris

Wind-borne debris is a concern during any strong wind event because of its potential harm to people and its destructive effects on any object in its path, e.g., cars, buildings, and window systems. Countless buildings with boarded windows, especially in the more densely populated areas such as New Orleans, LA, were observed. Boarding of windows was the predominant temporary repair for broken glazing.

Approximately 75 percent of the glass windows on the north façade of the New Orleans Hyatt Regency were broken during Hurricane Katrina (Figure 3-45a). Wind-borne debris was the primary cause. The aggregate was found mixed with the glass in several hotel suites with broken windows (Figure 3-45b) was consistent with aggregate observed on the roof of the buildings immediately to the north. Extensive damage to window systems from wind-borne roof aggregate was observed in many other high-rise buildings in downtown New Orleans (Figure 3-45c).

(a) (b) (c)

Figure 3-45 Window system damage from wind-borne roof aggregate: (a) New Orleans Hyatt Regency, (b) the aggregate mixed with glass found in rooms, (c) upwind highrise building (Photo credit: Keith Porter, Scawthorn Porter Associates).

Wind-borne debris during Hurricane Katrina also caused damage to window systems in Gulfport, MS. Approximately 50 percent of the windows of the Memorial Hospital of Gulfport and the Hancock Bank building (Figure 3-46) were broken by roof aggregate and other types of wind-borne debris typical to hurricane level winds. For the Hancock Bank building, such debris may have originated from a severely damaged, unreinforced masonry building upwind.

Figure 3-46 Hancock Bank building (background) in downtown Gulfport, Mississippi, downwind (north) of partially collapsed unreinforced masonry building (Photo credit: NIST).

In Port Arthur, TX, the Memorial Ninth Grade School experienced extensive window damage during Hurricane Rita along one side of the building (Figure 3-47). The failures were directly attributable to wind-borne aggregate from the roof of the adjacent auditorium. In Orange, TX, windows on the south side of the third floor of the Orange County Courthouse were apparently[15] damaged by aggregate from a lower roof of the building.

Figure 3-47 Broken glass at Memorial Ninth Grade School in Port Arthur, TX. The gravel among the broken glass was consistent with that on the aggregate-surfaced roof adjacent to this school (Photo credit: Jon Heintz, Applied Technology Council).

3.3.2 Wind-Driven Rain

Water damage and disruption of facility operations were also caused by wind-driven rain from Hurricane Rita. At Memorial Hermann Baptist Orange Hospital in Orange, Texas, wind-driven rain penetrated the masonry facade causing water damage to interior walls. This was likely[15] a result of a window failure (due to wind pressure) that allowed the building to pressurize, which caused cracking of the exterior masonry wall on that floor. This damage combined with water from other sources to force closure of the hospital. At the Medical Center of Southeast Texas in Port Arthur, which opened in 2005, wind-driven rain penetrated the weatherproofing around windows that otherwise remained intact. This water combined with water from other sources to force temporary closure of the hospital. Similar observations were made at the Christus St. Mary Hospital in Beaumont, TX. As of mid-October 2005, three weeks after Hurricance Rita made landfall, the first two facilities were still being cleaned up and were available to provide only partial medical services to the surrounding communities. Wind-driven water penetration through otherwise undamaged cladding was a damaging occurrence that warrants further detailed study.

3.4 CLADDING

The strong winds during Hurricanes Katrina and Rita compromised many of the lighter-weight cladding systems, such as EIFS. Most of the hotel buildings in Biloxi, MS, lost portions of their EIFS in their upper levels, which caused wind-borne debris and water damage to the building. Wind-induced failures of other types of cladding, such as brick or stone masonry and metal curtain walls, were observed in the areas of the NIST reconnaissance, but were less prevalent than the EIFS failures.

3.4.1 Exterior Insulation and Finish Systems (EIFS) and Metal Curtain Walls

The EIFS was blown off the leeward sides of buildings in Biloxi, MS, New Orleans, LA, and Orange, TX. A few incidences of the damage were at an elevation subjected to storm surge, so water may have also contributed to the EIFS failure (Figure 3-48a). Commercial buildings in New Orleans also experienced damage to their EIFS, e.g., the AMC Palace Shopping Mall (Figure 3-48b). Similar damage to EIFS was observed at Lamar State University in Orange, TX. Many of these EIFS walls did not appear to be subject to substantial wind- or water-borne debris, suggesting that wind pressure alone caused the damage.

(a)

(b)

(c)

Figure 3-48 EIFS damage to (a) a hotel in Biloxi, MS and (b) the AMC Palace Shopping Mall in New Orleans, LA, and (c) a building at Lamar State University, in Orange, TX (Photo credit:(a) NIST; (b) Robb Smith, Amtech Roofing Consultants; (c) Jon Heintz, Applied Technology Council).

The St. Tammary Parish Government Administration Complex in Slidell, LA, is a six-story, reinforced concrete building. Six foot flood levels were observed inside the building. Flood damage included broken windows on the ground floor and a cladding panel of unknown material that was pushed into the building (Figure 3-49a). There was also extensive wind damage to the building, which included wind-borne debris between the first and second floors, a pushed-in cladding wall between the fourth and fifth floors on the windward side of the building (Figure 3-49b), broken windows at various locations and at various heights, a missing cladding panel between the fifth and six floor on the side of the building, and metal flashing damage around the roof perimeter.


(a) (b)

Figure 3-49 Damage to the St. Tammary Parish Government Administration Complex in Slidell, LA: (a) flood damage to the ground floor and wind-born debris, (b) pushed in cladding wall (Photo credit: NIST).

3.4.2 Masonry Veneer Cladding

Masonry veneer cladding consists of, for example, brick walls that act as an architectural façade to the building. It is anchored to the structural wall of the building by metal clips placed in the brick mortar and fastened to the building. Two brick cladding walls in Beaumont, TX, separated from the structural wall and collapsed outward during Hurricane Rita (Figure 3-50). The metal clips were observed to have failed either through pullout from the mortar, by rusting due to age, or by complete fracture.


(a) (b)

Figure 3-50 Wind-induced collapse of (a) a roughly 40 ft wide by 30 ft high and (b) a roughly 60 ft wide by 25 ft high, poorly anchored brick masonry cladding in Beaumont, TX (Photo credit: NIST).

A high-rise building in downtown New Orleans lost one of its marble panels (Figure 3-51). Wind likely[15] instigated this failure, which posed a serious risk to the immediate area.

Figure 3-51 Unusual instance of damage to stone cladding due to wind pressure (Photo credit: Keith Porter, Scawthorn Porter Associates).

3.5 WATER DAMAGE TO BUILDING CONTENTS AND EQUIPMENT

The damage to roofing and window systems described in the last two sections allowed water to infiltrate the buildings' interiors. Regardless of the extent of damage to these systems, water ingress had several implications: general deterioration of walls, ceilings, furnishings, and equipment; opportunity for mold growth; and a need for abatement of damaged asbestos-containing insulations. These consequences are expensive and time-consuming to remediate and often rendered critical facilities, such hospitals and police stations, inoperable. These problems were compounded by the loss of backup power due to poorly located backup generators. The NIST-led reconnaissance team observed many instances where flooding of the basement and ground levels of buildings damaged key facilities and equipment critical to the building's operation, such as back up generators, electrical equipment, water chillers, kitchen facilities, vacuum pumps and emergency (i.e., 9-1-1) call centers.

In New Orleans, flooding and water infiltration caused extensive damage to interior architectural finishes and mechanical, electrical, and plumbing (MEP) systems. By mid-October 2005, it was estimated by the Chief Building Inspector in the City of New Orleans that 100,000 out of 160,000 New Orleans buildings had experienced some flooding. Police stations, fire stations, schools, hospitals, post offices, and other major buildings experienced flooding that rendered them inoperative, in part because of the biohazard posed by mold in the architectural and MEP components, in part because flooding damaged MEP equipment located near ground level and in basements. Entering these buildings between September and mid-October typically required protective clothing and respirators. Mold problems were aggravated by the lack of electric power and air conditioning immediately after the hurricane.

None of the several hospitals examined in downtown New Orleans were operable by mid-October 2005. For example, at the Veterans Administration Hospital, according to the facility engineer, floodwater in the basement and subbasement destroyed the chiller, electrical equipment, main kitchen, medical air equipment, medical vacuum equipment, and miscellaneous administrative services. Repairs were underway. All finishes in the flooded areas were being demolished and replaced. Wind damage was minimal, with fewer than five windows broken; thus, without flooding, the hospital would have remained in operation.

According to a New Orleans Police Department (NOPD) officer in charge of facilities engineering, numerous NOPD facilities were similarly rendered inoperative by flooding and water infiltration. The NIST-led reconnaissance observed little damage to NOPD buildings due to wind and wind-borne debris. Water chillers, generators, electrical panels and even a 9-1-1 call center were damaged because of their location within the building at or below grade. At police headquarters on South Broad Street, the five-story building elevated above street level filled with water up to the basement ceiling because it was connected to an adjacent court building by an underground tunnel. The court building basement flooded due to failure of the pump in the court building. Flood water passed through the tunnel to the basement of the NOPD building. The flooding of the police headquarters destroyed the backup generator and electrical equipment and at the time of observation, the building was being dried out and having mold removed.

3.6 REFERENCES

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Chapter 4
DAMAGE TO INFRASTRUCTURE

This chapter discusses observations and findings on the performance of key infrastructure, i.e., those structures or facilities that protect and maintain quality of life and lifeline systems, during Hurricane Katrina and Rita. Key infrastructure plays a vital role in emergency response, rescue, repair, and recovery in areas impacted by natural disasters. Performance of the following key infrastructure systems during Hurricane Katrina and Rita were studied by the NIST-led reconnaissance efforts:

- Flood protection systems (levees and floodwalls)
- Transportation systems, including bridges, highways, railways, and airports
- Ports and harbors
- Utilities, including electric power, natural gas, water, and communication systems
- Other industrial facilities, including oil refineries and chemical plants

4.1 LEVEES AND FLOODWALLS

4.1.1 Levees and Floodwalls in New Orleans

The immediate regions in and around New Orleans are divided into four separate areas for flood protection. Each area is protected by a separate system, consisting of floodwall segments and earthen levees. These areas include the Orleans East Bank area, the New Orleans East area, the St. Bernard Parish area, and the Plaquemines Parish area, which stretches from south of St. Bernard Parish to where the Mississippi River meets the Gulf of Mexico.

Orleans East Bank, New Orleans East, and St. Bernard Parish are separated by the IHNC in the north-south direction, and the Intracoastal Waterway (IWW) part of the Mississippi River Gulf Outlet (MRGO) in the east-west direction. Specifically, the Orleans East Bank protected area is bounded by Lake Pontchartrain to the north, the 17th Street Outfall Canal to the west, the Mississippi River to the south, and the Inner Harbor Navigation Canal (IHNC) to the east. The New Orleans East protected area is also bounded by Lake Pontchartrain to the north and east, the IHNC to the west, and MRGO/IWW to the south. The St. Bernard Parish area is bounded by MRGO/IWW to the north, IHNC and the Mississippi River to the west/southwest, and MRGO to the east. The approximate areas and boundaries of these three protected areas are shown in Figure 4-1 (shaded red, orange, and purple). It was breaches in the flood protection systems of these three areas that caused widespread flooding in and around New Orleans. The breaches include (1) the 17th Street Outfall Canal breach, (2) the London Avenue Outfall Canal breach at Robert E. Lee Road, (3) the London Avenue Outfall Canal breach at Mirabeau Road, (4) the IHNC breach at Jordan Road, (5) the IHNC breach at France Road, (6) the IHNC Lower Ninth Ward south breach, (7) the IHNC Lower Ninth Ward north breach, and (8) site of floodwall overtopping on the MRGO/IWW at the Entergy Michoud Power Plant. Figure 4-2 shows the locations of the major breaches that were inspected as part of this study.

Most of the floodwalls that failed had the typical I-Wall cross section as shown in Figures 4-3 (a) and (b). These I-wall sections consist of I-shaped reinforced concrete cap walls cast on top of interlocking Z-shaped, ½-in. thick steel sheet piles (about 33 inches of the sheet piles are embedded in the concrete cap wall). The concrete cap wall-sheet pile system is anchored into the embankment soil to a specified depth, forming a cantilever system to resist deep seated slope failure (lateral displacement of levee through movement in the foundation) and prevent rotational failure of the sheet pile itself. USACE Engineer Manual for Design and Construction of Levees (EM 1110-2-1913) [3] provides the minimum factors of safety for deep seated failures in Table 6-1b. The minimum standard is 1.4 for long-term steady seepage to prevent deep seated instability to include failure due to underseepage. According to the USACE Engineer Manual for Design of Sheet Pile Walls (EM 1110-2-2504) [1], the steel sheet pile is required to have sufficient length to (1) achieve a depth of penetration corresponding with a minimum safety factor against rotational instability of 1.10 or 1.50 for fine-grain soils (drained soil condition or undrained soil condition, respectively), or 1.50 for free-draining soils. The concrete cap walls are cast in segments. The joint between two adjacent wall segments is made watertight by using type "Y" rubber or vinyl water stops, embedded in the concrete of the adjacent segments, in combination with contraction joints.

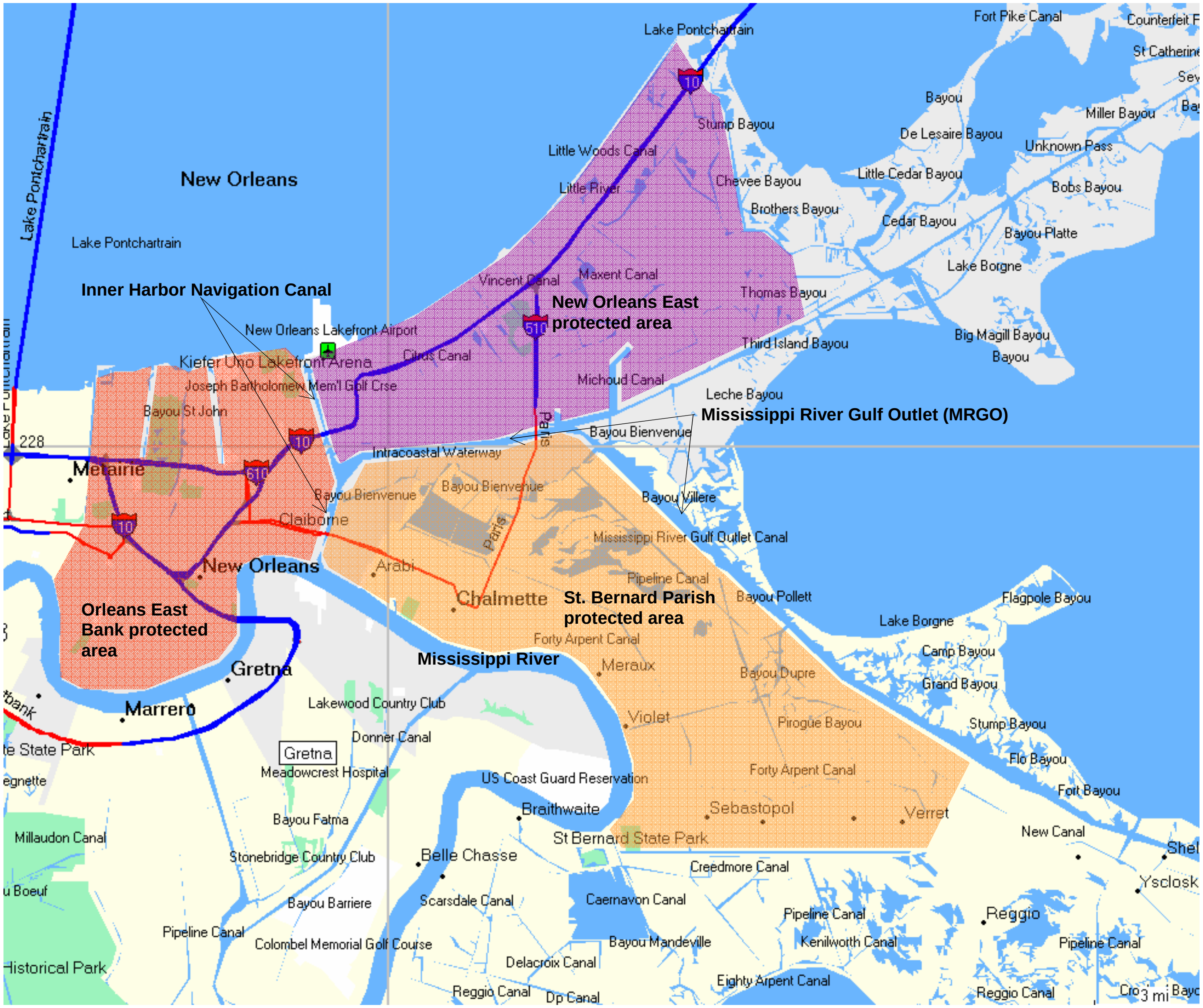

Figure 4-1 Approximate areas and boundaries of the Orleans East Bank, New Orleans East, and St. Bernard Parish protected areas. (© Copyright 2006 Garmin Ltd. or its subsidiaries. All rights reserved. Map data © 2002 NAVTEQ. All rights reserved. Enhancement by NIST)

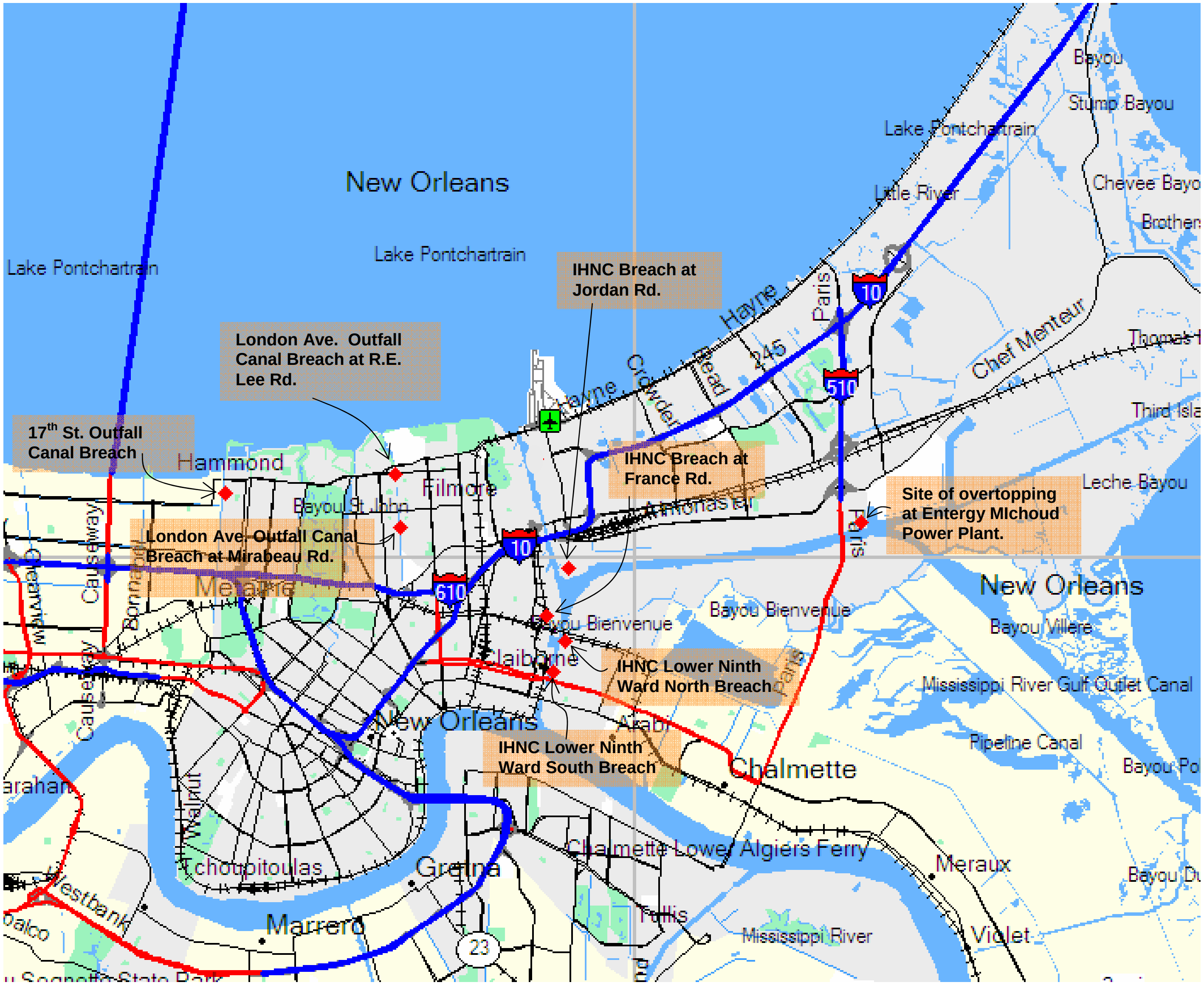

Figure 4-2 Major breaches in the flood protection systems of the three protected areas (© Copyright 2006 Garmin Ltd. or its subsidiaries. All rights reserved. Map data © 2002 NAVTEQ. All rights reserved. Enhancement by NIST)

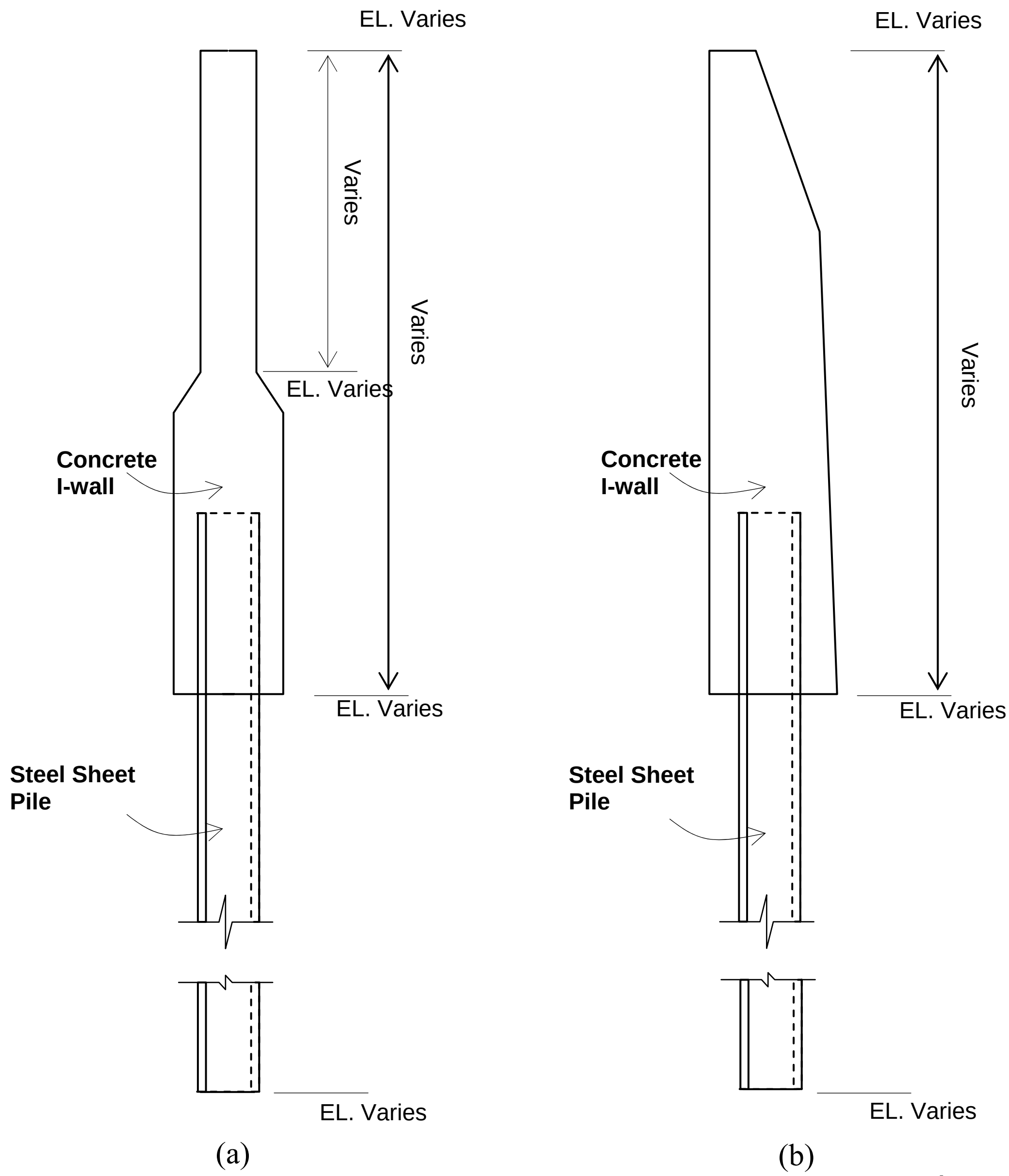

Figure 4-3 Typical I-Wall cross-sections of the floodwalls along (a) the 17th Street and London Avenue Outfall Canals and (b) the IHNC (Source: NIST)

4.1.2 Major Breaches Inspected

4.1.2.1 The 17th Street Outfall Canal Breach

The 17th Street Outfall Canal runs north-south and carries water discharged from Jefferson Parish on the west side and New Orleans Parish on the east side to Lake Pontchartrain at its north end. The breach in the flood protection system along this canal occurred on the east side and near the north end of the canal (at approximate coordinates N30 00.972 W90 07.239), and caused extensive flooding of New Orleans Parish. Figure 4-4, taken on September 29, 2005, shows the extent of the breach at this location looking northwest from the protected side of the floodwall. Also shown are the emergency embankment that has been put in place to plug the gap, and a few failed segments of the concrete I-walls which were disconnected from the steel sheet piles and displaced east ward by approximately 40 feet.

Figure 4-4 View to the northwest of the 17th Street Outfall Canal breach from the protected side (photo credit: NIST)

Figures 4-5 (a) and (b) show the intact floodwalls at the north and south edges of the breach. There are no transitional distressed sections between the failed sections and the intact sections, i.e., the failed wall segments were cleanly separated from the intact I-walls along the vertical wall-to-wall joints (along the "Y" rubber water stops). There is also no scour of the embankment soil on the inboard side at the toe of the floodwall in areas immediately adjacent to the breach.

The failed I-walls have all been separated from their adjacent walls. Some of the failed I-walls were also found to have been disconnected from the sheet piles at the time of the NIST inspection (see Figure 4-6). However, the disconnection between the I-walls and the sheet piles was likely[15] the result of emergency repair work immediately after the hurricane, and not an indication of structural failure due to increased hydrostatic pressure. The final location and condition of the steel sheet piles that were part of the breached section are not known since they were covered by the emergency embankment at the time of the inspection. Figure 4-7 shows the water mark due to ponding on a house in the New Orleans Parish directly behind the breached section, indicating a flood depth of about 2/3 of the first story height.

The failure of the 17th Street Outfall Canal floodwall differed from failures observed elsewhere in the following ways: (1) there was no scour of embankment soil along the toe of the floodwall on the inboard side; (2) there were no transitional distressed sections at the edges of the breach (clean disconnection between the failed and intact sections along the vertical wall-to-wall joint); and (3) the failed concrete I-walls were all disconnected from each other. The combination of these observations indicates that it was unlikely that overtopping occurred here and failure was likely[15] caused by sliding instability of the floodwall-levee system due to foundation failure[16]. The foundation failure was likely caused by shear failure within the clay in the foundation beneath the levee and the floodwall, according to observations and geotechnical evaluation by IPET [2]. Further detailed investigation and analysis, with access to the buried steel sheet piles and tests for properties of the supporting soil, are necessary to determine the sequence of events leading to failure of the floodwall at this location.

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(a) (b)

Figure 4-5 View looking north (a) at the north edge of the breach, and (b) at the south edge, showing no scour along the toe of the floodwall and the clean failures at the vertical joints between the failed and intact I-wall sections (photo credit: NIST)

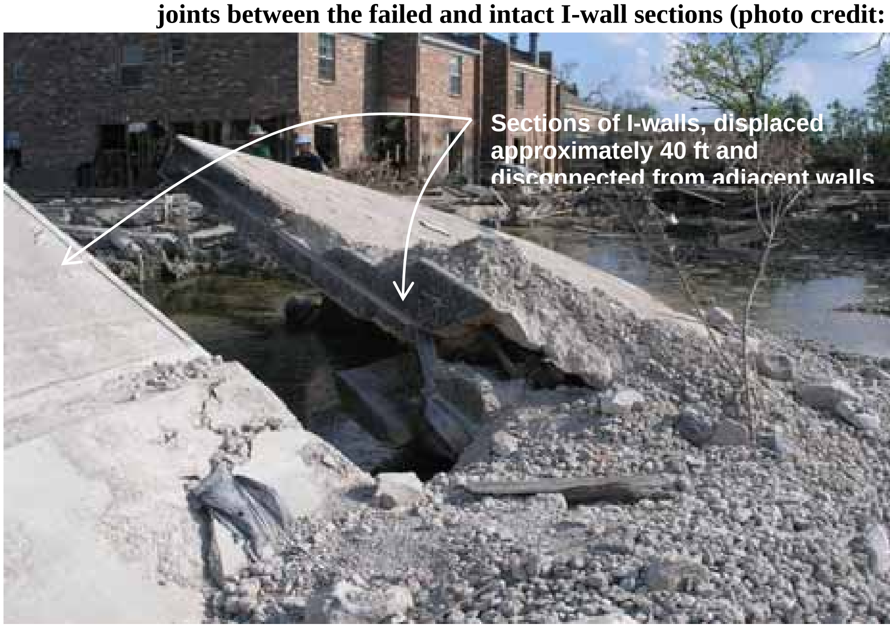

Figure 4-6 Sections of concrete I-walls displaced and disconnected from each other and from the steel sheet piles (photo credit: NIST)

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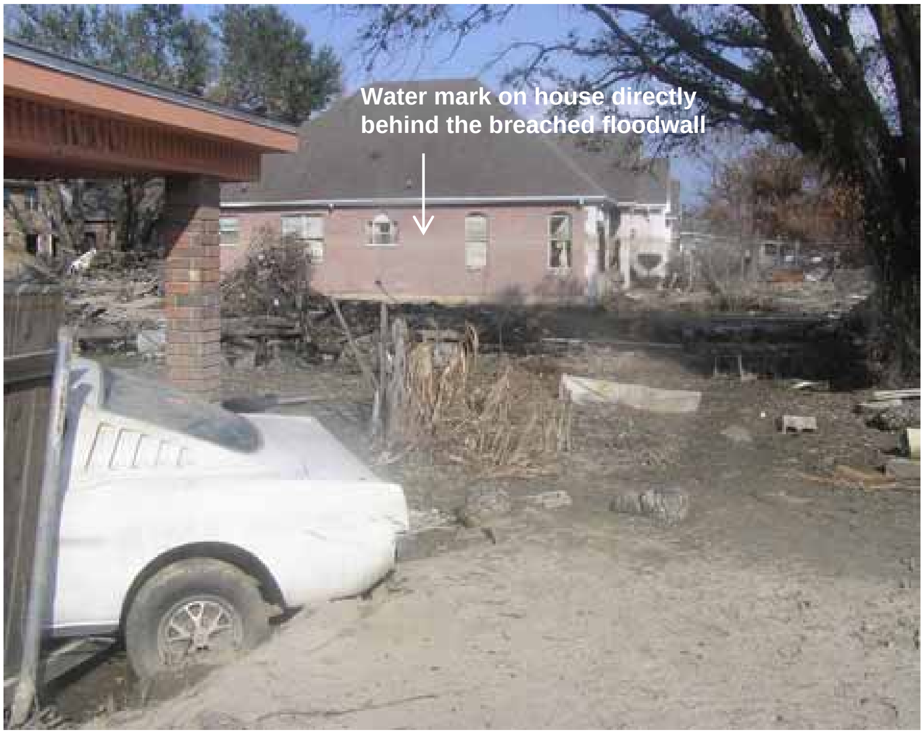

Figure 4-7 Water mark showing extent of flooding in area of New Orleans Parish directly behind the breached section of the floodwall (photo credit: NIST)

4.1.2.2 The London Avenue Outfall Canal Breach at Robert E. Lee Road

The London Avenue Outfall Canal also runs north-south and carries discharged water from parishes along its east and west banks to Lake Pontchartrain at its north end. Two major breaches occurred in the flood protection system along this canal, one, located at Robert E. Lee Road toward the north of the canal (at approximate coordinates N30 01.265 W90 04.246), and one further south at Mirabeau Road.

The London Avenue Outfall Canal breach at Robert E. Lee Road is on the west bank of the canal. The floodwall on this side is the typical concrete I-walls/steel sheet pile system. According to information provided by USACE, the bottom elevation of the steel sheet piles along the west bank is -11.4 feet. However, it should be noted here that all references to elevations of the floodwall system (top elevation of concrete cap walls and bottom elevation of steel sheet piles) in this and subsequent sections of this report refer to the design elevations, and not the actual elevations at the time of Hurricane Katrina. In fact, according to the IPET's Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System Draft Final report [2], the actual elevations of many sections of the levees and floodwalls were found to be substantially below their original design elevations due to soil subsidence across Louisiana. Typically, structures associated with the IHNC were found to be about 2.7 feet below their design elevations. The embankment soil adjacent to the floodwall on the outboard side (canal side) on both banks was above normal water level and was covered with grass, small trees, and other vegetation.

Figure 4-8 shows the view looking south along the breached section of the floodwall on the west bank. This figure clearly shows that the floodwall system at this location has been laterally displaced by several feet and overturned westward (toward land side). The lateral displacement and rotation of the floodwall created a gap between the floodwall and the embankment soil on the outboard side (see Figure 4-8), allowed water to enter the gap and exerted hydrostatic pressure on the floodwall below the surface of the levee. These observations indicate failure was likely due to sliding instability of the floodwall-levee system due to foundation failure[17]. The foundation failure was likely triggered by erosion and piping of soil due to underseepage, according to observations and geotechnical evaluations by IPET [2]. The concrete I-walls in the failed section were still connected to the steel sheet piles, but were separated from adjacent panels along the vertical joints (water stops), since there was no reinforcement connecting adjacent I-wall panels. Inspection of the inboard side revealed no scour along the toe of the floodwall, indicating overtopping did not occur at this location.

Figure 4-8 View looking south of the breach on the west bank of the London Avenue Outfall canal near Robert E. Lee Road (photo credit: NIST)

[17] The failure mechanisms are based on visual observations and engineering judgment and as such are preliminary in nature. The mechanisms should be fully investigated using rigorous models and experimental analysis before firm conclusions can be drawn.

Water pressure was also sufficient to cause cracking of the concrete I-wall at the junction between the thin upper section and the enlarged lower section, as shown in Figure 4-9. Inspection of the intact section of the floodwall indicates that the location of the crack would be above the line of lateral soil support. Figure 4-10, taken at the north end of the breach where the concrete I-wall has been removed, provides some details of the interlocking steel sheet piles and arrangement of reinforcement for connection with the concrete I-wall.

4.1.2.3 The London Avenue Outfall Canal Breach at Mirabeau Road

The floodwalls on the east bank of London Avenue Outfall Canal consist of a concrete I-wall-steel sheet pile system. The I-wall cross section is the same as the typical section shown in Figure 4-3(a). According to information provided by USACE, the floodwall here has a design bottom sheet pile elevation of -10.3 ft and a top wall design elevation of 13.9 ft.

The breach on the east bank of this canal occurred at approximate coordinates N30 00.462 W90 04.144, just north of Mirabeau Road, which runs in the east-west direction and crosses the canal with a concrete bridge. The breach occurred in the section just north of the bridge on Mirabeau Road. Figure 4-11 shows a view looking north at the breached section of the floodwall taken from a bridge crossing the canal on Mirabeau Road. Figure 4-12 shows a closer view of the breach, looking south toward the Mirabeau Road bridge.

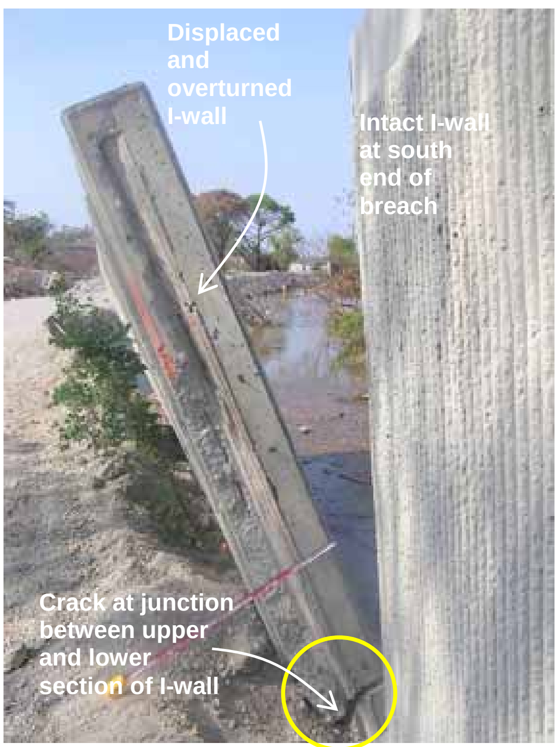

Figure 4-9 Cracked I-wall (photo credit: NIST)

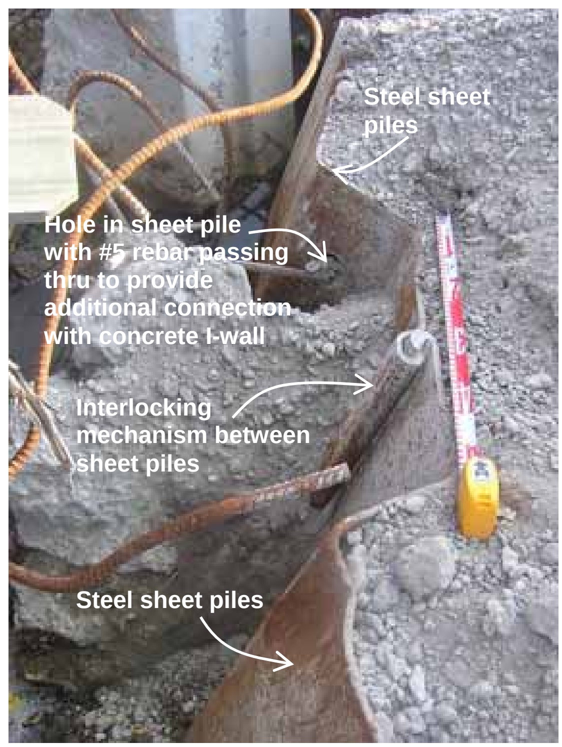

Figure 4-10 Sheet piles details (photo credit: NIST)

Figure 4-12 also shows that the breached section of the floodwall and the levee had laterally displaced and partially overturned toward the protected side of the floodwall. The lateral displacement and rotation observed here are similar to, but not as pronounced as, the lateral displacement and rotation observed at the Robert E. Lee Road breach on the west bank. The failed I-walls were also separated from adjacent panels along the vertical water stop joints but appeared to remain along the same line and in a somewhat vertical position, indicating they were still connected to the steel sheet piles (see Figure 4-13). The wall segments at the edges of the breach also show signs of pending separation and failure at the vertical water stop joints (see Figure 4-14). At the time of the inspection on September 30, 2005, even with the emergency embankment materials in place, it was clear that scour due to overtopping did not occur and that overtopping did not take place prior to failure of the floodwall. The top elevation of the flood on the London Avenue Outfall Canal was less than 13.9 ft.

The combination of lateral displacement and partial rotation of the breached section, and the lack of evidence of overtopping, suggests that the floodwall failure here was likely[15] due to sliding instability of the floodwall-levee system due to foundation failure[18]. The foundation failure was likely triggered by underseepage erosion and piping according to observations and geotechnical evaluations by IPET [2]

Figure 4-11 View looking north from Mirabeau Road bridge toward the breach on the east bank of the London Avenue Outfall Canal (photo credit: NIST)

[18] The failure mechanisms are based on visual observations and engineering judgment and as such are preliminary in nature. The mechanisms should be fully investigated using rigorous models and experimental analysis before firm conclusions can be drawn.

Figure 4-12 **View looking south from the breach on the east bank of the London Avenue Outfall Canal toward Mirabeau Road bridge (photo credit: NIST)**

Figure 4-13 **I-walls of failed floodwall section separated along water stop joint (photo credit: NIST)**

Figure 4-14 **Partial separation of adjacent I-walls along water stop joint (photo credit: NIST)**

4.1.2.4 The IHNC Breaches at France Road

Two major breaches in the flood protection system protecting the Orleans East Bank area occurred in the same vicinity along the west bank of the IHNC near the intersection between France Road and Florida Avenue (at approximate coordinates N29.9852, W90.0263). One breach was caused by the failure of the floodwall. The other was caused by erosion of the earthen levee that intersects the breached floodwall and France Road. Figure 4-15 shows the general locations of the breaches at this site.

The breached floodwall has the typical concrete I-wall/steel sheet pile construction and runs in the north-south direction parallel to France Road and the New Orleans Public Belt railroad track. The breached earthen levee is perpendicular to the floodwall and is south of the breach in the floodwall. The junction between the earthen levee and the floodwall is a short transition concrete I-wall/steel sheet pile system, connected to a concrete closure monolith that provides an opening to allow the New Orleans Public Belt railroad track to go through. At this site, the unprotected side of the floodwall/earthen levee is not immediately adjacent to water. Instead, on the unprotected side there are other Port of New Orleans facilities with asphalt paved road and railroad track serving these facilities. It is not known which of the breaches occurred first, or if they occurred simultaneously.

Figures 4-16 and 4-17, taken on October 18, 2005, show views looking north at the breach in the floodwall from the protected side. The floodwall section at the breach displaced laterally and rotated toward the protected side. At the north and south edges of the breach, panels of distressed I-walls showed signs of pending separation but were still connected to the steel sheet piles. Along the inboard toe of the floodwall, scour trenches more than 6 ft deep were observed, indicating overtopping occurred at this location. The section of the New Orleans Public Belt railroad track directly behind the breach was disconnected and laterally displaced westward (toward the protected side). It is not clear if this was evidence of failure of the supporting soil behind the breach or if this was caused by impact against the railroad track by flood-borne debris.

The floodwall failure appeared to be caused primarily by rotational instability. The failure was likely[15] triggered by the loss of soil support due to scour along the inboard toe caused by water overtopping[19]. The combined effect of rising lateral hydrostatic pressure on the outboard side and increasing cantilever action due to loss of supporting soil on the inboard side caused the floodwall to become increasingly susceptible to rotation in the direction of pressure. Other sections of the floodwall in the vicinity of the breached section were also observed to have signs of the pending rotational failure. Figures 4-18 and 4-19, taken from the protected side, show a section of the floodwall just south of the breach being tilted toward the protected side (in the direction of pressure) and partially separated from the adjacent I-walls.

Further south from the floodwall breach, where the earthen levee intersects with the floodwall through the transition I-wall and the concrete closure monolith, is the breach in the earthen levee. This breach resulted in massive erosion of the levee embankment material and scour of the asphalt road on the protected side. Figures 4-20 and 4-21 show severe erosion of a large section of the asphalt pavement and supporting soil of France Road, at the junction between the earthen levee and the transition I-wall.

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[19] The failure mechanisms are based on visual observations and engineering judgment and as such are preliminary in nature. The mechanisms should be fully investigated using rigorous models and experimental analysis before firm conclusions can be drawn.

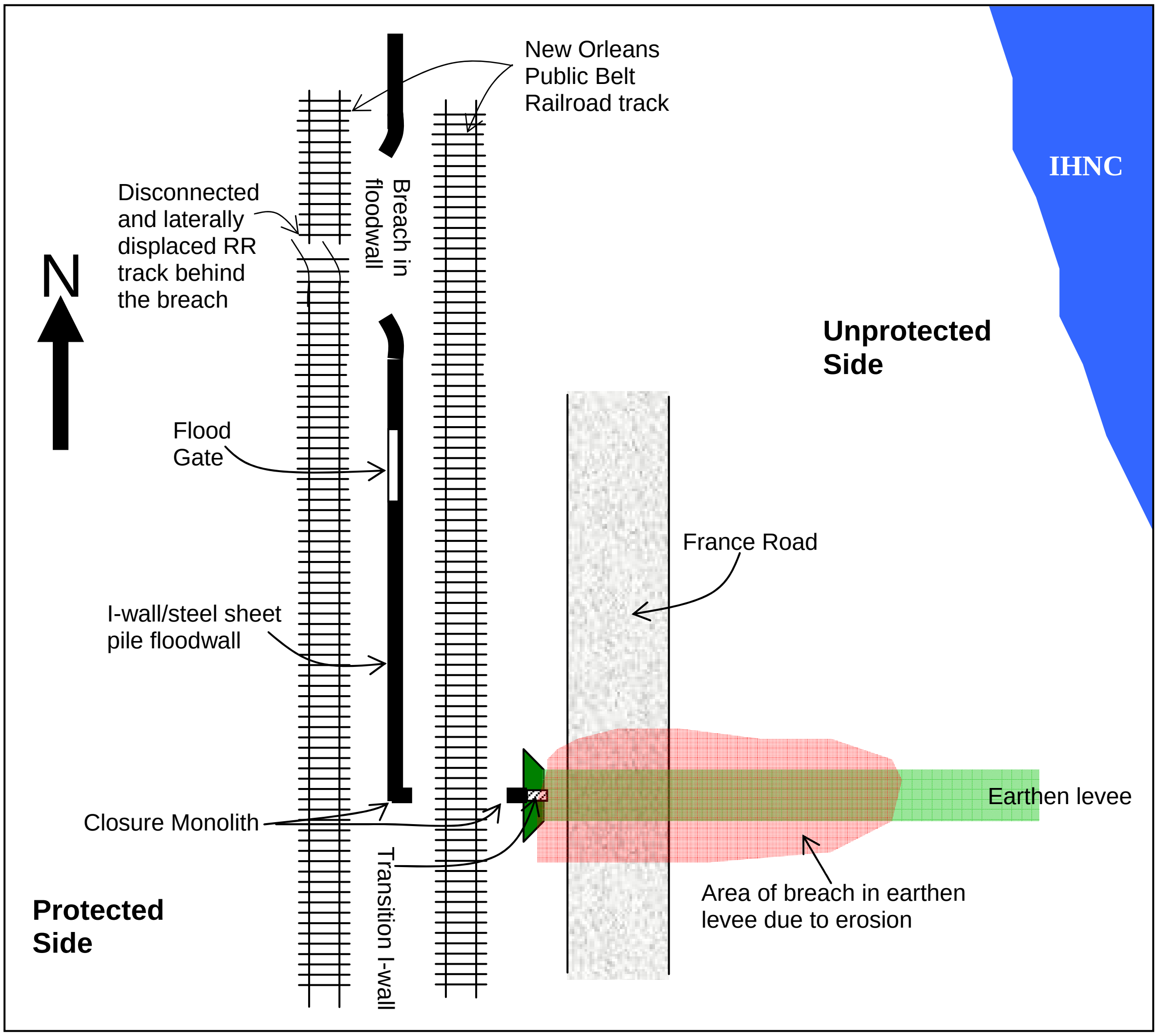


Figure 4-15 General locations of the IHNC breaches at France Road (drawing credit: NIST)

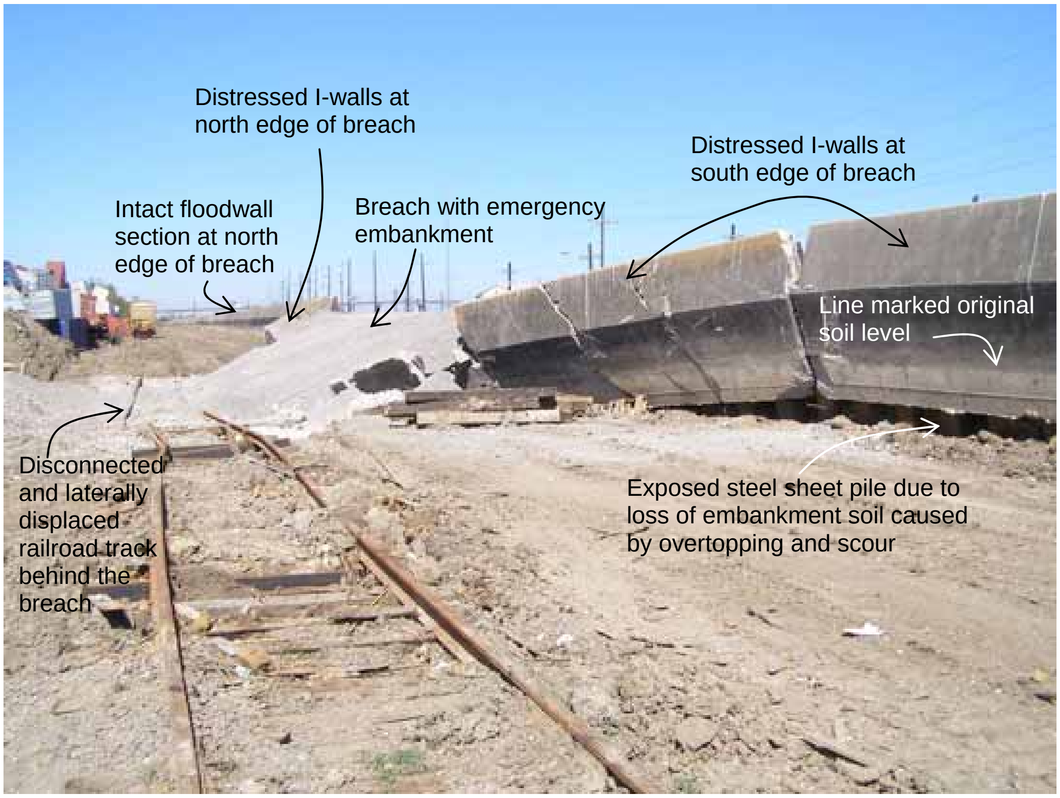


Figure 4-16 View looking north at the breach on IHNC at France Rd from the protected side (photo credit: NIST)

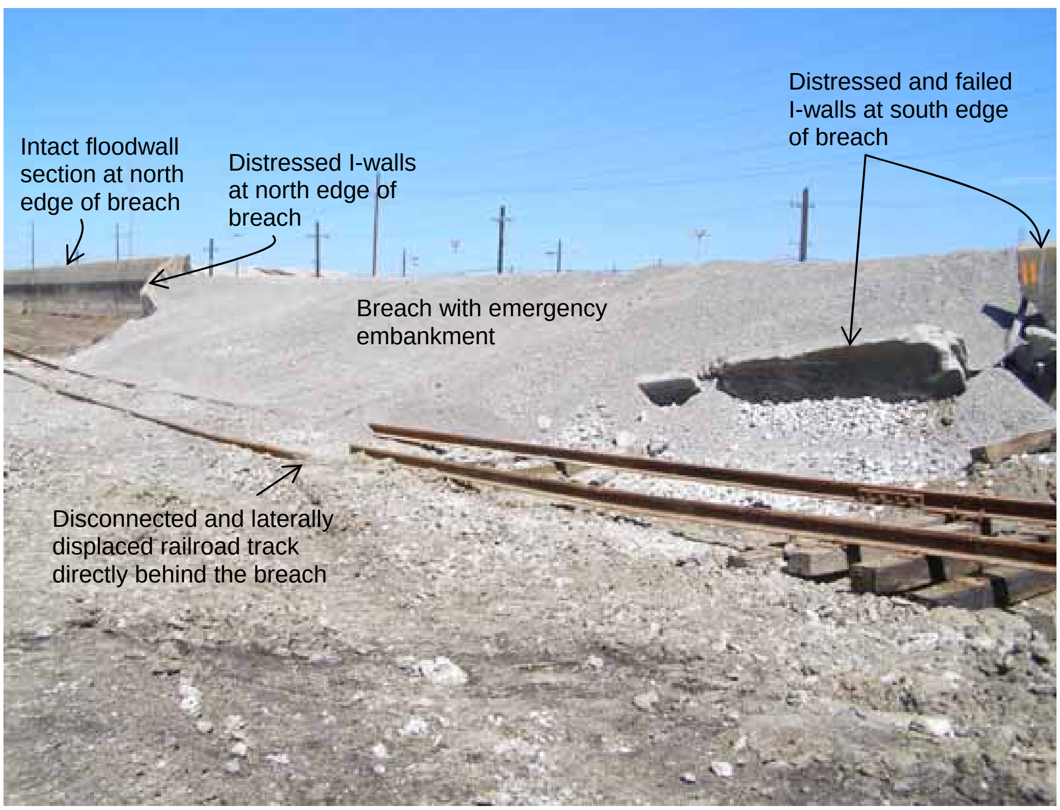


Figure 4-17 A closer view of the breach on the IHNC at France Road (photo credit: NIST)

Figure 4-18 View from the protected side looking south from the breach showing distressed I-walls adjacent to floodgate on IHNC at France Rd (photo credit: NIST)

Figure 4-19 View from the protected side south of the breach showing distressed I-walls near the floodgate on IHNC at France Rd. (photo credit: NIST)

Figure 4-20 Erosion due to scour at France Road at section south of the breach in the floodwall on the west bank of the IHNC (photo credit: NIST)

Figure 4-21 Erosion behind breached earthen levee. The breach occurred at the transition between the earthen levee and the transition I-wall (photo credit: NIST)

4.1.2.5 The IHNC Lower Ninth Ward North Breach

Two major breaches in the flood protection system protecting the St. Bernard Parish and the Lower Ninth Ward areas were inspected on October 17, 2005. Both are on the east bank of the IHNC at a section south of the IWW/MRGO. The IHNC Lower Ninth Ward North breach is slightly more than 200 ft long and is located just south of Florida Avenue and the Norfolk Railroad bridges, at approximate coordinates N29 58.712, W90 01.235.

The floodwall construction at this location is also the typical concrete I-wall/steel sheet pile system. The steel sheet pile, measured from its bottom end to its connection with the concrete I-wall, is about 13 ft long. Figure 4-22 shows the view looking south at the breach section, taken from the unprotected side of the canal. Complete failure of the floodwall occurred with the concrete I-wall/steel sheet pile system completely uprooted and pushed more than 50 ft eastward in the direction of pressure (toward the protected side). The failed sections of the floodwall close to the south edge of the breach appeared to have been overturned and then uprooted, with the concrete I-walls pointing toward the protected side direction and the steel sheet piles pointing toward the canal. However, at sections closer to the middle and north edge of the breach, the concrete I-walls were pointing toward the canal while the sheet piles were pointing toward the protected side, as if the system had been pushed out from under. The concrete I-walls and steel sheet piles of the entire failed section remained connected, however. This suggests failure[20] was likely[15] due either to (1) foundation instability (for the sections closer to the middle and north edge of the breach), or (2) instability due to rotation (for sections closer to the south edge of the breach). Further geotechnical evaluations and analyses are necessary to establish the cause of this breach with a higher degree of certainty.

Figure 4-23 shows the view looking north toward the intact section at the north edge of the breach. The failed section of the floodwall has been separated from the intact section along the vertical water stop joints of adjacent I-wall panels. Scour trenches along the inboard toe of the floodwall section south of the breach were also observed, indicating overtopping occurred at this location, similar to the breach on the IHNC at France Road.

[20] The failure mechanisms are based on visual observations and engineering judgment and as such are preliminary in nature. The mechanisms should be fully investigated using rigorous models and experimental analysis before firm conclusions can be drawn.

Figure 4-22 View looking south at the IHNC Lower Ninth Ward North breach (photo credit: NIST)

Figure 4-23 View looking north at the north edge of the IHNC Lower Ninth Ward North breach (photo credit: NIST)

4.1.2.6 The IHNC Lower Ninth Ward South Breach

The second major breach causing widespread flooding of St. Bernard Parish and the Lower Ninth Ward areas is the IHNC Lower Ninth Ward South breach. This breach is located about 750 ft north of the N. Clairborne Avenue bridge, which carries vehicular traffic across the IHNC in the east-west direction.

The floodwall construction at this breach is the same as the floodwall construction at the IHNC Lower Ninth Ward North breach, with similar concrete I-wall profile and steel sheet piles. Figure 4-24 shows the view looking north at the IHNC Lower Ninth Ward South breach, taken from the N. Clairborne Avenue bridge. This figure shows a scour trench, measuring approximately 6 ft wide and 8 ft deep, caused by overtopping along the inboard toe of the floodwall. This scour trench runs from the south edge of the breach to the N. Clairborne Avenue bridge (approximately 750 ft long). Figure 4-25 shows another view of the scour trench, looking south toward the N. Clairborne Avenue bridge from the protected side. Also shown in Figure 4-24 is a barge that was drawn through the breach and settled on the protected side of the canal near the south end of the breach. This barge apparently[15] impacted the floodwall at the south end of the breach (rust stain marks from the barge were observed by the ASCE team on the canal side of the floodwall), causing the concrete I-walls at this end to be broken into smaller pieces. The rest of the concrete I-walls that were part of the breached section appear to remain fully connected to the steel sheet pile even when overturned and uprooted from the embankment (Figures 4-26 and 4-27). The entire failed floodwall was pushed toward the protected side (in the direction of pressure), with the concrete I-walls pointing toward the protected side direction and the steel sheet piles pointing toward the canal. This suggests rotational failure caused by full outboard pressure and increased cantilever action from the loss of the supporting soil along the inboard toe due to overtopping scour as the likely[15] mode of failure[21].

Figure 4-24 View looking north at the IHNC Lower Ninth Ward South breach (photo credit: NIST)

[21] The failure mechanisms are based on visual observations and engineering judgment and as such are preliminary in nature. The mechanisms should be fully investigated using rigorous models and experimental analysis before firm conclusions can be drawn.

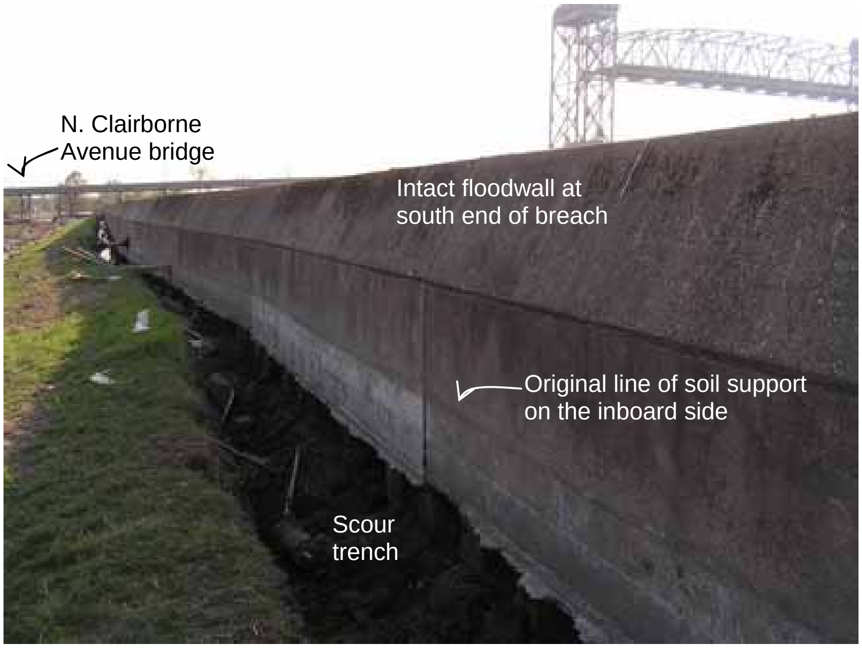


Figure 4-25 View looking south along the inboard side of the IHNC Lower Ninth Ward South breach (photo credit: NIST)

Figure 4-26 Overturned and uprooted floodwall at the IHNC Lower Ninth Ward South breach, with the I-walls remained connected to the sheet piles (photo credit: NIST)

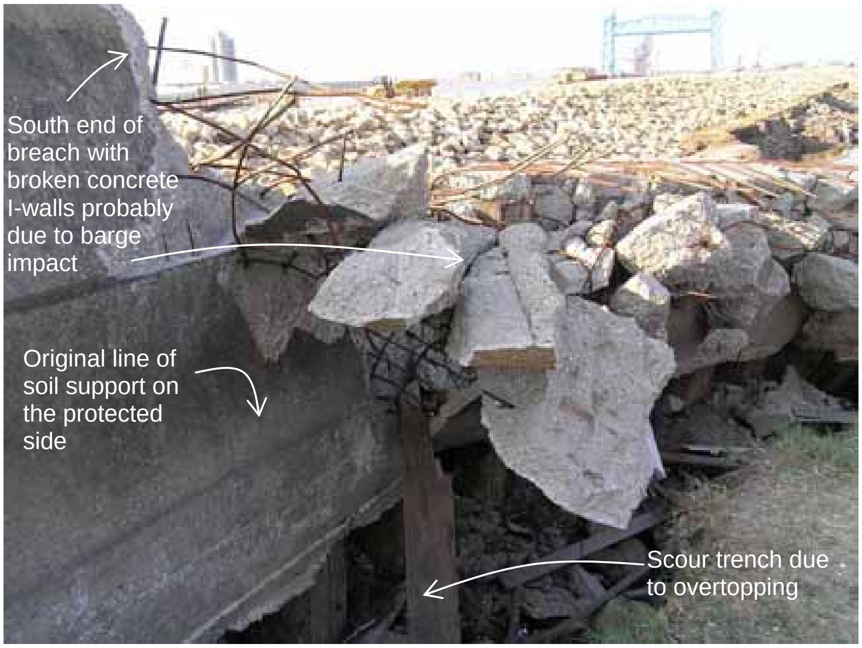


Figure 4-27 South edge of breach with broken concrete I-walls apparently[15] due to barge impact (photo credit: NIST)

4.1.2.7 The IHNC Breach at Jordan Road

On the east bank of the IHNC, a breach in the flood protection system protecting the New Orleans East area occurred just north of the junction between the IHNC and the MRGO/IWW at approximate coordinates N29.99725, W90.019616. The construction of the flood protection system at this breach is very similar to the construction of the flood protection system at the IHNC breach at France Road. It consists of a concrete floodwall connected to an intersecting earthen levee through a concrete closure monolith that provides access for a railroad track. The unprotected side of the flood protection system here is also not immediately adjacent to water.

The floodwall is the typical concrete I-wall/steel sheet pile system with the I-walls having similar profile as the I-walls discussed at other breaches along the IHNC. However, the floodwall along the IHNC at Jordan Road did not fail, rather, it exhibited signs of pending rotational failure with several I-wall panels rotated toward the unprotected side and separation from the adjacent panels (Figure 4-28). Also different from observations at other breached sites was the formation of long scour trenches along the toe of the floodwall but on the outboard, unprotected side (see Figure 4-28). The scour trenches ended at the junction between the beginning of the floodwall (south end) and the concrete closure monolith. The loss of embankment material along the outboard side of the floodwall due to scour was significant, with a maximum scour trench depth of about 7 feet and width of about 10 feet. Had flow continued over a longer duration, it is likely[15] that the scour trenches would have grown in size and led to failure of the floodwall.

While the floodwall did not ultimately fail at this site, the adjacent earthen levee was breached at the transition between the floodwall/railroad closure monolith and the earthen embankment. This resulted in significant flooding of the New Orleans East protected area, washing out of a large portion of Jordan Road at its intersection with the levee, complete erosion of the asphalt pavement and subsoil foundation, and severe scour of the areas around Jordan Road (similar to what observed at the IHNC breach at France Road).

(a) **(b)**

Figure 4-28 View of scour trench on the outboard side toward junction of floodwall and closure monolith (a); View looking north along scour trench on the outboard side toward flood gate (b) (photo credit: NIST)

4.1.2.8 Overtopping of floodwall at the Hot Water Discharge Canal of Entergy Michoud Power Plant

The Entergy Michoud Power Plant is located on the north bank of the IWW/MRGO (approximate coordinates N30.00905, W89.93327) and is adjacent to the Interstate 510/Paris Road bridge crossing the IWW/MRGO. The flood protection system here is part of the system protecting the New Orleans East areas, and the floodwall construction is the typical concrete I-wall/steel sheet pile system, with the I-walls having similar profile to those used along the IHNC (see Figure 4-3b).

While the Entergy Michoud Power Plant was flooded, the flooding was not due to failure of the floodwall. Rather, it was caused by both overtopping of the floodwall along the Plant's Hot Water Discharge Canal (observed and videotaped by plant personnel) and water pouring in through an open access road at an elevation about 2 feet lower than the top of the floodwall. The access road intersects the floodwall and provides access to a small loading dock on the unprotected side of the floodwall.

The observed overtopping and subsequent formation of a scour trench along the inboard toe of the floodwall provided the most direct evidence of the effect of overtopping on the loss of embankment soil. Figure 4-29 show views in both directions of the scour trench along the inboard side of the floodwall. The scour trench was approximately 8 feet wide by 5 feet deep. The loss of embankment soil due to scour trench exposed the steel sheet piles along the floodwall, reducing the embedment depth and rotational stability of the floodwall. However, the floodwall here did not yet exhibit signs of impending failure (tilting and separation) due to this increased cantilever action.

(a) (b)

Figure 4-29 Scour trench along floodwall next to Entergy Michoud Power Plant (photo credit: NIST).

4.1.3 Summary of New Orleans Floodwall performance

Failures of the levees and floodwalls in New Orleans were observed to have been caused by three different mechanisms: rotational failure of the floodwall-sheet pile system triggered by soil erosion due to overtopping (likely[15] occurred at two breaches of floodwalls along the IHNC); massive erosion and scour of the earthen levee at the levee/floodwall junction (with water overtopping, likely[15] occurred at two breaches of earthen levee along the IHNC); and sliding instability of the floodwall-levee system due to foundation failure (without water overtopping, likely[15] occurred at the two London Avenue Outfall Canal breaches and the 17th Street Outfall Canal breach). The foundation failures due to sliding instability at the above breaches could have been possibly caused either by underseepage erosion and piping (London Avenue Outfall Canal breaches) or by shear failure within the clay in the foundation beneath the levee and the floodwall (17th Street Outfall Canal breach).

No structural failure at the connection between the concrete I-walls and steel sheet piles was observed. Where the connections between the I-walls and the steel sheet piles could be inspected, the reinforcements between the concrete I-walls and the steel sheet piling appeared to be in place as shown on typical drawings. Concrete I-wall panels of the floodwalls along the 17th Street and London Avenue Outfall canals separated from adjacent panels along the vertical water stop joints.

The loss of embankment material due to erosion and scour trenches was widespread at breaches along the IHNC and the IWW/MRGO, where overtopping occurred. None of the sites inspected, where erosion and scour trenches occurred, was armored. Scour trenches, due to either overtopping or flow disturbance or both, were observed on both the protected and unprotected sides of the floodwall. At many breaches along the IHNC, the scour trenches were measured at more than 6 feet deep. In some cases this represented a loss of up to ½ of the total embedment depth of the floodwall at this location, making it much more vulnerable to rotational instability. Significant erosion and failure of the earthen levee at the transitional junction between the levee and the floodwall (i.e., the short transition concrete-capped sheet piling I-wall and the railroad closure monolith) were observed on both sides of the IHNC, at France Road and Jordan Road. While the breaches at the IHNC at France Road were caused by failures of both the earthen levee and the concrete floodwall, and it is not known which of the two failed first, the IHNC at Jordan Road breach was caused mainly by failure of the earthen levee. It is likely[15] that flow disturbance at the levee-floodwall junction, with consequent erosion and scour, was a strong contributing factor in the failure of the earthen levees at these two locations.

Comprehensive investigation and analysis of the supporting soil was outside the scope of this reconnaissance study. It is not known if the sheet pile lengths used at the breach sites satisfied the required 95 percent penetration of all pervious strata. The failure of levees and floodwalls in New Orleans is the subject of ongoing detailed investigations by USACE, ASCE and several universities, including University of California Berkley (UC Berkley) and Louisiana State University (LSU). Further review is necessary to ascertain a complete picture of all the failures and their mechanisms.

4.2 TRANSPORTATION SYSTEMS

Transportation systems include highway networks and their components (e.g., pavements, ramps, bridges, signs, and sound barriers). Storm damage to highway infrastructure was generally limited to the area south of U.S. Interstate 10 (I-10), the major east-west corridor across southern Florida, Alabama, Mississippi, and Louisiana. With the exception of US-90, which runs along the coast south of I-10, and US-82 in western Louisiana, damage to pavement in the region was light. Damage to bridges was most significant at bay crossings and major rivers due to wave actions caused by high storm surges.

4.2.1 Bridges

Hurricane Katrina caused extensive damage to highway bridges, especially their superstructures, across Alabama, Mississippi, and Louisiana. Structural damage to bridges was caused primarily by direct effects of storm surges, which induced the following effects:

- Dynamic lateral wave forces acting on the superstructure and substructure of the bridges.
- Uplift due to buoyancy when the bridges became inundated.
- Horizontal impacts from barges and other debris (shipping containers, vehicles, logs, large appliances, boats, and brush).
- Scour, or undermining of foundations.
- Flooding of electrical/mechanical rooms of moveable bridges.

4.2.1.1 Bridges over Lake Pontchartrain

Four major bridges carry vehicular and railroad traffic between New Orleans and areas north of Lake Pontchartrain in Louisiana. These include the I-10 twin span bridges, the US-11 bridge, the Norfolk Southern railroad bridge, and the Lake Pontchartrain Toll Causeway. All are concrete bridge spans supported by concrete piers. Except for the US-11 bridge, which has partial continuity provided by the deck and a positive connection between the concrete girders and the pier cap due to its cast-in-place construction, the bridges were built with simply supported, non-continuous concrete girders that had very little capacity for resisting the dynamic forces of the waves and surge. Figure 4-30 shows the locations of the bridges over Lake Pontchartrain.

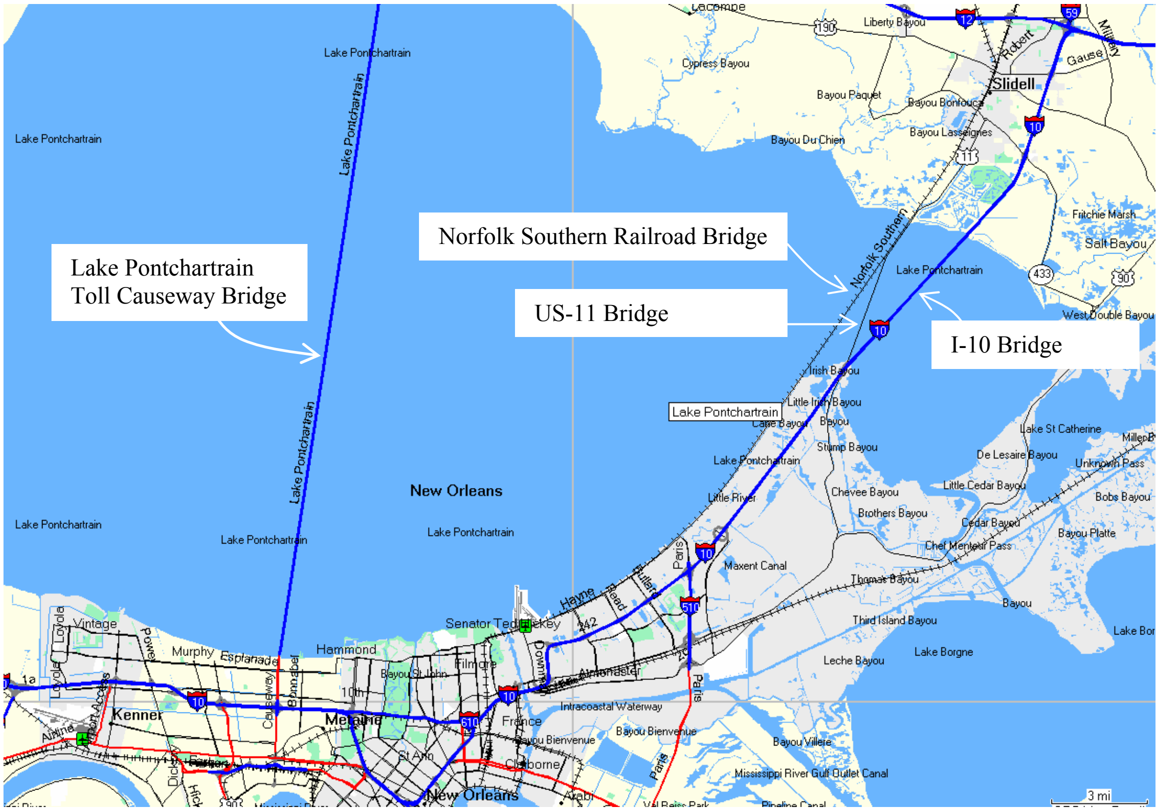


Figure 4-30 Major bridges over Lake Pontchartrain in Louisiana (© Copyright 2006 Garmin Ltd. or its subsidiaries. All rights reserved. Map data © 2002 NAVTEQ. All rights reserved. Enhancement by NIST)

I-10 twin span bridges. The I-10 twin span bridges (two separate bridges, nominally eastbound and westbound) over Lake Pontchartrain connect New Orleans and Slidell, Louisiana to the north. Each bridge is two lanes wide and 5.4 miles long. According to the Louisiana Department of Transportation and Development (LA DOTD), the deck level stands at 14 feet above mean sea level. The bridges were built in the early 1960s using prefabricated construction. The superstructure is comprised of 65-foot-long prestressed concrete spans weighing approximately 285 tons each. Each superstructure span is a monolithically cast concrete system comprising a concrete deck, fascia section (safety walk curbs with vertical solid parapet), and six concrete girders with I-cross section. The span was cast at a factory offsite and transported by barge for erection on the piers. Each span was simply supported and seated on the piers through steel bearing plates that provide little restraint against lateral displacement. The steel bearing plates were bolted into the cap beam of the pier on top of low risers (or pedestals). This connection design facilitates easy replacement of the superstructure spans but provides no provision for restraint against uplift (aside from the span dead weight) or lateral displacement.

The I-10 twin span bridges sustained extensive damage, primarily due to high storm surges and associated wave forces caused by Hurricane Katrina. Surge-induced wave forces (lateral and uplift forces), combined with the lack of restraint against uplift and lateral displacement of the superstructure spans, caused many spans of both the eastbound and westbound bridges to be uplifted and displaced laterally in a southerly direction. According to a damage summary by the LA DOTD, a total of 38 eastbound spans and 26 westbound spans were displaced and dropped completely into the water. In addition, 170 eastbound spans and 303 westbound spans were shifted out of alignment. In most cases, the misaligned superstructure spans displaced less than 5 feet in the transverse direction (one riser spacing) due to the fascia girder making contact with the adjacent riser. Wave forces also broke more than 14,000 ft of the concrete railings along the base of the curb line, leaving them dangling and connected to the bridge deck only by the reinforcing bars. Surge damage to the superstructures of the I-10 bridges established the surge height at this location to be at least 14 feet. Figure 4-31 shows view looking north of the westbound I-10 bridge with missing spans and broken curb rails.

While the lack of restraint at the connection between the superstructure and the bridge piers contributed to the loss and misalignment of many of the I-10 bridges' superstructure spans, this type of construction does facilitate quick repair. The eastbound bridge was quickly returned to service by moving undamaged spans on the westbound bridge to fill the gaps in its superstructure, and by realigning and repairing the shifted and damaged spans. The eastbound I-10 bridge was reopened to two-way traffic on October 14, 2005, 34 days after being damaged by Hurricane Katrina.

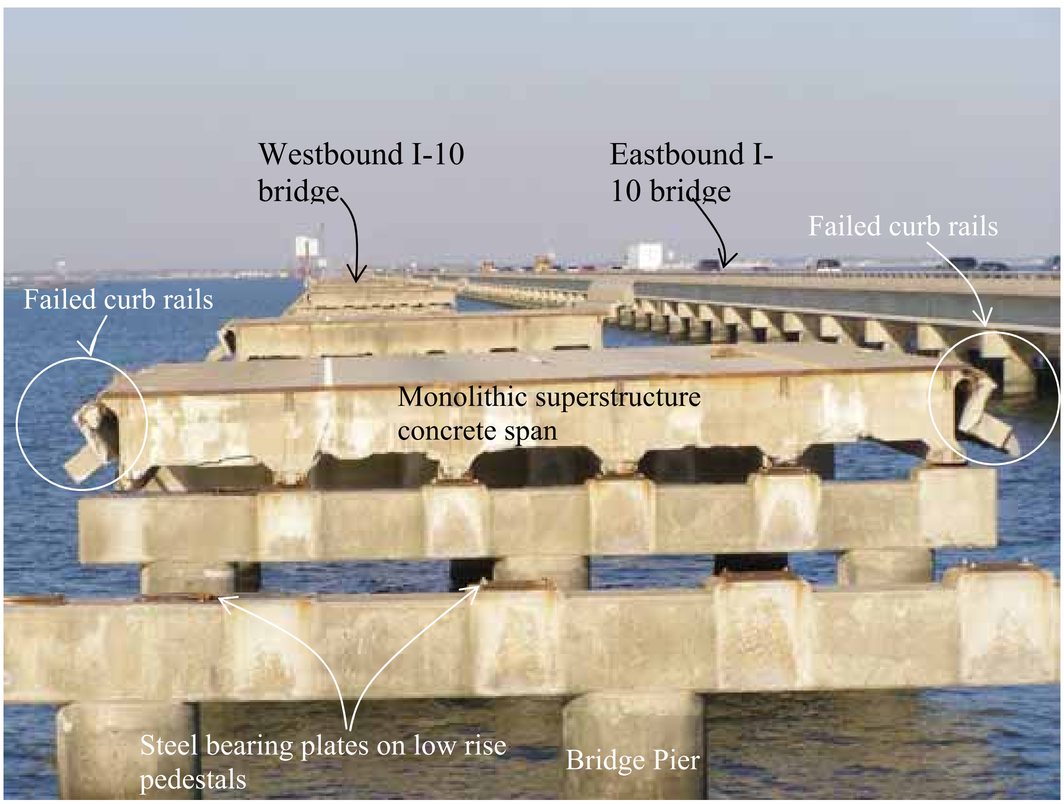


Figure 4-31 View looking north from west abutment of I-10 twin span bridges over Lake Pontchartrain (photo credit: NIST).

US-11 bridge. The two-lane US-11 bridge is just to the west of the I-10 bridges (see Figure 4-30), and carries vehicular traffic of US-11 between Slidell and New Orleans over Lake Pontchartrain. Its superstructure is a series of reinforced concrete girders (three per span) with a concrete deck. The bridge deck, girders, and piers were cast in place and the connections between the girders and the bridge piers were monolithic, thus providing positive connection between the bridge superstructure and the supporting piers. According to the bridge tender, a new concrete deck was cast over the length of the bridge in 2001. This provides continuity between the individual spans and likely[15] contributed to the good performance of the bridge. The deck level of this bridge stands at 11 feet above mean sea level.

Despite being 3 feet lower in elevation compared with the adjacent I-10 twin span bridges, and thus likely[15] subjected to the same surge and wave actions from Hurricane Katrina that affected the twin span bridges due to their close proximity, the US-11 bridge sustained very minor damage. The damage was nonstructural and was limited to a few sections of the concrete bridge rails and the approach guard rail from the west side shore being torn off by surge-induced wave forces, and the bascule lift span (drawbridge) was damaged by flooding and rendered inoperable. The extent of damage to the bridge rails of this bridge was also much more limited compared to damage to the bridge curb rails of the I-10 twin span bridge. This is likely[15] due to the difference in the construction of the curb rails. The I-10 bridges have solid parapet curb rails which attracted more wave force due to the larger surface, while the US-11 bridge has open-face curb rails and thus less surface area for application of wave force.

Unlike the twin span bridges, none of the superstructure spans of the US-11 bridge was lost or misaligned during Hurricane Katrina. This can likely[15] be attributed to the fact that the superstructure is continuous and positively connected to the supporting piers through cast-in-place construction methods. Figure 4-32 shows a view looking north along the US-11 bridge.

Figure 4-32 Cast-in-place concrete bridge carries the traffic of US-11 over Lake Pontchartrain (photo credit: J. O'Connor, MCEER).

Norfolk Southern Railroad bridge. The Norfolk Southern railroad bridge is a 5.8-mile long concrete bridge that is also in close proximity to the US-11 bridge and the I-10 twin span bridges (see Figure 4-30). Thus, it was likely[15] subjected to the same surge and wave actions that affected the I-10 and US-11 bridges. The bridge's superstructure consists of a concrete deck supported by pre-stressed concrete box girders. The superstructure is supported by concrete piers with shear block detailing at each end to provide restraint against lateral displacement (see Figure 4-33). This restraint probably contributed substantially to its successful performance during Hurricane Katrina. Surge-induced wave forces swept the railroad tracks and ties off the structure, but the bridge itself sustained no structural damage and was able to be returned to service just a few weeks after the storm.

Figure 4-33 The Norfolk Southern Railroad bridge over Lake Pontchartrain had its tracks stripped from the superstructure but otherwise remained intact (photo credit: J. O'Connor, MCEER).

Lake Pontchartrain Toll Causeway. The Toll Causeway is a 24-mile long concrete bridge that runs across the middle of Lake Pontchartrain in a north-south direction and carries vehicular traffic into the City of New Orleans from areas north of the lake. Similar to the I-10 twin span bridges, the Toll Causeway is comprised of two separate bridges, each carrying one-way traffic. In addition, there are turn-around ramps, which are separate bridges (supported by separate set of piers) that run between the two main bridges to allow traffic to change direction midway on the bridge. The deck surfaces of the main bridges stand at 20 feet above mean sea level, making them the tallest bridges over Lake Pontchartrain. The superstructures are comprised of simply supported concrete spans. Similar to the I-10 twin bridges, each span was monolithically cast in a factory offsite. Each is comprised of a concrete deck, fascia section, and I-section concrete girders. Each span was connected to the piers by steel bearing plates, which provide only restraint against displacement in the longitudinal direction, not lateral or vertical direction. The steel bearing plates were bolted into the concrete piers. The superstructure of the turn-around ramp was similarly constructed and supported, but has progressively lower elevation, with the lowest span being only a few feet above mean sea level.

Due to their high elevation (20 feet) and the observed surge height at their location (about 9 feet, see Figure 2-11), the superstructures of the main Toll Causeway bridges were not subjected to surge-induced wave actions and sustained no damage. However, several superstructure spans of the turn-around ramps, being at lower elevation and not restrained against lateral and uplift displacements, were subjected to the lateral and uplift wave forces and were either dropped into the lake or misaligned. As in the cases of the other bridges over Lake Pontchartrain, the substructures of the Toll Causeway bridges sustained no damage. Figures 4-34 and 4-35 show the turn-around ramp with missing and misaligned superstructure spans. Figure 4-36 shows the supporting pier with the steel bearing plates/shear keys that were used at the connection between the superstructure and the substructure.

Figure 4-34 Toll Causeway turnaround bridge ramp failures (photo credit: Ron T. Eguchi, ImageCat).

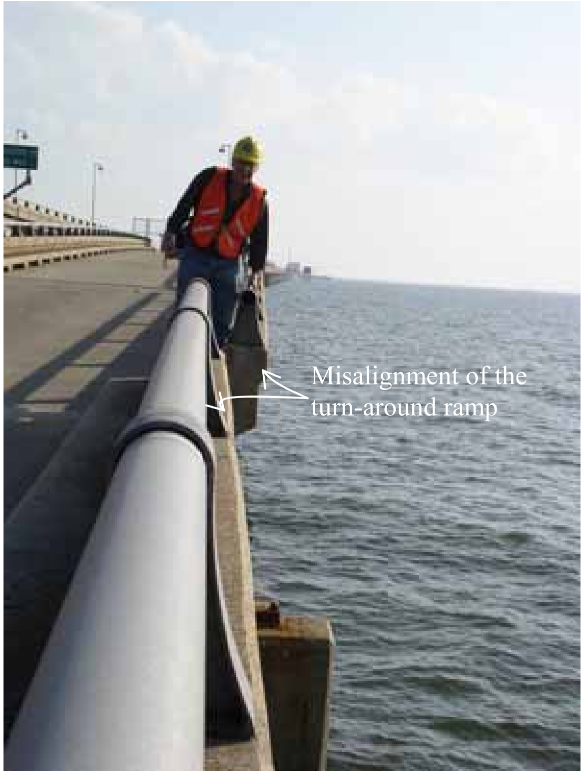


Figure 4-35 Misaligned spans of the Toll Causeway's turn around ramp (photo credit: Ron T. Eguchi, ImageCat).

Figure 4-36 Steel Bearing Plates/Shear Keys connection between the superstructure and the bridge piers (photo credit: Ron T. Eguchi, ImageCat)

4.2.1.2 Bridges over St. Louis Bay

St. Louis Bay is part of Bay St. Louis, Mississippi, and is about 30 miles east of Lake Pontchartrain. It is on the east side of the path of the eye of Hurricane Katrina and is the site of the greatest surge. There are two bridge crossings over St. Louis Bay: the US-90 bridge and the CSX railroad bridge. The US-90 bridge carries vehicular traffic of coastal US-90 in the east-west direction, connecting points along the Gulf coast such as Long Beach, Pass Christian, and Waveland in Mississippi. The CSX railroad bridge carries rail traffic along the Mississippi coast into and out of eastern New Orleans. Figure 4-37 shows the locations of the US-90 and the CSX railroad bridges over St. Louis Bay.

Figure 4-37 Bridges over St. Louis Bay (© Copyright 2006 Garmin Ltd. or its subsidiaries. All rights reserved. Map data © 2002 NAVTEQ. All rights reserved. Enhancement by NIST)

US-90 bridge The US-90 bridge is a 1.8 mile long, four-lane, low-water crossing concrete bridge with operating bascule (moveable) spans across the navigation channel of the Bay. It is located slightly north of the CSX railroad bridge over St. Louis Bay. Similar to the construction of the Toll Causeway and the US-11 bridges over Lake Pontchartrain, the US-90 bridge is also a simply supported, multi-span concrete bridge. Its superstructure consists of simply supported, prefabricated and monolithically cast spans, each comprised of an 8 in.-thick concrete bridge deck with fascia section and eight rectangular concrete girders (1ft-7 in. x 2 ft-11 in.) at 7 ft-11 in. spacing across the span. Each superstructure span is simply supported on concrete piers with steel bearing blocks. The connection between the superstructure span and the piers is mainly by gravity and provides little restraint against transverse lateral and uplift displacements. The cap beam of the pier does not have shear blocks and thus provides minimal restraint against lateral displacement of the superstructure spans. As was typically observed for this type of bridge construction subjected to storm surge and wave actions, most of the US-90 bridge's superstructure spans were displaced and dropped from the supporting piers. Figure 4-38 shows the US-90 bridge with the displaced and dropped superstructure spans. Figures 4-39 (left) shows the detailed connection (steel bearing blocks) between the superstructure span and the pier. Many of the US-90 bridge's piers were also lost, possibly due to tidal scour (i.e. undermining). Figure 4-39 (right) shows some remaining piers of the US-90 bridge over St. Louis Bay.

Figure 4-38 **Displaced and dropped superstructure spans of US-90 bridge over St. Louis Bay (photo credit: NIST).**

Figure 4-39 **Steel bearing blocks (left, photo credit: NIST) and few piers remain in this section of US-90 bridge over St. Louis Bay (many piers scoured out in the surge) (right, photo credit: J. O'Connor, MCEER).**

CSX Railroad bridge. The CSX railroad bridge over St. Louis Bay is also a concrete bridge, consisting of simply supported spans. Each span is a monolithically cast unit comprising of a 17 ft-6 in. wide concrete deck and a 10 ft-2 in. wide rectangular concrete box girder. Each individual superstructure span is simply supported, with one end resting on one concrete pier by gravity, while the other resting on the adjacent pier also by gravity is further restrained against longitudinal and transverse displacements by capping over three reinforcing bars protruding about 8 in.from the piers and acting as dowels. Further restraint against transverse lateral displacement of the superstructure span is provided by 4 in. high concrete shear keys on the cap beam.

Despite the restraint against lateral displacements provided by the 4 in. concrete shear keys and the 8 in. dowel bars, many of the superstructure spans of the CSX railroad bridge were displaced and dropped into the Bay due to surge-induced wave actions. This suggests that the uplift wave forces (buoyancy) were able to overcome any restraint against vertical displacement and lift the spans high enough (over 8 in.) for them to move off the piers and drop into the water. Most of the bridge piers appeared to have sustained no damage from wave actions, with a few piers sustaining minor damage probably due to impact by the displaced superstructure spans. Figure 4-40 shows the piers of the CSX railroad bridge with missing superstructure spans.

Figure 4-40 CSX railroad bridge with remaining spans (top) and the supporting piers (bottom) (photos credit: NIST).

4.2.1.3 Bridges over Biloxi Bay and Back Bay

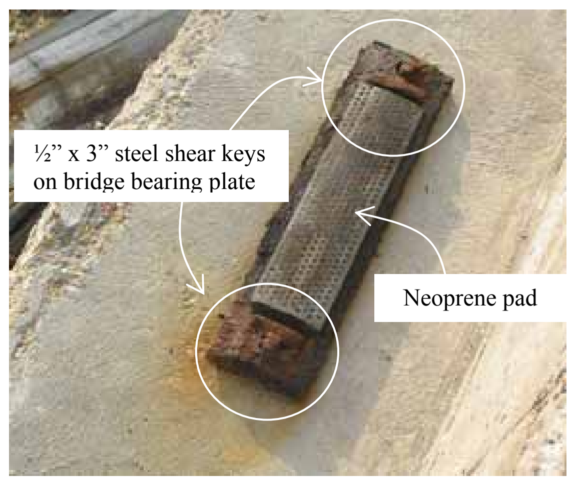
Less than 30 miles east of Bay St. Louis along the Mississippi coast line are the Bay and Back Bay of Biloxi. Here, the surge due to Hurricane Katrina was measured to be approximately 22 feet. There are five bridge crossings over the Bay and Back Bay of Biloxi. These include the US-90 (Biloxi-Ocean Springs) bridge, the CSX Biloxi-Ocean Springs railroad bridge, the I-110 bridge, the D'Iberville bridge, and the Popps Ferry bridge (see Figure 4-40). All are concrete bridges. The D'Iberville bridge is an old bridge that no longer carries vehicular traffic and is used mainly as a pedestrian bridge and a fishing wharf.

Figure 4-41 Bridges over Bay and Back Bay of Biloxi, Mississippi (© Copyright 2006 Garmin Ltd. or its subsidiaries. All rights reserved. Map data © 2002 NAVTEQ. All rights reserved. Enhancement by NIST)

US-90 bridge. The US-90 bridge (Biloxi-Ocean Springs) is a 1.6 mile long, four lane, concrete bridge. Most of the bridge has low elevation except for the segment toward the middle of Biloxi Bay at the navigation channel where the superstructure was gradually raised higher to allow passage of boat traffic. The superstructure is comprised of simply supported spans with 42 feet long pre-stressed concrete I-girders. The substructure consists of multiple bents (concrete piers and cap beams). Each superstructure span was supported on the pier through steel bearing plates, which were bolted on top of the cap beam of the pier and cast into the bottom of the bridge girder. The steel bearing plate on top of the pier has low-rise steel shear keys (½ inch thick) at each end to provide restraint against lateral displacement (see Figure 4-43(b)). There is no provision for restraint against vertical displacement except for gravity.

The superstructure of the US-90 Biloxi-Ocean Springs bridge was subjected to direct surge and wave actions and sustained significant structural damage. The lack of positive connection between the superstructure and the supporting piers allowed many individual superstructure spans to be lifted up and displaced transversely northward (in the direction of the waves) and either partially or completely dropped into the water (see Figure 4-42). The ½ inch low-rise steel shear keys on the bearing plates were clearly unable to provide restraint against the combined uplift and lateral wave forces. The superstructure spans that were constructed at a higher elevation near the navigation channel, i.e. spans above an elevation of approximately 22 feet, were apparently high enough to avoid direct surge and wave actions and survived intact (see Figure 4-43(a)).

Figure 4-42 Looking west toward Biloxi from the east shore, many superstructure spans of US-90 Biloxi-Ocean Springs bridge were displaced north off their piers (photo credit: J. O'Connor, MCEER).



(a) **(b)**

Figure 4-43 (a) Looking west toward Biloxi, spans above the surge line near the navigation channel survived, but the superstructure in the foreground was dropped off the piers (photo credit: J. O'Connor, MCEER), (b) A typical bearing plate from the US-90 bridge with ½ in. thick shear keys (photo credit: NIST).

CSX Railroad bridge. The CSX Biloxi-Ocean Springs railroad bridge successfully survived Hurricane Katrina's surge and wave actions with only minor structural damage despite being a low-water crossing and subjected to the same forces that destroyed the US-90 bridge slightly to its south. Its superstructure is comprised of simply supported spans, each consisting of a 9 in. thick, 17 feet wide concrete bridge deck cast on top of four 4 ft-10 in. deep pre-stressed concrete girders with I-section. The four girders are further tied together to perform as a unit using 1 ¼ in. diameter threaded bars (see Figure 4-44). Each superstructure span rests on the cap beam of the bridge piers, with vertical uplift resisted only by gravity. On both ends of the cap beam, there are two 15 in. high concrete shear blocks to provide restraint against lateral displacement of the superstructure span.

The bridge had its railroad tracks and ties completely washed off by wave forces, but the superstructure remained largely intact and connected to the supporting bridge piers. This successful performance is in contrast with the adjacent US-90 bridge and the CSX Pass Christian-Waveland railroad bridge over St. Louis Bay, which were completely destroyed. This is likely[15] due to the presence of the high shear blocks (15 in.) at the end of the pier cap beams that confined and restrained the girders from being displaced transversely by lateral and uplift wave actions. Some of these shear blocks were damaged and later repaired by CSX. This is evidence that they were indeed carrying load and contributing to their horizontal restraint.

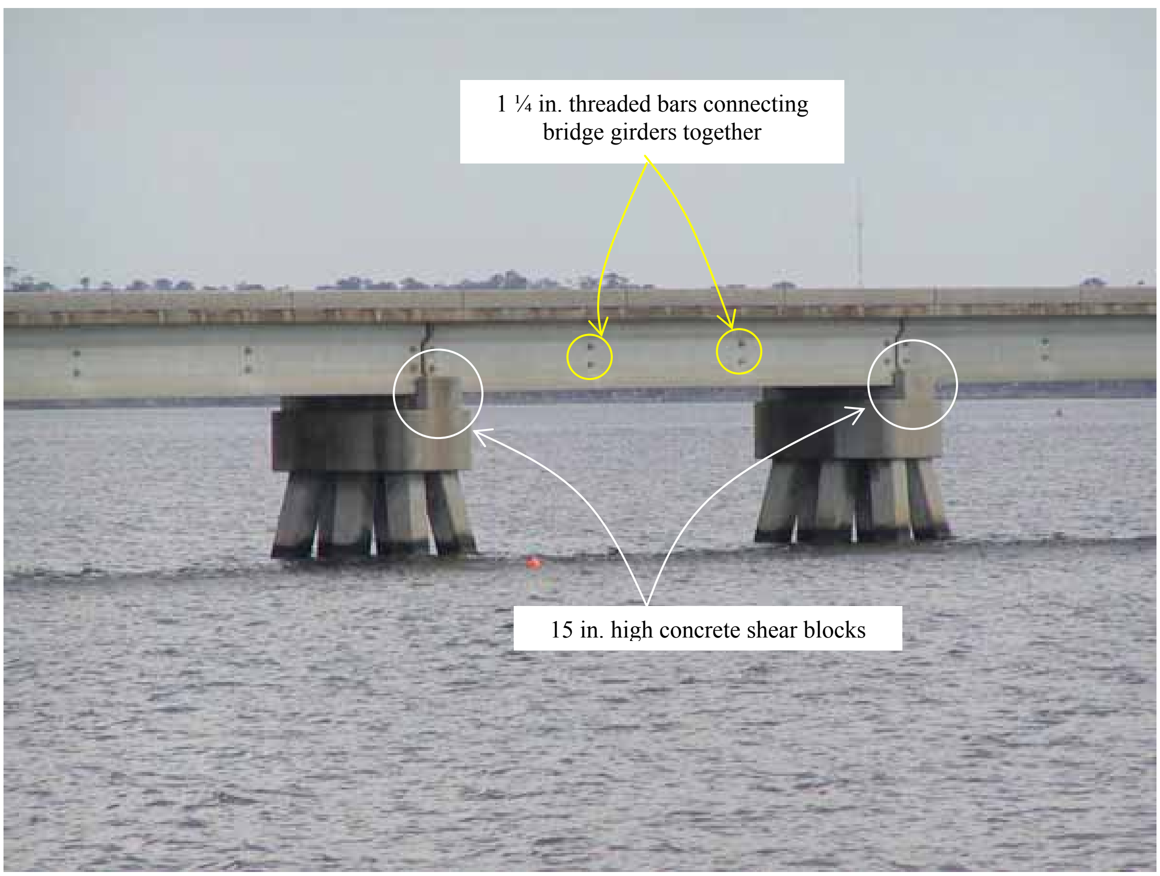


Figure 4-44 The CSX railroad bridge survived with minor damage, most likely[15] due to the presence of high shear blocks (photo credit: LA DOTD).

I-110 bridge and I-110 bridge ramps. The I-110 bridge and the I-110 bridge ramps are part of the I-110 highway system that connects the two major coastal highways, I-10 and US-90, and carries traffic in the north-south direction over the Back Bay of Biloxi (see Figure 4-41). Due to its high elevation, the superstructure of the I-110 bridge was not directly affected by Hurricane Katrina's surge and wave actions and thus sustained no structural damage. The surge carried in a barge that hit one or two supporting piers near the navigation channel causing the bridge to be briefly closed down following Hurricane Katrina for inspection, but the damage was repaired fairly quickly and the I-110 bridge was fully reopened shortly thereafter.

At the southernmost end of I-110, immediately adjacent to the beach and Gulf, are ramps connecting I-110 (which runs north-south) and US-90 (which runs east-west) (see Figure 4-41). The I-110 bridge ramps are cast-in-place, continuous concrete box girder bridges. The superstructure has gradually changing elevation and is positively connected to some of the supporting piers through cast-in-place connections. These bridge ramps are very close to the beach and aligned transversely along the shore line, making them fully exposed to direct effects of Hurricane Katrina's surge and wave actions. However, despite the full effects of the surge and wave forces, the I-110 bridge ramps survived intact. This can likely[15] be attributed to the continuity of the superstructure and the positive connection between the superstructure and the bridge piers. Figure 4-45 shows a view looking south (toward the Gulf) of the I-110 bridge ramps taken on September 29, 2005. Although the I-110 bridge ramps are not over the bays under discussion, they are in the area and because of their proximity to the Gulf were likely[15] subjected to similar surge and wave actions as the bridges over the bays. They are, therefore, included in this discussion for comparison purposes.

Figure 4-45 I-110 bridge ramps with cast-in-place, continuous box girder superstructure positively connected to bridge piers (photo credit: NIST)

D'Iberville bridge. Parallel and adjacent to the I-110 bridge, but at a lower elevation, is the concrete bridge crossing to D'Iberville (Figure 4-46). The old bridge, which had been used as a pedestrian bridge and fishing wharf, lost several spans, most likely[15] from scour, since the piers were also missing. The spans that remained had sections of railing broken off, probably from wave impacts.

Figure 4-46 Back Bay facing southeast. D'Iberville bridge lost several spans and piers. I-110 bridge was hit by a barge, damaging some of the supporting piers (photo credit: MSDOT, provided by J. O'Connor, MCEER).

Popps Ferry bridge. The Popps Ferry bridge is a bridge crossing located further west in the Back Bay of Biloxi (see Figure 4-40). It is a concrete bridge with non-continuous, simply supported superstructure spans seated by gravity on concrete piers. Due to the lack of restraint against lateral displacement in the transverse direction, many superstructure spans of the Popps Ferry bridge were laterally displaced by several feet by storm surge and wave actions (Figure 4-46). However, none of the displaced spans was dropped from the supporting piers. In addition to the misalignment of the spans, the lift spans in the middle of the bridge were rendered inoperable, and a section of the fascia and concrete barrier were observed to have been broken up, apparently[15] due to impact of surge-borne debris (Figure 4-47).

Figure 4-47 Displaced spans of Popps Ferry Bridge (photo credit: J. O'Connor, MCEER)

Figure 4-48 Broken curb rail, Popps Ferry bridge (photo credit: J. O'Connor, MCEER)

4.2.1.4 Bridge Over Pascagoula River

Many bridges were not subjected to direct effects of Hurricane Katrina's storm surge and wave actions, but nevertheless sustained structural damage due to impact by surge-borne debris. The US-90 bridge over the Pascagoula River in Mississippi, approximately 45 miles east of the storm track, is one such bridge. Storm surge in the eastern part of the state caused several barges to break loose from their moorings and strike the eastbound lanes of the US-90 bridge, causing misalignment of the superstructure spans (over four feet to the north, see Figure 4-49) and tipping of piers. The damage required the complete replacement of six spans (about 300 linear feet).

Figure 4-49 US-90 bridge over Pascagoula River with displaced spans due to barge's impact (photo credit: MSDOT, provided by J. O'Connor, MCEER)

4.2.1.5 Bridges over Mobile Bay, Alabama

Although Mobile Bay, Alabama was almost 100 miles from the eye of the storm, it saw a rise in water elevation of over 10 feet. At the I-10 bridge over Mobile Bay, storm surge washed out the approach. Where US-90 merges onto I-10 eastbound, the ramp bridge has some spans displaced northward (Figures 4-50 and 4-51). At another site in Mobile, Alabama, a large new cable stay bridge over the Mobile River, the Cochrane-Africatown USA bridge, was hit by a 13,000 ton oil drill rig that had broken free of its moorings. The bridge spans were shifted 4 inches due to the impact (Figure 4-51). This made it necessary to post the bridge with a weight restriction and reduce the number of traffic lanes on it from four to two while a detailed assessment of damage was performed.

Figure 4-50 Surge waters overtopped US I-10 bridge ramp over Mobile Bay. View is eastbound, taken on the same day Hurricane Katrina hit (8/29/06). (Photo credit: George Conner, MSDOT)

Figure 4-51 Bridge spans pushed north by the surge (photo credit: LA DOTD, provided by J. O'Connor, MCEER).

Figure 4-52 The Cochrane-Africatown USA bridge was hit by an oil rig that had been swept to Mobile Bay by Hurricane Katrina's surge. The impact displaced the bridge spans by four inches, necessitating the restriction of traffic on the bridge (photo credit: LA DOTD, provided by J. O'Connor, MCEER).

4.2.2 Moveable Bridges

Highways and roads in Louisiana, Mississippi, and Alabama have a variety of moveable bridges, including lift spans, swing bridges, and bascule bridges (drawbridges). Many of these bridges sustained structural damage due to the direct effects of Hurricane Katrina's surge and wave actions. In addition, many of these moveable bridges sustained flood damage to motors and controllers and were rendered inoperable. Flooding of control rooms and/or mechanical rooms caused failure of electrical systems and jamming of gear mechanisms (Figure 4-53). Even when repairs were made quickly, commercial power was typically unavailable for several weeks after the storm. In some cases, auxiliary diesel generators were available to operate the bridges; however, such operations are time-consuming and are undertaken only in emergency situations. Examples of these problems include the Portage Bridge on Hampton Road in Pass Christian and the swing bridge on US-82 at the Texas-Louisiana state line, which was closed due to undermining of the Louisiana approach and damage to the bridge railings. Because these bridges could not be used following the disaster, recovery efforts were delayed. The lift spans carrying US-90 over St. Louis Bay became inoperable in the down position and had to be removed under emergency contract to clear the navigation channel for vessel traffic (Figure 4-54).

Figure 4-53 Typical debris buildup in the gear mechanism of a moveable bridge (photo credit: LA DOTD, provided by J. O'Connor, MCEER).

Figure 4-54 The lift spans of the US-90 bridge over St. Louis Bay became inoperable, blocking use of the channel by vessels (photo credit: J. O'Connor, MCEER).

4.2.3 Pavement – US-90 and US-82

The transportation network in the hurricane-affected regions was left severely debilitated as a result of damage to bridges, as well as damage to pavement due to undermining and debris deposit. From Biloxi westward, the pavement of US-90 was undermined in many locations, and was left either buckled or dropped into sinkholes. Some sections of US-90 west of Biloxi were somewhat protected by a concrete seawall between the eastbound lanes and the beach (Figure 4-55). It appears that the highway was submerged by rising water before the storm surge impacted that area and was thus protected from the most violent wave action. From Long Beach to Bay St. Louis, there were many stretches of highway pavement sustaining heavy localized damage due to the effects of Hurricane Katrina.

Pavement scour was observed on US-82 along the Gulf coast of western Louisiana from Sabine Pass, through Cameron to Creole, where the road had little protection from the surge induced by Hurricane Rita.

Other typical hurricane-induced damage to pavement was scour and erosion at the approaches to bridges or near bridge abutments. In many cases, the bridges survived the hurricane yet were unavailable for recovery efforts until the approaches could be rebuilt.

Figure 4-55 Seawall along US-90 protected much of the pavement from being undermined and washed out (photos credit: J. O'Connor, MCEER).

4.2.4 Railroads

The primary rail service corridor in the areas of Mississippi and Louisiana affected by Hurricane Katrina lies between I-10 and US-90. For the most part, the rail line consists of a single track on a raised bed. The rail bed was scoured out and suffered a variety of debris impacts. Some rail cars were also derailed by storm surge. However, the most significant damage to rail line was observed at water crossings where the rail line is supported by bridges.

Extensive damage to railroad bridges at major water crossings in the affected region, discussed in section 4.2.1, also resulted in significant damage to rail lines and disruption of rail service. The ties and tracks of railroad bridges at Pascagoula and St. Louis Bay were lost when the bridges' superstructures were displaced off their supporting piers by storm surge, making the entire line unusable. In some cases, i.e. Biloxi Bay and Lake Pontchartrain, the railroad bridge structures suffered little or no structural damage; however, the rail, ties, and ballast were still completely stripped off the bridge by wave action. Typically, the rails are laid in quarter mile sections that are end welded and spiked to the ties to provide a continuous track, but are not fastened to the bridge structure. As much as two miles of rail were washed off some bridges and their approaches. Figures 4-56 and 4-57 show some damage to the rail line due to Hurricane Katrina.

Figure 4-56 The superstructure was lost on this railroad bridge along the Mississippi coast, leaving only the dangling tracks and the substructure units (photo credit: J. O'Connor, MCEER).

Figure 4-57 CSX railroad bridge over Biloxi Bay after tracks and ties were washed off by storm surge and wave action (photo credit: J. O'Connor, MCEER)

4.2.5 Airports

Commercial air facilities at Gulfport and Stennis, Mississippi, New Orleans, Lakefront, and Slidell, Louisiana, and Port Arthur, Texas, suffered cladding and water damage from Hurricane Katrina. Storm surge caused extensive damage to a large hangar at Lakefront Airport in New Orleans, while wind damaged a hangar at Stennis Airport (Figure 4-58). Debris and electrical power outages, as well as minor flooding, disrupted airport operations, but flight services were restored quickly.

Figure 4-58 Hangar damage at Stennis Airport, Mississippi (photo credit: NIST)

4.3 SEAPORTS

Ports provide both immediate and on-going support for re-supply and recovery of the regional economy. Port facilities visited by the NIST-led reconnaissance team included: Mobile, Alabama; Pascagoula, and Gulfport in Mississippi; New Orleans, Louisiana; and Sabine Pass, Orange, and Port Arthur in Texas. As expected, the extent of damage observed increased with the proximity of the port to hurricane landfall.

4.3.1 Port of Gulfport, Mississippi

The port facilities sustained major structural damage to piers, wharves, and warehouses and were not functional at the time of the visit. Most of the damage can be attributed to Hurricane Katrina's storm surge and waves, but extensive damage to sheet metal roofs and walls of warehouses that were above storm surge and wave elevation showed that wind and debris impact were contributing factors. Most of the heavy warehouse steel frames were still standing, although some were severely twisted. The inside of the warehouses, however, was totally wrecked (see Figures 4-59 to 4-61).

The two main piers, which supported warehouses and loading/unloading facilities, were severely damaged. The older of the two, the West Pier, consisted of a wharf supported on timber piles. It appears that pile failure led to collapse of the wharf (Figures 4-62 and 4-64). Port officials noted that the West Pier, the port's busiest, was old and in relatively poor condition, and plans were actually being developed to replace it before Hurricane Katrina hit.

The newer East Pier was a concrete pile-supported structure that was built in stages, with the newest section completed in 2000. Major portions of the pier failed along joint lines under what appeared to be upward pressure (Figures 4-63 and 4-64), caused by storm surge, via water or entrapped air. The foundation wall and piers, however, appeared intact where visible. The Mississippi State Port Authority plans to investigate the failures.

There was also extensive damage to the port's fender systems and rail lines. Utilities, infrastructure, and the Mississippi State Port Authority's administrative and support facilities were completely destroyed. A 30 metric ton capacity lifting crane had three of four hurricane tie-downs lost to storm surge and waves, but appeared otherwise structurally unaffected. Motors on cranes and other equipment were damaged by flooding (see Figure 4-65).

Moored, loaded barges drifted over the port area due to the storm surge and waves. Battering from these barges caused or contributed to the destruction of some port facilities, particularly a commercial fishing fleet dock on the west side of the port. Many of the barges settled on the north side of US Hwy. 90, approximately one-quarter mile inland. Aids to navigation in the channel were destroyed, and the navigation channel depth was reduced by debris accumulation or sand bed migration.

Very limited electrical service was restored after approximately six weeks, but it was inadequate for most cargo operations, and the port was unable to load/offload containers from ships.

Figure 4-59 Damaged warehouse at Port of Gulfport (photo credit: NIST)

Figure 4-60 Damaged warehouse at Port of Gulfport, with steel frames still standing (photo credit: NIST)

Figure 4-61 Damaged warehouse at Port of Gulfport, collapsed steel members (photo credit: NIST)

Figure 4-62 West Pier, showing collapse of wharf structure due to pile failure (photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)

Figure 4-63 East Pier, showing damage to cargo shed deck and sheet metal siding (photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)

Figure 4-64 **Wharf buckled upward due to storm surge pressure (photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)**

(a) **(b)**

Figure 4-65 **(a) Container crane with tie-down damage at Port of Gulfport, Mississippi and (b) Broken restraint (photo credit: NIST)**

4.3.2 Port of New Orleans

The Port of New Orleans is one of the busiest in the country and, together with the Port of Gulfport, accounts for approximately 25 percent of U.S. shipping. Container cranes are critical to the operation of such facilities, and three container cranes were damaged in Hurricane Katrina. Each was secured with four hurricane tie-down connections designed for hurricane winds (Figures 4-66a and b). The tie-downs were overstressed, resulting in tension failure of several of the 2 in. threaded rods. All three cranes were pushed as far as 50 feet, ending up together at the end of wharf. One crane was also pushed off track and had a wheel carriage broken. Replacement or repair of this equipment can be problematic because it is not easily transported and has long lead times for assembly and delivery.

(a) **(b)**

Figure 4-66 Damage to crane wheel carriage (a) and restraints (b) (photo credit: NIST)

4.3.3 Mobile, Alabama

The Alabama State Docks/Port of Mobile facilities are located near the head of Mobile Bay. These facilities were near the easternmost limit of Hurricane Katrina's effects, and were well inland (30 miles) of the Gulf of Mexico, which helped reduce the impact of the storm. Most damage was associated with submergence of electric motors on container cranes and coal dock loaders. Wind damage was modest and was primarily confined to warehouse sheet metal cladding and doors. Although empty shipping containers were placed in a staging area and surrounded by loaded boxes, many of the containers floated free and caused minor damage to port facilities. Debris, including large trees and other materials that had been washed down into Mobile Bay in past floods, were carried back up the Bay by the surge and waves and caused minor damage to fences and other light shoreline structures.

Navigation channels were not significantly impacted, and port operations were not severely disrupted.

4.3.4 Pascagoula, Mississippi

Hurricane Katrina's impacts on the Jackson County Port Authority/Port of Pascagoula were slightly worse than at Mobile Bay, Alabama to the east. Primary damage was to electrical equipment (motors, controllers, panels, etc.) that was submerged in the flooding. Washouts occurred under some facilities and large equipment stations, but there was no significant structural damage. Wind damage was modest and consisted mainly of sheet metal roofs blown off warehouses and doors blown in.

Navigation channels in the area were not substantially impacted, and port operations were not severely disrupted. The low level of damage is attributed to the location of the port relatively far from the hurricane and the open waters of the Gulf of Mexico.

4.3.5 Port Arthur, Texas

Located well inland on Sabine Lake, Port Arthur, Texas did not suffer any storm surge and wave damage from Hurricane Rita; however, warehouses of differing construction suffered wind damage. The port was functioning at the time of the visit.

One warehouse, measuring 480 feet by 210 feet in plan, had a roof system constructed of light gauge steel panels and open web steel joists supported on perimeter steel frames. The roof suffered cladding damage, and several overhead doors were blown off.

Another warehouse, measuring 600 feet by 210 feet in plan, had a roof system constructed of double-T concrete roof panels resting on steel frames (Figure 4-67). The external overhang on the northwest side of the building was damaged when concrete panels blew off and subsequently hit and damaged several overhead doors.

The newest warehouse observed by the team, built in 2003 and measuring 510 feet x 240 feet in plan, had a roof consisting of a PVC-coated polyester architectural fabric tensioned over light, galvanized steel trusses (Figure 4-68). As the hurricane wind entered on the open north side of the warehouse, the wind pressure caused the south wall and roof to balloon outward. The ballooning fabric was pierced by lamp posts outside the warehouse, which initiated tears that eventually ruptured the wall and southern half of the roof.

Figure 4-67 Concrete double-T beam blow-off on warehouse overhang, Port of Port Arthur, Texas (photo credit: NIST)

Figure 4-68 Fabric roof failure on warehouse, Port of Port Arthur, Texas (photo credit: NIST)

4.3.6 Port of Sabine Pass, Texas

The roof and boardwalk of the dock and the envelope of the port authority building were damaged, apparently[15] due to wind from Hurricane Rita, although there was evidence of storm surge and waves over 5 feet in the township of Sabine Pass, approximately ½ mile from shoreline. The warehouse at Gabby's Dock suffered envelope damage, apparently[15] due to storm surge, waves and debris impact.

4.3.7 Port of Orange, Texas

There was evidence that Hurricane Rita caused slight flooding at the Port of Orange, with water levels 1 foot to 2 feet above dock level. Several warehouses of steel frame construction suffered damage to the roof and envelope, but not to the steel frames. Of the two types of overhead doors at warehouses at the Port of Orange, light metal doors were damaged, but heavier ones were not. One of the warehouses, measuring 600 feet x 150 feet in plan, had a concrete roof that consisted of channel sections resting on steel frames. Some of these panels were blown off at several locations. In contrast, the port office, located in a Spanish mansion built in the early twentieth century, suffered only the loss of some roof tiles and one window broken by debris.

4.3.8 Signs, Traffic Control Devices, and Lighting

The entire Gulf Coast region suffered extensive loss of traffic control devices such as traffic lights, regulatory signs, and directional signs. This made driving conditions hazardous in the aftermath of the storm and hampered recovery operations overall. For the most part, mast-arm installations for traffic control signals fared better than suspended signals. The Mississippi Department of Transportation reported damage by Hurricane Katrina to 12,000 roadway signs, but was able to restore most signals by September 19, 2005. Although the assessment team observed no downed overhead traffic signs, the FHWA Louisiana office reported that such damage had occurred due to Hurricane Katrina but had been cleared away quickly for rescue and recovery operations.

Much of the roadway lighting in the median of US Hwy. 90 between Pascagoula and Ocean Springs, Mississippi was destroyed when the fiberglass poles broke off near the base. The damage was most likely[15] from storm surge and waves, as several boats were found grounded in the same area.

Almost all large, tall advertising signs along US I-10 were severely damaged from both hurricanes (Figure 4-69). This damage included missing panels, structural failure of large tubular columns, and complete foundation failure in swampy soil.

Figure 4-69 Typical billboard failures along US Interstate 10 near Beaumont, Texas (photo credit: NIST)

4.4 UTILITIES

Many utility companies (electric power, natural gas, potable water, wastewater and communication systems) reported significant loss of service, extensive damage to equipment, and difficulty accessing damage zones because roads were blocked by fallen trees, downed electrical lines, and debris deposited by wind, storm surge and waves.

4.4.1 Electric power

4.4.1.1 Service Disruption

Mississippi Power Company, a subsidiary of Southern Company, provides electricity in the southern third of the state (Gulfport to Meridian), the area affected by Hurricane Katrina. Mississippi Power serves primarily municipal areas, whereas rural areas are served by electric power cooperatives. Some 200,000 Mississippi Power customers lost power as a result of Hurricane Katrina. Recovery operations were further hindered by the loss of the use of corporate offices in Gulfport due to water infiltration. Linkage to the 800 MHz Southern Company link allowed good communications for Mississippi Power repair crews in the immediate aftermath of the storm, and also provided alternatives to landline and cellular telephone services for local government agencies and other responders.

Overall, Mississippi reported that 402 cable support towers were broken, leaning, or required major work to repair damaged conductors, insulators and switchgear. Most of the damaged support towers were classified as follows:

78 structures on 46 kilovolt (kV) systems,

177 on 115 kV systems,

47 structures on 230 kV systems,

1 structure on a 500 kV system.

In most cases, the damage was attributed to trees falling on equipment, windborne debris, and the effects of wind whipping the lines against insulators and equipment. In some instances, line failures resulted in cascading tower collapses due to unbalanced line tension. Electrical service was restored throughout most of the service area within 10 days after the storm. By September 10, 2005, every industrial customer, and most other customers had power available (approximately 165,000 overall). By October 20, 2005 service was available to approximately 175,000 customers. At the time of the site visit power was available in even the most heavily damaged areas, although most customers in those areas were still unable to accept service.

Entergy is the main power company in New Orleans, southern Louisiana and east Texas. Entergy suffered significant damage to its distribution and transmission structures, as well as some flooding at power stations. It was reported that in excess of one million distribution poles were lost in the two hurricanes, with the main loss attributed to tree fall, storm surge, and waves. In the east Texas region, Entergy lost its seven main high voltage transmission lines with failures of lattice steel or timber towers. These failures were caused by wind, and many were of a cascading nature (e.g., failure of one tower caused failure in adjacent towers due to tension forces in the wire). Typically, the towers at the most exposed river and estuary crossings collapsed. These areas are also the most difficult to repair because the swampy terrain makes access extremely difficult.

4.4.1.2 Transmission Lines

Many transmission lines in Mississippi, southern Louisiana, and east Texas were affected by Hurricanes Katrina and Rita. Following Hurricane Katrina, there were only two power lines energized in southern Mississippi, and both were fed from Alabama. Power available from those lines could not be routed to the affected area due to the extensive damage to transmission lines. The lack of interconnection with less affected power companies in east Texas led to delays in re-establishing electric power in that region. Damage to transmission lines ranged from complete toppling of several 100-foot-tall lattice tower river crossings (Figure 4-70), to felled timber H poles, to insulators broken from line whipping.

Figure 4-70 Failure of transmission line lattice tower on the Neches River (Ocean Springs to Moss Point) near Bridge City, Texas following Hurricane Rita (photo credit: NIST)

4.4.1.3 Distribution Systems

The loss of distribution poles (largely timber) to storm surge and waves and wind is unprecedented; over a million poles must be replaced as a result of Hurricanes Katrina and Rita (Figure 4-71). Restoration work was impeded by the enormous amount of debris on roadways and near substations and other equipment sites. Traffic presented additional challenges: roads that were not blocked were in heavy use by the huge workforce responding to the storm damage.

In addition to physical damage and debris lodged on lines and towers, Mississippi Power reported that salt spray contamination on insulators and other equipment was a major concern. The salt accumulations had to be removed before the lines could be re-energized. Although salt accumulation is not unusual in coastal areas, the impacts from Hurricane Katrina were far worse than from past storms, reaching 10 miles to 15 miles inland. Municipal fire departments contributed significantly to the restoration of electric power by using high pressure pumps to wash the salt off lines and equipment. Even so, Mississippi Power expects ongoing problems and accelerated corrosion as a result of salt contamination.

Figure 4-71 Distribution lines on US Route 82 in Louisiana damaged by Hurricane Rita (photo credit: NIST)

4.4.1.4 Generating Plants

Mississippi Power has three major generating plants in the region:

- Watson Electric Generating Plant (Plant Watson) at 10406 Lorraine Road in Gulfport, just south of US Interstate 10 and east of US 49;
- Daniel Electric Generating Plant (Plant Daniel) on Highway 63 North in Escatawpa; and
- Chevron Pascagoula Refinery COGEN (Chevron COGEN) Plant on Bayou Casotte in Pascagoula.

The Chevron COGEN and Plant Daniel suffered only minor damage to buildings, cooling towers, and auxiliary equipment from wind and flooding. Service was restored quickly at both generating plants. As a result of having raised the height of the protective levees and electrical equipment after Hurricane Georges in 1998, the plants reported a lower level of flooding and flood impacts than they had experienced in past hurricanes.

Plant Watson, however, experienced flooding of critical pumps and controllers, which were below flood level. This led to long delays in cleanup, repair, and re-start. A major problem in getting Plant Watson back on line was the lack of electric power needed for startup of the auxiliary equipment. Under normal conditions, power is available from alternate sources, but in this case, the entire regional system was down.

Entergy's Neches River power station near Port Arthur, TX had to be shut down when its major transmission lines were damaged and/or downed. In addition, cooling tower shrouds and fans were ripped away by extreme wind, as was some cladding on the station itself. The Entergy power station at Sulphur, near Lake Charles, LA, also lost transmission capability when several 500 kV lattice towers collapsed.

At Entergy's Michoud power generation facility, flooding at a nearby substation resulted in damage to relays and relay protection equipment. Other damage common to power plants in the hurricane-affected region included:

- Loss of cooling tower shrouds and fans;
- Piping;
- Flooding damage to switchgear and transformer houses;
- Fuel tanks floated off their foundations; and
- Damaged electric motors on coal yard equipment.

4.4.1.5 Substations

Low-lying power substations in Mississippi and Louisiana, particularly in areas affected by storm surge and waves from Hurricanes Katrina and Rita, suffered significant damage to controllers, switches, and other components (Figure 4-72). There was no physical damage to the transformers, although oil reservoirs on older equipment were flooded and had to be drained, flushed, and refilled. Most equipment enclosures survived with only minor to moderate damage from wind and debris.

Saltwater promotes rapid corrosion of electrical components. Even equipment that was pressure washed with clean water immediately after the storm will have to be replaced sooner than would otherwise be the case.

Figure 4-72 Substation damaged by surge and waves on US Route 82 in Louisiana following Hurricane Rita (photo credit: NIST)

4.4.2 Natural Gas Service

Because major gas system components were underground, there was no reported damage. Gas service was not affected by the loss of electrical service. Gas mains were not affected by storm surge and waves, but there was some damage to regulator stations throughout the surge and waves impact zone in Mississippi. Although the gas distribution system was not damaged, selective system shutdowns were necessary to stem the uncontrolled venting of gas to the atmosphere at damaged homes and businesses.

4.4.3 Potable Water

Mississippi coastal communities obtain their water from city-owned and -operated deep wells located throughout the communities, generally in individual neighborhoods and developed areas. There are no water treatment plants and no surface treatment of water, as the excellent water quality requires only chlorination. Each well site has an electrical pump and a chlorine injection system, while some sites have backup generators. The cities provide fresh water to residents and businesses through a system of lift stations, elevated storage tanks, and distribution piping. All of the regional systems were shut down for several days because of loss of electrical power. There was no damage to the elevated tanks throughout the region and little damage to water mains. There was significant damage, however, to water well equipment and distribution piping due to storm surge and waves.

In addition to the loss of electrical service, restoration of water service was hampered by the scope of damage, difficulty in gaining access to cut-off valves due to debris, and insufficient repair part inventories to respond to an event of such magnitude as Hurricane Katrina. Restoration of service was further challenged by the loss of system pressure due to massive damage to distribution networks at the user level.

Fire main systems and domestic potable water systems are fed from common mains. Many fire hydrants were sheared off in the surge and wave zone and, along with massive damage to individual customer service lines, allowed uncontrolled flow of water. Although service was nearing normal levels at the time of the NIST field surveys in October 2005, the communities anticipate ongoing long-term problems and accelerated rates of equipment failures due to saltwater damage to motors, pumps, electrical components, and generators.

The city of Beaumont, Texas, lost water supply because a roller door on the backup power generator failed (Figure 4-73). The five-year-old Caterpillar backup generators sustained transformer damage, it was difficult to locate spare parts and qualified technicians, and repairs were not completed for nearly 48 hours. Power was not re-connected and consequently communication with outlying pump stations was lost for approximately a week. This meant that water could not be stopped from arriving at the treatment plant, and had to be dumped into the street. Reaching the remote pump stations was very difficult due to extensive tree damage.

The fiberglass chemical storage tanks, which were exposed without protection from debris, survived intact. After the water supply was restored, there were major treatment difficulties with very high turbidity levels and strong coloration from foliage in the water supply. Fortunately, demand for water was low due to mandatory evacuation of the population.

Figure 4-73 Roller door failure (with temporary framing and cladding) that led to auxiliary generator shutdown at Central Water Treatment Plant in Beaumont, Texas (photo credit: Christopher Letchford, Texas Tech University)

4.4.4 Wastewater Treatment Systems

Sewage treatment plants in the Gulf Coast region became inoperable when their pumps and generators were submerged in saltwater and damaged. Most plants were without power for several weeks.

Harrison County, which includes Biloxi and Gulfport, has six wastewater plants and one waste treatment lagoon, all operated by a single contractor, Operations Technologies, Inc. (OpTech). All of the plants were out of service for various lengths of time, due to a range of damage from Hurricane Katrina. Flooding caused the most damage and storm-driven debris accounted for the rest, with one building damaged by a falling tree. The chemical laboratory at the Port Arthur, Texas, Sewage Treatment Facility lost its roof to wind (Figure 4-74) and testing had to be moved to a different site.

The pump building at Eagle Point Lagoon in Oaklawn was damaged by storm surge and waves and collapsed. Most pump stations, however, survived with only minor structural damage, although some were damaged by debris. Damage to pump stations resulted primarily from flooding of pump motors, controllers, power panels, and back-up power diesel generators. Generally, wastewater plants are located in low-lying areas; as a result, many are in exposed locations that are prone to flooding. The plants sustained varying levels of damage, depending on the elevation of the process unit, pumps, and motors above grade, and to a lesser degree, on plant design. For example, the Keegan Bayou Plant in east Biloxi was inundated to approximately seven feet above the elevated floor of the process unit/control system building. While damage to the plant structure was minor, flood damage to computerized control systems and electrical equipment was estimated to be in the tens of millions of dollars. Similarly the Long Beach/Pass Christian Plant was inundated to approximately 14 feet.

In Mississippi, wastewater plants built since 1969 have site elevations based on flood levels experienced during Hurricane Camille (1969). Witnesses to both Hurricane Camille and Hurricane Katrina estimate that the surge level exceeded that of Hurricane Camille by 6 feet to 12 feet.

The New Orleans Eastbank Wastewater Treatment Facility experienced significant damage to pump equipment (Figure 4-75). This facility was underwater for approximately three weeks. Flood levels were estimated to be about 16 feet above ground level. Louisiana State Department of Transportation pumps along the 17th Street Canal were damaged by high floodwaters, which reached about three feet in depth.

Figure 4-74 Port Arthur Sewage Treatment Facility showing laboratory roof destroyed and resulting debris field (photo credit: R.T. Eguchi, ImageCat)

Figure 4-75 Eastbank Wastewater Treatment Facility. Damaged pumps in lower right-hand corner. Facility was under water for approximately three weeks (photo credit: Ron T. Eguchi, ImageCat)

4.4.5 Communications Systems

All public works agencies, utility companies, vital commercial entities, and emergency responders were hampered by widespread loss of communications capabilities during the hurricanes, and to varying degrees for days and weeks afterward. While most communications infrastructure survived and much of the damage has been repaired, lingering communications outages at the time of the reconnaissance continued to hamper the recovery efforts.

4.4.5.1 Telephone

Both land line and cellular telephone service were severely disrupted in surge and waves regions (Mississippi, Louisiana, Texas) and regions where aerial lines and poles were downed by wind, debris, and falling trees (Louisiana, Texas). All land line service in the area was interrupted for at least brief periods during and after the storm. Restoration of service varied with the scope of damage and the return of electrical power in each region. There were no reports of switching stations or other critical equipment installations being damaged.

Cellular services were disrupted to varying degrees. There are dozens of cellular service providers in the region, including most of the major mobile telephone service companies. Surprisingly, very few users reported cellular service disruption lasting more than a few days, thanks to network redundancy. Most cellular towers survived, although some experienced damage to tower-mounted equipment. A lattice communication tower failed in Orange, Texas (Figure 4-76). The reconnaissance team found two tall, guyed communication towers that had collapsed, one in Sabine Pass, Texas, the other near Holly Beach, Louisiana (Figure 4-77). Both were in storm surge and wave zones, but it was not clear whether the immediate causes of collapse were wind loads, undermining of foundation, or impact of debris. Overall, it appears that damaged equipment was replaced quickly. Two temporary towers had been erected in Gulfport, and one new permanent tower had been completed in Pass Christian at the time of the NIST field reconnaissance.

Figure 4-76 Cell tower downed by Hurricane Rita, in Orange, Texas (photo credit: NIST)

Figure 4-77 Downed communications tower on US Route 82 near Holly Beach Louisiana following Hurricane Rita (photo credit: Christopher Letchford, Texas Tech Universityy)

4.4.5.2 Radio and Television

The major disruptions to radio and television communication services were due to loss of electrical power. There was at least one case of structural failure: WLOX-TV in Biloxi, Mississippi went off the air because its broadcast tower collapsed when the guy wire anchors were pulled out of the ground.

4.5 OTHER INDUSTRIAL FACILITIES

The regions affected by Hurricanes Katrina and Rita are major centers of the petro-chemical industry, with exploration, production, and refining of oil and gas and associated industries lining the coast of Mississippi, Louisiana, and east Texas. The NIST reconnaissance team was able to adequately document damage that was visible from aerial photographs or from outside the perimeter fence.

For the plants and refinery facilities located along the path of Hurricane Rita (e.g., Port Arthur, Orange, Sabine Pass, Lake Charles), only minor to moderate levels of damage were observed, with a few exceptions: several oil refinery tanks suffered buckling failure in Port Arthur, Texas, and a guyed flare tower collapsed near Orange.

4.5.1 Refineries and Chemical Plants

Chevron operates the Pascagoula Refinery on Bayou Casotte at the Port of Pascagoula East Harbor, Mississippi. The refinery is surrounded by a storm levee that had been raised after being overtopped by Hurricane Georges storm surge and waves (1998). As a consequence, the refinery experienced less flooding and less damage from Hurricane Katrina than it had from earlier storms. The plant was shut down due to loss of electrical service during and immediately after the storm, but only minor wind damage was reported.

DuPont Chemical's De Lisle Plant at Bay St. Louis, Mississippi, produces titanium dioxide for use in white pigments for paints and plastics. The storm surge and waves from Hurricane Katrina overtopped the eight-foot levee surrounding the plant. While there appeared to be no significant structural damage, saltwater flooding caused extensive damage to electrical and mechanical equipment. In anticipation of Hurricane Rita, the facility went through a formal shutdown procedure to secure the plant.

Figure 4-78 This tank at the Dupont Sabine River Plant in Orange, Texas, lost its wall insulation in Hurricane Rita (photo credit: NIST)

Damage to the wall insulation of tanks (Figure 4-78) was observed in many plants along the Texas and Alabama coastline, including: the Valero and BASF-FINA Plants in Port Arthur, the Exxon-Mobil plant in Beaumont, and the Motiva Plant in Port Neches. Damage to roof insulation was observed in some cases and was also evident in aerial photographs of tanks on Texaco Island (South of Port Arthur) and at the CITGO plant in Lake Charles. Roof damage extended between one half and one quarter of the roof surface of many tanks. (Tanks are often insulated to keep the contents at a given temperature in order to transfer it through piping and equipment.)

Figure 4-79 Buckled oil storage tank in Port Sulphur, LA (photo credit: Keith Porter, Scawthorn Porter Associates)

Structural failure of tanks was not observed in the refineries affected by Hurricane Rita, but was common in tank farms located in the vicinity of the landfall area of Hurricane Katrina. An example of collapse due to wind forces is shown in Figure 4-79, where buckling was accompanied by failure of the welding between the cylindrical part and the bottom plate. Oil storage tanks in Port Sulphur, Venice, Pointe a la Hache, Cox Bay, bore the highest winds in Hurricane Katrina, and many suffered collapse without evidence of being floated off foundations. In other cases, flooding led to unrestrained (and perhaps empty) tanks floating off their foundations (Figure 4-80). Failure of other structural components in oil refineries was also observed, such as the collapse of a guyed flare tower at the LANXESS plant in Orange, TX, which was observed at a distance.

Figure 4-80 Shifting of oil storage tanks, Monroe Petroleum plant, Biloxi, MS. (photo credit: D. Fratta, U. of Milwaukee)

Monroe Petroleum operates a fuel oil storage facility on Back Bay in Biloxi, Mississippi that serves both marine and land customers. Located at the site are nine large diesel oil and gasoline storage tanks of welded steel construction with diameters up to approximately 30 feet, and a number of smaller horizontal tanks for lubricants and other products. The tanks are surrounded by a berm, as required by Environmental Protection Agency rules. At least five of the storage tanks had shifted or moved completely off their foundation pads. Most were jammed against other tanks near the northwest corner of the bermed area (Figure 4-80). One tank (estimated 20-foot diameter) had even floated over the berm. All of the tanks appeared to be intact, with only minor damage visible from outside the berm. A variety of cladding damage was visible at the terminal, which was not in operation. As the City of Biloxi contracts with Monroe Petroleum to provide fuel for city vehicles and services, the loss of the facility had a significant impact on city recovery operations while alternate sources of fuel were identified.

The City of Gulfport had contracts in place with local service stations to provide fuel for city vehicles and equipment, with priority access in emergency conditions. Access to gasoline and diesel fuel stored at these facilities was hampered by the lack of electric power for station pumps and manual pumps had to be employed.

The failure of canopies supported by a single row of columns over gas stations was widely observed throughout regions affected by both hurricanes. Some of these failures prevented access to pumps. The causes of failure may be weak structural design and poor maintenance. In the first case, typical failure modes include the development of plastic hinges at the base of the columns (Figure 4-81), foundation pullout (Figure 4-82), and failure of the joints between the columns and the beams, so that frame action could not develop. In the second case, some of the failed columns had internal drainage and might have corroded due to maintenance problems. Canopies supported by two rows of columns showed a better performance and only in a few cases, structural failure was identified.

Figure 4-81 **Gas station near Port Arthur, Texas with column failure (photo credit: NIST)**

Figure 4-82 **Gas station canopy near Port Arthur, Texas pulled out of its foundation (photo credit: NIST)**

4.5.2 Cooling Towers

Cooling towers at oil refineries, chemical plants, and power stations were extensively damaged (Figure 4-83). The shrouds, typically constructed of fiberglass, sit atop a timber or metal structure, and many were observed to have failed. Aerial photographs allowed a preliminary statistical survey of cooling tower failures in the region affected by Hurricane Rita, as shown in the table below. Apparently, repair or replacement of these shrouds is not very onerous.

Location	Facilities	Failures (from aerial survey) (Percent)
Port Arthur	Oil refineries	50
Port Neches	Oil refineries	54
Bridge City	Power Station	44
Orange	Chemical plants	36

Figure 4-83 Cooling tower failures at the BASF Fina Plant in Port Arthur/Groves, Texas (photo credit: Christopher Letchford, Texas Tech University)

4.6 REFERENCES

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Chapter 5
DAMAGE TO RESIDENTIAL STRUCTURES

This chapter discusses observations and findings on the performance of residential structures during Hurricanes Katrina and Rita. Single family dwellings make up the vast majority of residential structures in the areas affected by both hurricanes. Multi-family dwellings (e.g., apartment buildings and condominiums) were predominantly engineered buildings, and are generally not covered in detail in this chapter. The nature and scope of damage sustained by engineered dwellings were in general similar to those of other types of major buildings covered in Chapter 3.

Residential structures in the affected areas were typically wood-frame single-family dwellings with pitched roofs. The most prevalent roof covering for residential structures was asphalt shingles. Other roof coverings, seen occasionally, included metal (standing seam and through-panel attached), clay tile, fiber-reinforced cement shingles, and wood shakes. Exterior wall claddings were predominantly wood siding on older houses and brick veneer or a combination of brick veneer and siding boards (wood, vinyl, or aluminum) on newer houses.

Documentation of damage in residential areas was, for the most part, limited to what could be observed from vehicles driven on paved roads and streets. This was dictated by the extensive region of the storm impact, the need to cover large geographical areas in a short period of time, and an interest in determining if there were areas where the performance of residential structures differed significantly from that of structures in surrounding areas. In some areas damage was so severe that detailed inspections would not have provided any substantive additional information.

In general, residential structures in individual neighborhoods tended to be of approximately the same age. In most cases, observed construction details and types of damage were similar for the entire neighborhood, and types of damage observed in each broad geographic area did not vary greatly.

In many areas, there were very distinct patterns of damage. In the coastal areas exposed to the direct impact of the storm surge, damage was extreme. Extending about one-quarter mile inland, nearly all of the single-family residential structures were completely destroyed by the impact of the moving water, leaving only foundations and other rigid masonry components in place. Even much of the debris had been washed away. The only exception was when storm surge height did not exceed foundation elevations, the performance of elevated residential structures was noticeably better. Farther inland, surge flooding caused massive damage, pushing homes off their foundations and moving them some considerable distances. This level of damage was generally found in the downtown areas of larger coastal communities such as Biloxi and Gulfport, Mississippi.

Inland flooding, specifically in the New Orleans area, also resulted in heavy damage to residential structures. Houses near levee breaches were subjected to flood and debris impact forces, resulting in significant structural damage and in some cases, complete destruction. Houses that experienced gradual and steady flood rise experienced substantial water damage and in some cases, floated off their foundations.

Residential structures subjected only to wind sustained less structural damage than those subjected to storm surge and flooding. Structural damage, such as gable end roof damage and loss of roof sheathing, was observed infrequently. Overall, among the main exterior components of residential construction, roof coverings experienced considerable damage; in contrast, claddings, windows, soffits, porches, doors, and garage doors generally sustained relatively minor damage compared to roofing. For residential structures that suffered modest or no visible damage to the weather-resistant envelope due to wind, no assessment of wind-driven rain penetration could be made in most cases. This type of damage often results in significant economic losses.

5.1 RESIDENTIAL CONSTRUCTION AND FOUNDATIONS

5.1.1 Storm Surge Impacts

Overall, with few notable exceptions, residential structures exposed to impact forces of the storm surge did not survive, while structures that were somewhat protected from the force of the moving water survived but in many cases sustained major damage.

For the most part, destruction of single-family dwellings in coastal regions was limited to areas affected by the impact of storm surge flow and wave action. The nature and scope of the damage was similar in communities along coastal Alabama, Mississippi, Louisiana, and Texas. With few exceptions, non-elevated structures (i.e., houses built at grade level immediately adjacent to the coast) were completely destroyed (see Figs 5-1, 5-2, and 5-3). The surviving structures were, invariably, severely damaged with little prospect for restoration. Some had enough residual strength to remain standing, but most did not. In some cases, the upper levels of multi-story residential structures appeared to have sustained little damage, even though the ground level and the first floor above ground level were heavily damaged by the surge (Figure5-4).

Figure 5-1 Residential destruction from storm surge in Biloxi, Mississippi. (Photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)

Figure 5-2 Surge damage in a residential neighborhood in Biloxi, Mississippi. (Photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)

Figure 5-3 Residential damage in Biloxi, Mississippi. Masonry components survived. (Photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)

Figure 5-4 Severe damage and destruction to townhomes in Gulfport, Mississippi. (Photo credit: NIST)

Generally, where the surge height was above the first floor, the super-structure of the single family dwellings was completely destroyed, even for houses on elevated foundations. In most cases, it appeared that the destruction stemmed from the failures of the connections between the building structure and the foundation piers (Figure 5-5) that were not intended to resist storm surge impacts or buoyancy forces. The primary failure mode of the connection was connection pull out or inadequate rebar lap splices at the piers, which allowed the entire structure to be washed off the foundation. In most cases, failures could have been the result of hydrodynamic forces imposed by the storm surge in excess of design loads (mainly design wind loads) on the superstructure. Where residential structures were constructed with appropriately designed and installed connections between the foundation piers and the first floor systems, the superstructure, even though heavily damaged, remained connected to the raised foundations. This was especially the case where precast concrete beams spanned multiple concrete piers (Figure 5-6).

Conventional reinforced concrete construction that used columns and beams, slabs, and load bearing walls (e.g., 6-inch thick reinforced concrete walls) sustained noticeably less damage than did other types of structures, even when not elevated. Reinforced concrete construction appears to have been used very infrequently on houses, apartments, and condominiums in coastal Alabama, Mississippi, and Louisiana. Only a few structures of this type were observed by the NIST reconnaissance team. One such concrete residential structure near Pass Christian, Mississippi, north of U.S. Highway 90, appeared to have sustained no substantive structural damage, limited damage from storm surge flow through lower levels, and no wind damage above the surge impact height (Figure 5-7). In addition, the few observed uses of steel piers and frames in elevated houses and condominiums along the Mississippi coast performed well in terms of steel frame structure survival, but infill wood framing was completely destroyed in many cases where storm surge elevation exceeded first floor elevation. One such example is shown in Figure 5-8.

(a)

(b)

Figure 5-5 (a) A single-family residential structure near Pass Christian, Mississippi was pushed or floated off its elevated foundation, (b) shows a failed connection between a pier and the super-structure. (Photos credit: NIST)

Figure 5-6 Condominiums on the north side of U.S. Route 90 at Biloxi, Mississippi supported on precast conrete beams and piers. (Photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)

Figure 5-7 Reinforced concrete residential structure that survived storm surge impacts. Though the lower level is washed out, the structure suffered no apparent structural or wind damage. (Photo credit: Jay H. Crandell, Applied Residential Engineering Services)

Figure 5-8 Coastal residential structure with steel-frame skeleton and in-fill wood framing West of Bay St. Louis, Mississippi. The steel frame survived, but the in-fill wood framing was destroyed. (Photo credit: NIST)

Post-tensioned concrete slabs used in lower stories of a few apartments and condominiums failed, likely[15] due to reversal of moments in slabs due to surge uplift. In addition, the effect of the slab edge may have acted as a compression strut and transferred lateral loads from the surge, waves, and wind to the columns, where neither the connections nor the columns were designed for such loads (Figure 5-9).

Figure 5-9 Post-tensioned concrete residential structure in Pass Christian, Mississippi, north of US 90. (Photo credit: Jay H. Crandell, Applied Residential Engineering Services)

Surge-Borne Debris

Elevated residential foundations, predominantly on timber, concrete, or masonry piers, are common along the Mississippi coast. In most cases, the piers of these structures showed few signs of damage. In areas where severe damage to piers was noted, it was largely attributable to impacts from floating debris, especially drifting vessels and other large items carried by the storm surge. This is based on observations of damaged, leaning, or fallen piers immediately adjacent to upright, intact piers. In those areas, masonry piers exhibited more damage than other types. In the few cases where steel piers and frames were used for elevated houses and condominiums/apartment buildings, the support structures survived with no visible damage.

The full extent to which surge-borne debris contributed to residential damage could not be discerned. Overall, however, it probably was a significant factor only along the Mississippi coast, where surge-borne debris included barges, boats, vehicles, trailers, fuel tanks, and materials from demolished structures at port facilities and casinos. Casino barges were pushed across US 90 and came to rest on fixed structures. Boats, equipment, and materials from port area facilities were driven even farther inland. In many cases, the line of travel between the original location and the final site of that debris was readily apparent. In other areas, such as western Louisiana and eastern Texas, there was little development between the coastline and the residential areas, and surge-borne debris was not a factor.

5.1.2 Surge Inundation and Inland Flooding

Damage observations and reports from local witnesses indicated that surge inundation and inland flooding levels throughout the hurricane impact zones ranged from one foot or less to more than 20 feet (see Chapter 2). Inundation in coastal areas was the result of storm surge pushing inland. Flooding in inland areas, specifically New Orleans and surrounding communities, resulted when the surge overtopped lake banks and levees or broke through the levees. Rainfall from both hurricanes was modest and did not contribute significantly to flooding.

The storm surge pushed seawater about one-half mile inland along the coastline, and several miles inland along bays, bayous, and rivers along the Hurricane Katrina-affected area. In Louisiana and eastern Texas, the surge pushed much further inland. In most areas, water levels receded relatively quickly; the notable exceptions were areas where the water was trapped behind overtopped levees. In many cases, the surge was high enough and the force was strong enough to push houses off of their foundations (see Figure 5-10). In some instances, elevated houses were also pushed off of their piers.

In the coastal areas just beyond the direct surge impact zone, the water generally rose above the roofs of most residential structures, causing extensive damage to interiors even when major structural damage was not immediately evident. In those areas, floodwater was predominantly clean seawater that had not picked up large amounts of silt or other contaminants, and many buildings showed few outward signs of having been flooded. In such coastal areas, observations by the NIST reconnaissance team indicated that the clean floodwater and the relatively short duration of flooding apparently[15] helped to keep damage levels lower than those in and around New Orleans where floodwaters remained for much longer periods of time. Nevertheless, contents, interior finish, appliances, and mechanical/electrical equipment damage due to flooding was commonplace and extensive for residential structures experiencing predominantly low-velocity flooding.

Inland areas flooded primarily because the storm surge overtopped the banks of levees, rivers, and lakes. In and around New Orleans, the surge overtopped and, in some cases breached, the levees (see Chapter 4). Near the water ingress points at breached levees, floodwater velocity was large enough to cause major structural damage. Houses near the breaches in the levees were subjected to flood impact forces similar to those experienced in surge impact zones. Although the depth of water might have been less than that in coastal surge areas, the force of the moving water was sufficient to cause massive structural damage and, in some cases, complete destruction of the structures (Figs. 5-11 and 5-12).

Most areas, however, experienced a gradual and steady rise, rather than a sudden rush, of water. In those areas, some residential structures that were not securely affixed to their foundations floated off their supports. Floodwater that stood for long periods was the primary cause of damage.

Figure 5-10 A single-family residential structure in downtown Biloxi was pushed or floated off its low foundation. (Photo credit: Thomas B. Rodino, Shiner Moseley and Associates, Inc.)

Figure 5-11 Destruction of residential structures near the London Ave Outfall Canal breach in New Orleans. (Photo credit: Keith Porter, Scawthorn Porter Associates)

Figure 5-12 Destruction of residential structures near the failure of the Industrial Canal Levee in New Orleans. (Photo credit: Edwin T. Huston, Smith and Huston Inc.)

In New Orleans, in the areas where site-built residential buildings were moved off their foundations, they generally were relatively small, one-story wood frame structures on pier foundations, although a few larger buildings were similarly displaced. Most appeared to have little or no positive anchorage to their foundations (see Figure 5-13). Had they been securely anchored, many would have experienced significant structural damage, but overall damage would have been reduced if they remained on their foundations (Figure 5-14).

Figure 5-13 Typical foundation in New Orleans showed lack of anchor bolts. (Photo credit: Edwin T. Huston, Smith and Huston, Inc.)

Figure 5-14 Walls anchored to the foundation remained intact. (Photo credit: Edwin T. Huston, Smith and Huston Inc.)

In a number of cases, manufactured houses that rested on dry-stacked masonry pier foundations had been moved off their piers, even though anchoring systems were in place. In some cases, it appeared that slack in the anchors allowed the structure to shift along the tops of the piers. In others, the foundations themselves were not capable of resisting the loads imposed on them.

5.1.3 Wind Damage

Wind damage observed throughout the hurricane impact zone was far less severe than damage caused by storm surge and flooding. With few exceptions, severe wind damage was not observed. Even immediately adjacent to the coast, relatively little residential structural damage appeared to be attributable to loads imposed by wind. Data indicate that the wind speeds in both hurricanes were, in general, less than the design wind speeds specified by the International Residential Code [1] and ASCE 7 [2], and field observations support that conclusion (see Chapter 2).

Residential structures subjected only to wind loads sustained relatively minor damage to roofing materials, siding, windows, soffits, porches, doors, and garage doors. Structural damage, such as gable end roof damage and loss of roof sheathing, was observed infrequently. An example is seen in Figure 5-15, which shows an apartment building in Waveland, Mississippi. In the few cases where wind loads caused major damage, the buildings tended to be older and somewhat deteriorated. A few older buildings in relatively low wind speed zones (e.g., Pascagoula, Mississippi, see Chapter 2) had their roofs blown off; however, such cases were rare. For the most part, the scope of the wind damage steadily decreased with distance from the coastline. Isolated exceptions were noted where damage was substantial when residential structures were situated adjacent to large open areas.

Figure 5-15 Wind damage to an apartment building in Waveland, Mississippi. (Photo credit: NIST)

Localized heavy damage that might be attributable to tornadic or microburst effects was observed in a few isolated areas. For example, the second story of an apartment building in Orange, Texas lost both roof and wall elements (see Figure 5-16). That building was situated across the street from two single-family dwellings that experienced partial roof blow offs and some exterior wall damage. Coupled with reports from utility operators of apparent tornadic damage to electrical system structures and other instances of isolated severe damage and also similar observations in the Hurricane Katrina-affected areas, it is reasonable to conclude that both hurricanes generated localized severe wind speeds in some areas.

The near total destruction in most near-coast residential areas precluded any attempt to identify failure mechanisms. Where entire buildings were destroyed, there was no way to discern the specific failure mechanism. In many cases, it appeared that wind loading was not a major contributor to structural failures.

Figure 5-16 Localized damage to an apartment building in Orange, Texas likely[15] attributable to tornadic or microburst effects. (Photo credit: Hua He, Texas Tech University)

Wind-borne Debris

Damage caused by wind-borne debris was observed in both coastal and inland areas, but it did not appear to be a significant contributor to overall damage to residential structures. Damage caused by tree and limb impact was fairly common as most developed areas were extensively wooded. However, with the exception of locations where falling trees caused major structural impacts, such wind-borne damage was light. Where damage from debris was observed, debris impacts typically appeared to be of a magnitude sufficient to damage light cladding and occasionally break standard glazing, but not penetrate wall or roof assemblies. Figure 5-17 shows damage to cladding and exterior walls of an apartment building in Waveland, Mississippi due to penetration of wind-borne debris. Overall, however, there was relatively little damage to windows, doors, and appurtenances. Note that for most of the observed areas affected by wind, the 3-s gust wind speeds for open areas were generally less than the 120 mph threshold specified in ASCE 7 for classification of wind-borne debris regions.

Figure 5-17 Damage to apartment building in Waveland, Mississippi due to wind-borne debris. (Photo credit: NIST)

5.1.4 Performance of Manufactured Housing

As with site-built houses, damage to manufactured housing was usually limited to roofing, cladding, and nonstructural appurtenances. In rare cases, some older manufactured homes (pre-Housing and Urban Development Code) were observed to have sustained greater levels of damage, such as partial collapse. Overall, however, the damage to manufactured housing appeared to be consistent with that observed for site-built structures.

Anchoring issues for manufactured housing have been considered in other studies, but they have not yet been addressed in federal standards, such as in the Housing and Urban Development (HUD) code. HUD has undertaken a project to evaluate a proposed ground anchor test protocol and performance criteria for manufactured housing units. In HUD’s prior assessment of the impacts from Hurricane Charley in Florida (2004), a higher than expected frequency of ground anchor installation failures was noted, even with Florida’s more stringent strap and anchor spacing requirements. In that case and for the average wind speed and exposure condition represented by a sample of 100 manufactured homes, the wind loads typically were at or somewhat below design levels as required by the HUD *Manufactured Home Construction and Safety Standards* (which assumes exposure C for all sites). Therefore, the anchors were not subjected to their full design loading on average. Even so, the failure mode involved the structure sliding along and moving off of piers. The potential drift/uplift movement in most anchoring systems, typically two inches or more, allows the unit to move enough to precipitate failure of piers or to allow the unit to slide off the piers. Corrosion of the anchoring systems was another condition observed to influence the performance of manufactured housing.

Similar anchorage failures were common in areas affected by Hurricanes Katrina and Rita, where wind loads were also below design levels. Failures were observed in areas impacted by wind only, as well as in storm surge and flood zones. In a few cases, manufactured homes were toppled by wind, apparently[15] due to absence of anchoring. In stillwater flooding conditions, cases were observed where manufactured homes floated off their foundations because no anchorage was provided. Most significantly, however, observed units were pushed off of their support structures, even though they were secured with conventional ground anchors and straps. Anchorage systems for manufactured homes along the Gulf Coast, including performance criteria and installation practices, should be evaluated for adequacy with respect to the level of performance required by the HUD *Manufactured Home Construction and Safety Standards* for housing units.

The Port Arthur, Texas school system had a large number of manufactured buildings used as temporary classrooms, including one campus that consisted entirely of such portable structures. Port Arthur has strict requirements governing the installation of portable buildings, and those guidelines were followed for the installations. The portable classrooms sustained no damage from wind effects or wind-borne debris, and the anchoring systems were intact after Hurricane Rita. Comparing Port Arthur's requirements and practices to current model code provisions and practices elsewhere could lead to improved standards for the installation of such structures in other regions at risk of high winds. Such comparison should consider the wind speeds during Hurricane Rita, along with the site specific wind exposure and shielding effects as potential factors in explaining the observed performance.

5.1.5 Effects of Aging

The effects of aging, such as corrosion, deterioration, physical damage, and decay appeared to be a factor in the level of observed damage. For example, some structures exhibited significant corrosion in key elements of connection systems, framing, and bracing. The nature and extent of the observed corrosion was such that it could not be attributed solely to the effects of the storm surge inundation less than four to eight weeks earlier. In many cases where brick veneer failed, typically in storm surge impact areas, the metal ties connecting the brick to the wood frame were observed to have rusted through completely at the juncture with the back side of the brick. Dry rot, termite damage, and other physical factors also played a role in how individual residential buildings performed. This was particularly evident in areas where houses of similar age and design, but in different states of repair, were observed to have performed differently. Similar observations were made for structures such as garages and storage buildings, which apparently received less maintenance than the houses associated with them.

Aging effects and their impacts on the performance and safety of residential buildings are not well understood, and might not be adequately addressed in building codes and standards. Judgment is applied through the use of terms such as "corrosion resistant" or "decay resistant" with little documentation of service life performance over time in actual construction. Research in this area could help to quantify the effects of corrosion and decay and could provide an objective basis for including durability guidance in model building codes.

5.1.6 Effects of Trees

In Mississippi, most residential areas had substantial tree coverage, and in some locales the damage to and due to falling trees was extensive. Falling trees were the primary source of structural damage to houses outside the surge impact zones; however, such damage was not widespread. Overall, the damage to and due to trees was not as great as might be expected for a major hurricane.

In many areas, including those at or near the coastline, it appeared that wind loads on structures might have been significantly reduced due to protection afforded by dense tree cover. This was evidenced by observed damage to trees along the exposed faces of large stands, steadily diminishing damage further into the stands, and very little damage to trees or structures at the rear of the stands.

Trees are recognized, and in some cases their use is regulated, for landscaping, solar shading, and preserving water quality. Stands of trees in or adjacent to developed or developing areas are recognized as having environmental benefits. However, the benefits of wooded environments in terms of reducing wind load effects on structures are not well understood. Consequently, potential shielding effects are not explicitly addressed in current wind load design standards or in post-event wind damage assessments. Note that Exposure B in ASCE 7 Standard assumes some vegetation and tree cover.

The potential shielding effect of trees has received some attention outside the United States, and some recent research has begun to characterize those effects; however, additional research is necessary. Research should also weigh the potential benefits against the risks presented by trees in extreme wind events, and consider factors such as tree species, residential development, and landscaping practices.

5.2 ROOFING

5.2.1 General Observations on Roof Performance

The extent of damage to residential roofing in the impact zones for Hurricanes Katrina and Rita was found to be extensive even though the winds speeds were generally below design levels. Specifically, in most neighborhoods, an estimated 20 percent to 30 percent of the dwellings observed during the reconnaissance had some level of damage to the roof that was, with very few exceptions, limited to the coverings. Moreover, in most cases and particularly in the Hurricane Rita impact zone, damage to roof coverings was the only visible damage to the dwellings (see Figs. 5-18 and 5-19). An exception is illustrated in Figure 5-20, which shows a single-family dwelling with laminated asphalt shingles and vinyl siding. Note that the roof covering is intact, although extensive damage to the siding and fascia boards occurred.

In many cases, the damage appeared to be limited to a small percentage of the roof area (Figure 5-21). However, on some houses, as much as 40 percent to 50 percent of the roof covering had been stripped from the structure (Fig 5-22). In a small number of cases, nearly the entire roof covering was stripped away.

Temporary roof repairs, which limited the nature of the observations the field team could make, had already been made to a number of dwellings in virtually all of the neighborhoods visited by the reconnaissance team. These repairs consisted primarily of installation of tarps (with and without battens). Other temporary repairs were made with nailed-in-place roofing felts. At a few dwellings, roofing contractors were in the process of installing permanent replacement roofing.

In virtually all cases where damage to individual roofs was extensive and the observers were able to make detailed observations, roofing failures were attributed to improper installation that did not follow acceptable practice such as given in typical manufacturers' instructions and association guidelines. For example, in the case of asphalt shingles, nails were often applied "high" (i.e., towards the top of the shingle) so that they penetrated through only one shingle layer and not two. Moreover, only four nails were used for attachment instead of six, as is normally recommended for high wind zones. Also, examples of misapplied plywood deck panels were seen wherein the thickness, placement, and nailing of the panels were not consistent with the prevailing Engineered Wood Association (formerly the American Plywood Association) and International Residential Code standards.

Figure 5-18 Loss of three-tab asphalt shingles where the underlayment was lost along with the shingles in New Orleans. Note the bare deck on the right. For many of the homes having damaged shingles, the underlayment or a previously installed shingle layer was in place, which may provide secondary backup against water penetration (photo credit: NIST).

Figure 5-19 Damage to laminated asphalt shingles in Orange, TX. Shingles were temporarily repaired with tarps and roofing felt. No shingle debris was found throughout this and many other neighborhoods. (Photo credit: Dominic Sims, International Code Council)

Figure 5-20 Damaged home where laminated asphalt shingles were intact; in contrast, considerable damage to vinyl siding and fascia boards occurred. This observation was not typical. In many cases and particularly in the Hurricane Rita impacted areas, homes not damaged by fallen trees, storm surge, or flooding often only sustained loss of roof coverings. Wall claddings, doors, and windows were often undamaged. (Photo credit: Robb Smith, Amtech Roofing Consultants)

Figure 5-21 Limited damage (arrow) to relatively new three-tab asphalt shingles in Port Arthur, TX. (Photo credit: Dominic Sims, International Code Council)

Figure 5-22 Damage to older three-tab asphalt shingles wherein approximately 40 percent to 50 percent of the shingles were blown off the front side of the home in New Orleans. Note the vertical strips of blown-off shingles. This failure pattern is associated with applying the shingles in a process known as "racking" in which shingle are applied vertically or straight up the roof. Racked–applied shingles are susceptible to blow-off as illustrated here, and the process should not be carried out in regions susceptible to high winds. (Photo credit: Robb Smith, Amtech Roofing Consultants)

5.2.2 Asphalt Shingles

As indicated at the beginning of this chapter, the most prevalent roof covering for residential structures was asphalt shingles, and loss of those shingles was the predominant damage observed to residential roofs. Most older houses, and a minority of newer houses (i.e., age less than about 10 years old), had three-tab asphalt shingles. Some of the older homes that were re-roofed in recent years, and most of the newer homes, had laminated shingles (often referred to as architectural shingles and sometimes as dimensional shingles). With respect to both the number of houses sustaining damage and the extent of damage to the individual houses, three-tab shingle roofing suffered more damage than laminated shingle systems. Reasons for the relative difference in performance of the two types of shingles were not ascertained. Further information on factors affecting wind performance such as inherent resistance to wind uplift, shingle age, heat sealing of the shingles, and workmanship during installation needs to be developed. Many of the neighborhoods visited had been cleaned up at the time of the reconnaissance, which precluded examination of failed shingles or other roofing debris (Fig 5-19). Where debris was observed, it showed that the shingles were often not installed in accordance with manufacturers' instructions.

During the Hurricane Rita reconnaissance, members of the team purposely visited a number of newer developments in the coastal Texas and Louisiana areas on the premise that the roof coverings observed might be representative of those that would be installed during post-hurricane reconstruction. The observations showed that laminated shingles sustained little or no damage in most neighborhoods (Fig 5-23), although in a few cases 15 percent to 20 percent of the roofs suffered some damage. Where laminated shingle damage occurred, shingle loss ranged from less than a square meter to no more than 10 percent of the roof area. In contrast, in some neighborhoods where three-tab shingles predominated, up to 30 percent of the houses sustained shingle damage to as much as 50 percent or more of the roof area.

Figure 5-23 Home with undamaged laminated asphalt shingles estimated to be less than 5 years old, Beaumont, TX. (Photo credit: NIST)

The extensive loss to asphalt shingles during Hurricanes Katrina and Rita emphasizes the importance of selecting and installing shingles that have appropriate wind resistance for the design wind speeds in the geographic areas where they are to be installed. Ensuring that local building codes address roofing material selection and application is one step that could be implemented quickly to address local conditions.

The American Society for Testing and Materials (ASTM) International recently issued Standard Test Method D 7158 for "Wind Resistance of Sealed Asphalt Shingles (Uplift Force/Uplift Resistance Method)," which classifies asphalt shingle uplift resistance for wind velocities up to and including 242 km/h (150 mph). This new ASTM test method is complementary to ASTM Standard Test Method D 3161, "Wind Resistance of Asphalt Shingles (Fan-Induced Method), which classifies uplift resistance for wind velocities up to and including 177 km/h (110 mph), and which is referenced in the IBC and other codes. With the advent of ASTM D 7158, the roofing industry now has a mechanism for characterizing asphalt shingle wind resistance up to essentially the maximum basic wind speed included in ASCE-7 design criteria for the Gulf Coast. Modern building codes should reflect this new roofing industry capability for classifying shingle wind resistance. Moreover, contractors, homeowners, and other users of shingles must become well informed on the importance of selecting asphalt shingles that carry a wind resistance classification appropriate for the geographic area.

The ASTM D 7158 product classifications for the shingle installations observed in the field were not available. Such knowledge could contribute to explaining the relative difference in shingle performance observed in the Hurricanes Katrina and Rita impact zones.

In addition to selecting shingles with the appropriate wind resistance rating, installers must ensure that the selected shingles are installed according to manufacturers' recommendations and current design standards. Field observations of failed residential roof coverings provided instances of unacceptable installation, including rack-applied shingles (Figure 5-22). In a racking application, the shingles are applied vertically up the roof instead of diagonally (i.e., across the roof). This method should not be used in high wind areas because it can lead to shingles being installed with less than the recommended number of nails. Consequently the shingles are susceptible to blow-offs as depicted in Figure 5-22.

Throughout the study region, the team observed[22] shingles that were nailed high so that the nails penetrated only one shingle layer, which reduces the wind uplift resistance of the shingles. In addition, shingles had been fastened with only four nails, rather than six nails, as has been up to now a long-standing industry recommendation for high wind areas. Figure 5-24 is an example of a three-tab shingle that had been clearly misapplied. This shingle was fastened with four nails (denoted by yellow Xs in Figure 5-24), but no nail was put in place at the left and right ends of the shingle. Three nails were quite high on the shingle, and two were set at essentially the same location.

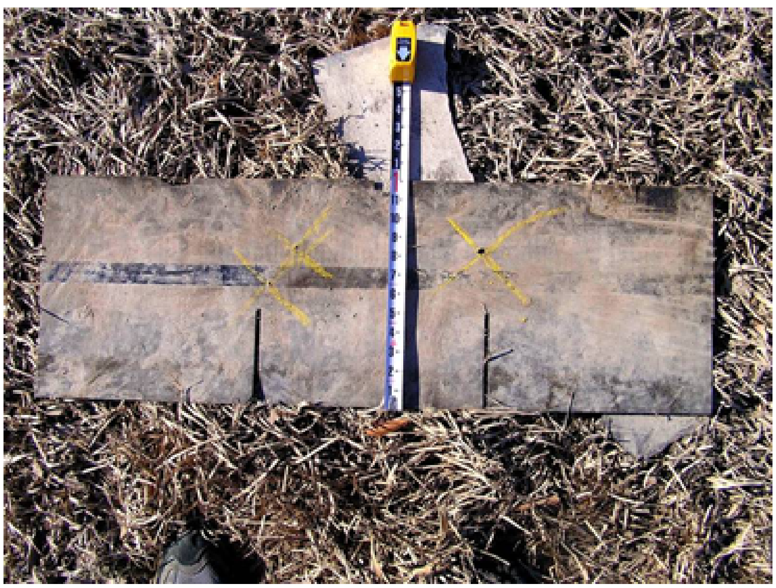

Figure 5-24 Example of a blown-off three-tab asphalt shingle that was clearly misapplied. The yellow Xs mark locations were the shingle was nailed in place. (Photo credit: Robb Smith, Amtech Roofing Consultants)

Where repairs were underway, the reconnaissance team also observed contractors replacing asphalt shingles in the same manner as the shingles that had failed, using only four nails. The need to ensure that contractors (and homeowners alike) are educated on proper shingle installation was clearly evident. Mechanisms to ensure education of roofing contractors providing the enormous amount of re-roofing necessary after Hurricanes Katrina and Rita should be put in place as soon as possible, and proper application should be enforced in the field by local building departments. Education activities should include workshops and outreach efforts undertaken in partnership with local building authorities and the roofing industry to help institutionalize sound installation practices. The development of common industry guidelines, including a standardized

[22] A statistically-based analysis of roofing performance, damage, and installation practices was beyond the scope of this reconnaissance study.

format for publishing clear pictures or drawings highlighting fastener positioning and prominently identifying wind-speed performance information, should also be considered. Moreover, it would be beneficial to have installation instructions on packaging and in brochures available in multi-lingual formats to reflect the makeup of local work forces. At present, at least one major U.S. asphalt shingle manufacturer prints wrappers in both English and Spanish.

5.2.3 Metal Roofing

The number of metal roofing installations for residential construction in the Gulf Coast region observed in the hurricane areas was small. Overall, however, observed damage to metal roofing was less than that for other types of roofing, and most residential metal roofs appeared to be undamaged.

Where damage attributed to direct wind force was seen, it was relatively minor, limited to small roof areas where a panel was missing or bent away from the roof structure (Fig 5-25). These observations indicate that standing-seam metal roofing can offer satisfactory performance in high winds such as those experienced in Hurricanes Katrina and Rita. Although limited, the observations are similar to findings reported from Florida after the 2004 hurricane season [3]. Additional study is necessary to validate or dispute these limited Hurricanes Katrina and Rita observations and evaluate metal roof system designs. Steps should also be taken to identify and remove the barriers that limit the use of standing seam metal roofing in residential construction. Initial installation of metal roofing is more expensive than asphalt shingles, but perhaps on a life-cycle cost basis that would not be the case. Guidelines that emphasize the potential value of metal roofing in high wind areas should be made available to homeowners and roofing contractors to assist them in their decision making. The guidelines should addresss the wind resistance of metal roofing systems including fasteners not only when new, but after long-term exposure to weather conditions expected in the areas where the systems are to be installed.

Figure 5-25 Damage to metal roofing (arrow), Orange, TX. Overall, little damage was seen to metal roofing; where seen, it was limited to a relatively small area of the covering and often along an edge of the roof. (Photo credit: Dominic Sims, International Code Council)

5.2.4 Membrane Roofing on Residential Construction

Only a few instances of residential construction with low-sloped membrane roofing systems were observed. For the most part, these buildings were one-story, single-family houses with gravel surfaced built-up membranes (Figure 5-26). In all such cases, no roofing damage was observed, although it was not always possible to have a good view of the entire roof because of the low-slope. At one apartment complex made up of two-story units with low-sloped roofs, piles of smooth-surfaced two-ply modified bituminous membrane debris were lying next to some of the buildings (Figure 5-27). The roofs were inaccessible, so the rooftop condition and the extent of damage were not observed. Examination of the debris piles indicated that 13 mm (1/2 in.) thick wood fiber insulation board had been nailed to the roof decking (presumably wood) along with a fiberglass base sheet, to which an APP (atactic polypropylene) modified bitumen cap sheet had been torch-applied. Wind damage to the system occurred at the interface of the base ply and the insulation board, as the base ply tore from around the center-nailed, thin metal fastening disks (possibly 28 gage to 30 gage with a diameter of about 25 mm (1 in.)). It could not be determined from the debris piles and examination of the buildings from the ground whether wind damage to the metal edge flashing (resulting from peeling up and lifting away from the roof edges) was the initial action that resulted in the membrane blow-offs; the vertical sections of the metal edge flashing (fascia) were not secured to the sides of the buildings.

Figure 5-26 A small number of single-family, single-story homes having built-up bituminous membrane roofing (BUR) were seen. Those observed were undamaged as was the case for this house in Orange, Texas. (Photo credit: Dominic Sims, International Code Council)

Figure 5-27 Blown-off polymer-modified bituminous membrane at an apartment complex in Orange, TX. (Photo credit: Hua He, Texas Tech University)

5.2.5 Roofing Considerations

Loss of roof coverings adds substantially to the overall cost of recovery from storm impacts. In addition to damage to the coverings, underlayments, and roof decks, the resultant wind-blown debris increased damage to nearby buildings, in particular the breaking of window glazing, and increased cleanup costs. Loss of roof coverings also allows penetration of rainwater into residential buildings during and after a storm, contributing to significant loss of personal property from water damage, collapsed ceilings, degradation of building materials and structural components, and mold growth.

The scope of damage to roof coverings could be reduced, and the habitability of dwellings after hurricanes could be improved if the following factors are considered for roof coverings in high wind zones:

1. Selection of a covering that is designed (and tested) for use in the wind zone where the structure is located.
2. Proper installation with particular emphasis placed on correct attachment of the selected covering and flashings in accordance with the manufacturer's instructions.
3. Application of an underlayment under the primary waterproof covering that can reliably serve as secondary protection against water penetration if the primary covering is lost during high winds.

There is no easy-to-use tool to determine the design rating of various roof coverings. Manufacturers and trade associations have developed application instructions for pitched roof coverings, but those often do not find their way to the installers. Overall, the damage noted in coastal areas appears to support a finding that the use of existing wind design specifications as outlined in ASCE 7 [2] and adopted in the International Building Code 2000 [4] should be strictly enforced in all construction.

5.3 CLADDING

Typically, exterior wall coverings on older single-family dwellings in the Hurricane Katrina- and Rita-affected areas were wood clapboard and wood siding. Clapboard installations typically were horizontal-lapped planking, while wood siding was predominantly vertical boards and battens. Fibrated cement shingles were also fairly common. In some cases, vinyl or aluminum siding had been fitted over or in place of original construction materials. Newer homes were primarily brick veneer or a combination of brick veneer and wood, vinyl, or aluminum siding. Brick and stucco combinations were noted in a number of areas.

In the Hurricane Rita, affected zone, exterior wall claddings of residential structures were for the most part undamaged by wind, except where impacted by fallen trees and branches. In the vast majority of cases, cladding was intact with no missing boards or siding.

Nevertheless, in both hurricane damage zones, a number of residential structures with aluminum or vinyl siding showed appreciable damage. Vinyl siding sustained more damage than did other types of cladding, regardless of the substrate over which it was installed (e.g., plywood, oriented strand board [OSB], fiberboard, or foam sheathing). The typical failure appeared to be that the siding was pulled over the nail heads with the nails remaining in the framing. In those instances where damage to aluminum siding was noted, reasons for siding failure were not apparent. Follow-up investigations should be undertaken to more fully understand the wind performance of retrofitted aluminum and vinyl siding (see Figure 5-28).

Figure 5-28 Damage to exterior cladding of a single-family residential structure near Pass Christian, Mississippi. (Photo credit: NIST)

Wood, wood-based siding materials, and brick veneer sidings appeared to sustain substantially less damage than did vinyl and aluminum sidings. An example of damage to brick veneer is shown in Figure 5-29.

Figure 5-29 Damage to brick cladding and other exterior wall components for a single-family dwelling in Pearlington, Mississippi. (Photo credit: Jay H. Crandell, Applied Residential Engineering Services)

Typical designs for residential masonry cladding systems use wood stud wall framing clad with unreinforced or lightly reinforced masonry walls, predominantly brick. Variations include the use of masonry walls on one or more sides and wood panels on the others. The masonry cladding is attached to the framing using brick ties, light gauge short metal strips. In typical installations, one end of the strip is placed in the mortar and the other end nailed to a wood stud. In other cases, light steel frames were used in place of wood framing, and the masonry was anchored at intervals of four to five feet using bolts. The typical observed failure was partial or full collapse of the masonry shell. The most common failure mode for brick veneer was related to corrosion of the brick ties at the juncture of the tie with the inner edge of the mortar joints.

Damage to doors and windows was very limited. Where it did occur, damage was minor, even in areas where it was apparent that shutters or other protective shielding had not been used. Window breakage was estimated to be well under 1 percent. The low rate of damage suggests that very little wind-borne debris capable of breaking glass in residential doors and windows was generated by the storms.

5.3.1 Water Intrusion

Discussions with a small number of residents in various neighborhoods provided anecdotal evidence of rainwater intrusion through chimney flues and windows during the storm. In these cases, such failures occurred to homes that had no identifiable damage to the exterior building envelope. Field teams did not often have contact with homeowners, and direct observation of such leaks through examination of homes having these problems was beyond the scope of the field reconnaissance. Indirect evidence was provided by discarded carpets lying outside a few homes that appeared undamaged (Figure 3-30).

The limited evidence of water intrusion into residential structures and the associated economic losses to residential construction indicate that the design of doors, windows, chimney flues, vents, flashings and seals, and other weather-resistant envelope accessories should be carefully considered for their effectiveness in protecting against water leakage from wind-driven rain in severe weather events.

Figure 5-30 Example of water-damaged carpeting that a resident of the neighborhood reported was due to window leaks during Hurricane Rita, Port Arthur, TX. None of the houses in the neighborhood displayed damage to the exterior envelope components. (Photo credit: Dominic Sims, International Code Council)

5.3.2 Cladding Considerations

Wind pressure and rain penetration are primary considerations for performance of traditional or innovative cladding systems; however, there is very little objective guidance available to aid designers in considering cladding performance in wind-driven rain events. Proper attachment of cladding requires knowledge of wind pressures across the various layers of a wall system; however, there is no guidance on the distribution of wind pressure to the various layers based on their relative porosity (air permeability). Dynamic wind loads, such as cyclic loading from gusting wind that causes flutter, are not considered in cladding system performance testing or design criteria. Air pressure differences across exterior claddings tend to drive rainwater through penetrations and flashings in exterior weather-resistant barriers, yet there is no objective guidance on how to reduce pressure differentials or how to design penetrations to address the expected pressure differentials. Observations from Hurricanes Katrina and Rita and other events confirm the need for advancement in basic and applied knowledge in these aspects of weather-resistant building envelope design.

5.4 PRACTICE

5.4.1 Residential Codes and Standards

National model building codes such as International Residential Code (IRC) include modern provisions for minimum structural performance of conventional residential construction where basic design wind speed is 110 mph (three-second gust) or greater. Industry recognized standards such as the Wood Frame Construction Manual and the SSTD10-99 Standard for Hurricane Resistant Construction are incorporated by reference. Those codes and standards, along with others such as the Flood Resistant Design and Construction Standard (ASCE 24-05), also address the provisions of the National Flood Insurance Program (NFIP) for development and construction in special flood hazard areas.

While those codes and standards incorporate widely accepted minimum levels of performance and provide minimum prescriptive construction requirements, they do not address all of the factors that contributed to the damage observed by the NIST reconnaissance field teams. For example, current standards do not provide adequate guidance for material specifications for and attachment of cladding materials in high wind hazard areas.

5.4.2 Risk from Storm Surge

There appears to be an imbalance between the policies and practices used in evaluating coastal flood hazards and those used for wind hazards.

Field observations indicate that the magnitude of the forces associated with storm surge and flooding significantly exceeded the potential wind-induced loads addressed in modern building codes and engineering standards. Buildings, especially conventional residential structures, designed and constructed to resist wind damage in coastal environments sustained little damage due to wind loads. Those buildings were much more likely[15] to have been severely damaged or destroyed by wave impacts and flooding. Currently, buildings are required to be placed on foundations raised to the 100-year flood elevation and the foundation to resist forces from a 100-year flood event.

5.5 REFERENCES

[1] International Residential Code, 2003.

[2] American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Stuctures, SEI/ASCE 2005.

[3] Federal Emergency Management Agency, Mitigation Assessment Team Report, “Hurricane Charley in Florida: Observations, Recommendations, and Technical Guidance,” FEMA 488, Chapter 3, April 2005.

[4] International Building Code, 2000.

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Chapter 6
KEY FINDINGS AND OBSERVATIONS

This chapter provides a summary of key findings and observations on the performance of physical structures in Hurricanes Katrina and Rita, including environmental actions and damage observed for each class of construction discussed in Chapters 2 through 5. These findings form the basis of the set of recommendations contained in Chapter 7.

The reconnaissance identified three key areas where detailed technical studies are essential: (1) to evaluate the performance of the New Orleans flood protection system and provide credible scientific and engineering information for guiding the immediate repair and future upgrade of the system, (2) to develop risk-based storm surge maps for use in flood-resistant design of structures, and (3) to evaluate and, if necessary, modify the Saffir-Simpson hurricane scale's treatment of storm surge effects due to hurricanes.

The findings of the reconnaissance highlight the critical importance of state and local entities adopting and then rigorously enforcing building standards, model codes, and practices. First, at the time of the hurricanes, there was no statewide building code in Louisiana, Mississippi, Alabama, or Texas, although some local jurisdictions within those states had adopted model building codes. The City of New Orleans had adopted the 2000 edition of the model building and residential codes issued by the International Code Council in January 2004. Second, the team observed significant damage in many instances where the winds were lower than those levels cited in codes and standards—suggesting that the structures did not perform as required. Third, older structures—only required to meet building codes in effect when they were built—were particularly vulnerable to wind damage. Current model building codes and standards contain provisions for the design of structures subject to high wind, flood, and storm surge; adoption and enforcement of such codes and standards in hurricane prone regions can greatly improve the performance of structures.

Detailed findings and observations are provided in the following sections for major buildings, infrastructures, and residential structures, as well as for the environmental actions caused by the hurricanes.

6.1 ENVIRONMENTAL ACTIONS

6.1.1 Wind Speed

In general, for most locations studied in this reconnaissance report, the observed and modeled/estimated wind speeds for both hurricanes were less than the design wind speeds prescribed in the ASCE 7- 2005 standard, although in some instances (New Orleans, LA, Gulfport, MS, Port Arthur, TX), wind speeds approached design values. Away from the immediate coastal areas, wind and wind-borne debris were the dominant causes of damage to structures, roofing and rooftop equipment, providing paths for water ingress into buildings. Wind-driven rain through walls and around intact windows was also responsible for water damage to the interiors of buildings.

- *Hurricane Katrina*. Wind speed estimates taken from two independent studies (NOAA and ARA) indicate that the maximum sustained wind speed at landfall along the Mississippi coast was between 110 mph and 120 mph. In New Orleans, the ARA maps suggest that wind speeds reached 90 mph, while the NOAA maps indicate that winds were 80 mph or less. Furthermore, according to a recent report by the National Hurricane Center (2005), the maximum sustained wind speed produced by Hurricane Katrina was estimated to be approximately 125 mph, near Buras, La. Based on wind speed information from these data sources, Hurricane Katrina was a Category 3 event on the Saffir-Simpson scale.
- *Hurricane Rita*. Based on an assessment of maximum sustained wind speeds (NHC tropical cyclone report), the highest level estimated was near 115 mph in extreme southwestern Louisiana. This corresponds to a Category 3 hurricane on the Saffir-Simpson scale. However, most of the affected region experienced Category 1 or 2 intensity wind speeds.

6.1.2 Storm Surge

Storm surge heights and flooding, in general, exceeded the levels defined by existing flood hazard maps as well as historical records. The Saffir-Simpson hurricane scale—which is used in part by emergency managers for evacuation planning and making evacuation decisions—specifies hurricane wind speeds and indicates storm surge heights associated with each hurricane category. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf and the shape of the coastline, in the landfall region. Hurricane Katrina and Hurricane Rita showed that it is possible for storm surge heights to substantially exceed heights associated with a specified category on the Saffir-Simpson hurricane scale. NOAA does not rely on the storm surge ranges associated with the Saffir-Simpson hurricane scale in its hurricane advisories. Instead, NOAA includes in its advisories storm surge forecasts based upon use of storm surge simulation models.

- *Hurricane Katrina*. A number of locations experienced storm surge heights greater than 20 feet. NOAA's NHC (tropical cyclone report) estimated a storm surge of up to 27 feet. An estimated surge height of 27 ft was reported by the Hancock, Mississippi Emergency Operation Center. Observations by the NIST reconnaissance team also suggest that in some locations between Biloxi and Long Beach, Mississippi, the surge reached as high as 28 feet. Estimates of surge heights in New Orleans ranged from 9 feet to 10 feet. This information is based on HWM data collected by FEMA investigators as well as on other observations. Hurricane Katrina's large horizontal size likely contributed to the exceptionally high storm surge.

  NOAA, in their advisories prior to landfall of Hurricane Katrina, predicted "coastal storm surge flooding of 18 to 22 ft above normal tide levels…locally as high as 28 ft along with large and dangerous battering waves…can be expected near and to the east of where the center makes landfall", and "storm surge flooding of 10 to 15 ft near the tops of the levees is possible in the greater New Orleans area." These storm-surge related advisories were consistent with observed high water marks along the Mississippi coast where the hurricane made landfall and the greater New Orleans area.

- *Hurricane Rita*. The maximum HWMs observed by NIST team members were in Cameron Parish, Louisiana, which were between 12 feet and 15 feet. The NHC reported storm surge estimates of 15 ft in Cameron, based on unofficial visual observations of HWMs and debris lines. In Sabine Pass, storm surge heights of 5 feet and greater were reported. The NHC also reported that "flood waters in downtown Lake Charles were as deep as about six feet in some places. Farther east, most or all of Vermillion, Iberia, and St. Mary Parishes south of Highway 14 and U.S. 90 (several miles inland) were inundated by the storm surge, visually estimated at 8-12 ft in some of these areas."

6.1.3 Flooding

The depth of flooding in New Orleans based on several independent sources (NOAA and Geospatial One-Stop), indicates that most of New Orleans was covered by at least 7 feet to 9 feet of water with some areas exceeding 20 feet (as of August 31, 2005). Field observations made by members of the NIST reconnaissance team noted that flood depths of up to 10 feet were observed in some areas of New Orleans.

6.2 MAJOR BUILDINGS

In many cases, buildings that suffered structural damage due to wind were built before current model building codes were available. Design wind speeds in current codes and standards provide a sufficient level of safety if provisions are properly implemented and enforced.

6.2.1 Structural Systems

- Storm surge caused partial collapse of concrete parking structures located in Biloxi, MS. All of these structures were constructed of concrete columns, precast concrete girders and beams, and pretensioned, double-tee beams for decks. Decks subjected to storm surge were lifted and displaced off of their beam seats due to inadequate, if any, lateral load capacity at the beam seat connections. The pre-tension loads in the double-tee beams combined with uplift forces caused by storm surge could also have contributed to their collapse.
- Storm surge devastated masonry walls along the coastlines of Mississippi and Alabama. coast. Both unreinforced and reinforced concrete masonry unit (CMU) walls were susceptible to storm surge. Winds likely[23] initiated failure of the rooftop parapets and the exterior walls of several masonry wall buildings. There was an apparent lack of adequate reinforcement within the walls or anchorage system to resist lateral movement.
- Collapse of non-load bearing masonry walls as a result of strong winds was due to the lack of adequate reinforcement within the walls or due to insecure attachment of these walls to the building frame. Instances of failure due to storm surge were also observed.
- Metal buildings throughout the reconnaissance areas were observed to have experienced damage ranging from minimal damage to partial collapse. The roof purlins in the windward end bay of several large, steel-framed warehouses buckled upwards due to uplift wind pressures, and the end frame collapsed inward. These failures allowed rain and wind to devastate the building's interior.
- Casino barge structures along the Mississippi coast broke free of their moorings during Hurricane Katrina and caused extensive damage. Barges were observed to have (1) partially collapsed all five levels to the corner bay of an otherwise structurally sound, precast, reinforced concrete parking garage, (2) drifted inland with the storm surge, (3) collided with multi-story hotels causing partial collapse of these buildings, and (4) sank

[23] The terms *possible, apparently,* and *likely* refer to increasing levels of supporting observations or technical certainty in the findings. These determinations are made based on visual observations and engineering judgment, and not on the basis of analytical, numerical, or statistical calculations.

in place. There are no national standards for the design of mooring systems used to secure permanently moored facilities such as casino barges.

6.2.2 Roofing

Roofing failures on buildings and residential structures were observed throughout the region. Typical damage to building roofs included failure of roof coverings and finishing details, loss of the roof deck, and in some cases the supporting structure. Failure of shingles on residential structures was observed throughout the region, and many cases of improper installation of shingles were observed by the team[24].

- Conventional bituminous membranes with and without gravel surfacing and polymer-modified bituminous membranes generally with granule surfacing were the predominant roof systems on major buildings. Other systems included metal roofing, synthetic single ply roofing, and spray polyurethane foam (SPF) roofing. Damage to all types of roofing was observed, but the extent of the damage varied according to the system. Examples of typical damage included: failure of metal flashings, puncturing of roof coverings or the total roof system, blow-off of the roof coverings often accompanied by loss of insulation, blow-off of the insulation and covering accompanied by loss of deck, loss of metal roof panels with and without damage to structural members, and combinations of these types of damage.
- Where detailed observations of roofing damage were made, the failures were in many cases attributed to installation that did not comply with currently accepted practice as given in manufacturers' literature and trade association guidelines. Examples included lack of an adequate number of fasteners, mislocation of fasteners, and inadequate heating of modified bituminous membranes.
- The predominant damage to bituminous membrane roofing was blow-off of some section of the membrane. Damage was generally associated with three modes of failure that have been commonly observed in past hurricanes: (1) poor performance of perimeter metal flashing, (2) inadequate inter-laminar strength of insulation and inadequate adhesion between membranes and insulation, and (3) poor attachment of bituminous base sheets to decks and other substrates. The three are associated with selection of a membrane roofing system that does not have adequate resistance to the maximum winds expected for the given geographic location or misapplication of the roofing including inadequate fastening and insufficient heating of bituminous roofing, particularly polymer-modified systems.
- Many metal roofs performed well, particularly standing seam metal roofs installed on commercial and industrial buildings and schools. Often where damage to such metal roofing occurred, it was limited to a small portion of the roof area whereby some panels on the structure were bent away or blown off. Such damage generally occurred near a windward edge of the roof where the attachment of the perimeter metal flashing may have been insufficient. Where metal roofing sustained considerable damage, it often, although not exclusively, occurred at industrial-type facilities and included the roofs and structural supports of all-metal buildings.

[24] A statistically-based analysis of roofing performance, damage, and installation practices was beyond the scope of this reconnaissance study.

- A limited number of spray polyurethane foam (SPF) roofing systems was observed in the Hurricane Katrina damage zone. Such roofing was found, with minor exception, to have sustained the winds extremely well without blow-off of the SPF or damage to flashings.
- Damage to rooftop equipment was observed in all study areas. In several cases, equipment and portions of rooftop mechanical screens became wind-borne, causing damage to the roof system itself, the building, or to other buildings downwind.

6.2.3 Window Systems

Major buildings suffered wind-induced damage to glazing (window glass) as a result of debris impact from aggregate surface roofs on adjacent buildings, debris from damaged equipment screens on top of buildings, and debris from the damaged façade or structure of adjacent buildings.

- Many buildings in areas of the NIST reconnaissance had roofs with aggregate surfaces. The aggregate typically became wind-borne during the hurricanes and caused damage to the windows of neighboring downwind buildings. The aggregate caused extensive damage to window systems in many high-rise buildings, particularly in New Orleans, and in many critical facilities such as schools and hospitals.
- Wind-driven water penetration through exterior masonry and other undamaged cladding and glazing elements combined with water from other sources to force closure of important hospital facilities as a result of Hurricane Rita. Facilities remained partially or totally out of operation for weeks, indicating a need to review resistance of exterior cladding and glazing systems for wind-driven water.

6.2.4 Cladding

- Damage to exterior insulation and finish systems (EIFS) was observed throughout the reconnaissance areas, in many cases without evidence of wind- or water-borne debris, suggesting that wind pressure caused the observed damage.
- Damage to masonry veneer due to high winds was observed throughout the hurricane affected areas. Damage was associated with a lack of reinforcement to resist lateral loads and inadequate or deteriorated mechanisms that anchor the masonry cladding to the building.

6.2.5 Water Damage to Building Contents and Equipment

- Flood damage to New Orleans hospitals, especially to critical equipment (e.g., backup electrical generators, electrical equipment, chiller plants) located below flood elevations in basements or near ground level, was responsible for extended closure of these facilities as a result of Hurricane Katrina.
- Flooding of the basement and ground levels of buildings damaged key facilities and equipment critical to the building's operation, such as back up generators, electrical equipment, water chillers, kitchen facilities, vacuum pumps and 9-1-1 call centers.

6.3 PHYSICAL INFRASTRUCTURE

6.3.1 Levees and Floodwalls

- Failures of the levees and floodwalls in New Orleans were observed to have been caused by three different mechanisms: rotational failure of the floodwall-sheet pile system triggered by soil erosion due to overtopping (likely[15] occurred at two breaches of floodwalls along the IHNC); massive erosion and scour of the earthen levee at the levee/floodwall junction (with water overtopping, likely[15] occurred at two breaches of earthen levee along the IHNC); and sliding instability of the floodwall-levee system due to foundation failure (without water overtopping, likely[15] occurred at the two London Avenue Outfall Canal breaches and the 17th Street Outfall Canal breach). The foundation failures due to sliding instability at the above breaches could have been possibly caused either by underseepage erosion and piping (London Avenue Outfall Canal breaches) or by shear failure within the clay in the foundation beneath the levee and the floodwall (17th Street Outfall Canal breach).

- The loss of embankment material due to erosion and scour trenches was widespread at breaches along the IHNC and the IWW/MRGO where overtopping occurred. None of the sites inspected where erosion and scour trenches occurred was armored. Scour trenches, due to either overtopping or flow disturbance or both, were observed on both the protected and unprotected sides of the floodwall. At many breaches along the IHNC, the scour trenches were measured at more than 6 feet deep. This represented a loss of up to one half of the total embedment depth of the floodwall at these locations, thus amplifying the applied moment due to full outboard pressure and making the floodwall much more vulnerable to rotational instability.

- The earthen levee at the transitional junction between the levee and the floodwall, as currently designed and constructed (perpendicular transition between the concrete I-wall/ railroad closure monolith and the earthen levee), is highly susceptible to erosion due to flow disturbances. This led to complete failure of the earthen levees at the breaches on both sides of the IHNC at France Road and Jordan Road. Provisions to armor the earthen levee at this transitional junction to limit the effect of flow disturbances, with consequent erosion and scour, were observed not to have been implemented.

- No structural failure at the connection between the concrete I-walls and steel sheet piles was observed. Where the connections between the concrete cap wall and the steel sheet piles could be inspected, the reinforcements between the concrete floodwall and the steel sheet piling appeared to be in place as shown on typical drawings. Concrete I-wall panels of the floodwalls along the 17th Street and London Avenue Outfall canals separated from adjacent panels along the vertical water stop joints at failure.

6.3.2 Transportation Systems

- The most extensive and obvious damage to bridges was caused by storm surge which led to the uplift and lateral displacement of superstructure spans. Many of which fell into the water. The bridge construction technique that was most susceptible to this type of damage was the simple span bridge construction where individual superstructure spans (deck, curb, rail, and girders) were prefabricated and simply supported on the bridge piers without adequate provisions for restraint against uplift or transverse displacement. This is a common damage scenario that has also been observed after many earthquakes when the bridge is subjected to dynamic loading and cannot accommodate the resulting displacements. While simply-supported bridge spans are easier and less expensive to design and build, they are vulnerable to damage due to direct effects of storm surge and wave action in coastal regions.

- Bridges with continuous spans and positive connection between the superstructure and the substructure, or even single span bridges but with adequate provisions for restraint against lateral transverse displacements, were observed to have sustained only minor, non-structural damage even with the direct effects of surge and wave forces caused by Hurricanes Katrina and Rita.
- Besides structural damage, moveable bridges were also susceptible to damage due to flooding of motors and control mechanisms when subjected to high storm surge and waves. The loss of control mechanisms of moveable bridges severely impacted some recovery efforts.
- Impacts from surge-borne debris (barges, vessels, etc.) and scour of approach pavement and embankments also led to loss of functionality of bridges. In some instances the pier fender systems did not afford protection at the elevated water levels due to storm surge or flooding.
- The entire Gulf Coast region suffered extensive loss of traffic control devices such as traffic lights, road lighting, regulatory signs, and directional signs. Failure of these signs also generated debris that impacted surrounding structures. Most obvious were large advertising sign failures adjacent to U.S. Interstate 10 in Louisiana and cable-suspended traffic lights in many coastal communities.

6.3.3 Seaports

Storm surge and waves from Hurricanes Katrina and Rita, rather than extreme wind, was the most destructive force to port facilities; however, most structural design focuses on wind effects. The height and force of the storm tide—which reportedly reached upward of 30 feet above mean sea level—along with wave impacts and saltwater inundation of coastal areas, caused widespread damage to buildings and facilities along the Louisiana, Mississippi, and Alabama coastline. Storm surge damage affected wharfs and warehouse structures in Gulfport, Mississippi, moored casino barges in Biloxi and Gulfport, and anchorage and motor-driven equipment of container cranes in Mobile and Gulfport. Wind was responsible for container crane anchorage failures in New Orleans, Louisiana, and warehouse failures in Orange and Port Arthur, Texas.

6.3.4 Utilities

- The loss of over one million timber power distribution poles in Hurricanes Katrina and Rita through a combination of storm surge, waves, wind, and impacts of debris and falling trees seriously affected the ability to restore power quickly.
- There was a significant loss of lattice and steel high voltage transmission lines that also delayed restoration of electric power. Many of these failures were in exposed locations,

across rivers and marshland, which further complicated replacement of fallen structures. Cascade failures were also observed.

- Underground components of the natural gas distribution system did not sustain damage. However, in buildings and houses that sustained significant damage, uncontrolled venting of natural gas often occurred as a result of damage to fixtures or appliances within these structures.
- Restoration of water service was hampered by the scope of damage, difficulty in gaining access to cut-off valves due to debris, and insufficient repair part inventories to respond to an event of such magnitude. Restoration of service was further challenged by the loss of system pressure due to massive damage to distribution networks at the user level in storm surge zones, resulting in uncontrolled flow of water.
- Sewage treatment plants in the Gulf Coast region became inoperable when their pumps and generators were submerged in saltwater and damaged.
- Both landline and cellular telephone services were severely disrupted. Landline service loss was primarily due to damage to lines and poles from wind and debris. There were a few cellular tower failures, but loss of backup power disrupted service.
- The major disruption to radio and television communication services was due to loss of power.

6.3.5 Other Industrial Facilities

- Many oil storage tanks south of New Orleans (in the vicinity of Port Sulphur) were destroyed and did not float off their supports, implying that they suffered wind-induced damage. This region experienced some of the highest land-based wind speeds during Hurricane Katrina.
- In many other cases, smaller oil storage tanks had no hold-down mechanisms and floated off their foundations upon inundation of the diked area meant to contain spills.
- By far the greatest damage observed to storage tanks was loss of insulating cladding to walls and roofs, leading to the potential for injecting debris into the wind field, causing further damage downwind.
- More damage was apparent on the periphery of tank farms, indicating that exposure should be an important consideration in design of such structures.
- Observed damage to major industrial facilities included the loss of shrouds on approximately 50 percent of all cooling towers.

6.4 RESIDENTIAL STRUCTURES

6.4.1 Structures

Storm surge and associated wave action led to breaches in the flood protection system in New Orleans, resulting in significant structural damage to residences in the immediate vicinity of breaches due to high-velocity water and flooding in approximately 75 percent of the city. It is important for building codes and standards to better define the hazards and design requirements in coastal flood prone regions in a risk-consistent manner.

- The types of damage observed in each broad geographic area did not vary greatly.
- The predominant causes of damage to residential structures were direct storm surge impacts, surge inundation, and inland flooding. Direct surge impacts extended as much as one-half mile inland; surge inundation extended up to several miles inland along the gulf coast, and inland flooding was concentrated in the New Orleans area and communities between New Orleans, Louisiana and Biloxi, Mississippi.
- Nearly all non-elevated residential structures exposed to storm surge impacts were completely destroyed. Many houses were swept off their foundations by surge and floodwaters.
- For residential structures on elevated foundations, the superstructure of the single family dwellings was completely destroyed. In most cases, it appeared that the failures stemmed primarily from inadequate elevation of the structure and secondarily from inadequate connections between the building structure and the foundation piers. Concrete, timber, and steel piers exhibited very little damage, except where impacted by surge-borne debris.
- Damage due to wind loading was not unusual or nearly as severe as damage caused by storm surge, waves, and flooding. Damage due to hurricane winds was observed to roofing materials, siding, windows, soffits, porches, doors, and garage doors. Wind-borne debris did not contribute significantly to overall damage, though various forms of debris damage were observed.
- Damage to manufactured housing was similar to that observed for site-built structures. In addition, failures of anchoring systems for manufactured housing were more common than anticipated given the magnitude of wind speeds involved.

6.4.2 Roofing

- The extent of damage to residential roofing in the impact zones for Hurricanes Katrina and Rita was found to be extensive with an estimated 20 percent to 30 percent of the dwellings observed during the reconnaissance having some level of damage, even though the wind speeds were generally below design levels. With few exceptions, the damage was limited to the coverings, with underlayment remaining on the structure.
- For many homes, particularly those in the Hurricane Rita impact zone, damage to roof coverings was the only visible (external) damage to the dwelling.
- In virtually all cases where damage to individual roofs was extensive and detailed observations were made, roofing failures were attributed to improper installation that did not follow standard installation procedures, such as given in typical manufacturers' instructions and trade association guidelines.
- The most prevalent roof covering for residential structures was asphalt shingles. Loss of those shingles was the predominant damage observed to residential roofs. Three-tab asphalt shingle roofing suffered significantly more damage than did laminated shingle systems. Reasons for the relative difference in performance of the two types of shingles were not ascertained.
- Relatively little metal roofing was observed on residential construction in the hurricane areas. Overall, however, observed damage to metal roofing was less than that for other types of roofing, and most residential metal roofs appeared to be undamaged. Where

damage attributed to direct wind force was seen, it was relatively minor, limited to small roof areas where a panel or two were missing or bent away from the roof structure.

6.4.3 Cladding

- Damage to cladding of residential structures was observed, but at a lower frequency than roofing damage.
- Brick veneer used as an exterior cladding to residential structures sustained less damage than other cladding systems. However, when brick veneer failed due to wind or storm surge forces, corrosion to brick ties was usually implicated in the failure mode.
- Vinyl siding, when observed to be damaged, often failed by siding pulling off from the fastener head rather than the fastener pulling out of the structure. This finding suggests that heavier vinyl nail flanges may be required in high wind areas.
- The effects of aging (corrosion, decay, rot) were evident in many cases where cladding system failures were observed.

Chapter 7
RECOMMENDATIONS

The National Institute of Standards and Technology is a non-regulatory agency of the Department of Commerce. *NIST does not set building codes or standards, but provides technical support to the private sector and to other government agencies in the development of U.S. building and fire practice, standards, and codes.* In addition to its research programs, NIST conducts failure investigations and reconnaissance of damage following natural disasters such as hurricanes, tornadoes, and earthquakes as these events provide opportunities to advance the understanding of how structures perform when subjected to extreme loads and to derive lessons that lead to improvements in the performance and safety of structures in the future.

Wind speeds produced by both Hurricane Katrina and Hurricane Rita were generally below, but in several instances (New Orleans, Louisiana, Gulfport, Mississippi, Port Arthur, Texas.) close to the design wind speeds specified by ASCE 7 and current model building codes (such as the International Building Code, International Residential Code, and NFPA 5000). Observed damage in the affected areas did not indicate deficiencies in the wind provisions of the current model building codes and standard. However, storm surge and associated wave action, which caused overwhelming destruction along the Mississippi coast and in other coastal areas, appeared to have exceeded design loads for onshore structures. There is an opportunity to develop risk-based storm surge maps for a number of mean recurrence intervals for coastal regions. Such risk-based maps would provide a technical basis for selecting sites for development and for the appropriate implementation of existing provisions for design and construction of foundations to resist hydrostatic, hydrodynamic, flood borne debris impact, and breaking wave loads for buildings and residences located in these coastal, high-hazard flood areas.

NIST sees an opportunity for improving practice throughout the affected region through adoption and enforcement of current model building codes and standards. Ensuring that buildings in the region are designed and constructed to current model building code provisions will reduce losses in future storms. *Rigorous enforcement of building codes and standards by state and local agencies, well trained and well managed, is critical in order for standards and codes to ensure the expected level of safety.* Further, NIST has identified opportunities to improve practice through education and licensing, to ensure that construction and repairs conform to applicable codes, manufacturers' instructions, and other relevant guidance.

As a result of its reconnaissance, NIST is issuing 23 recommendations for specific improvements in the way that major buildings, physical infrastructure, and residential structures are designed, constructed, maintained, and operated in hurricane prone regions. These recommendations are grouped as follows:

Group 1: Immediate impact on practice for rebuilding: these recommendations (1 through 5) have immediate implications for the repair and reconstruction of buildings, physical structures, and associated equipment damaged or destroyed by Hurricanes Katrina and Rita.

Group 2: Standards, codes, and practices: these recommendations (6 through 14) address the need for development or modification of codes, standards, and practices with a view toward improving the performance of buildings, physical structures, and associated equipment in future hurricanes based upon the observed damage due to Hurricanes Katrina and Rita.

Group 3: Further study of specific structures or research and development: these recommendations (15 through 23) identify needs for detailed performance assessments of structures or classes of structures to determine the factors that influenced their performance during the hurricanes or for research and development on specific technical issues. Implementation of these recommendations will provide the technical basis for recommendations for changes to practice, standards, or codes.

The recommendations call for action by specific entities regarding standards, codes, and regulations, as well as their adoption and enforcement; professional practice, education and training; and research and development.

The recommendations do not prescribe specific systems, materials, or technologies. Instead, NIST encourages competition among alternatives that can meet performance requirements. The recommendations also do not prescribe threshold levels; NIST believes that this responsibility properly falls within the purview of the public policy setting process, in which the standards and codes development process plays a key role.

NIST believes that the recommendations are realistic, appropriate, and achievable within a reasonable period of time.

Most of the recommendations deal with adopting and enforcing current requirements or with making improvements to existing requirements and practice. Some of the recommendations address developing a risk-consistent basis for consideration of storm surge as a design load for coastal buildings and structures.

NIST strongly urges state and local agencies to adopt and enforce building codes and standards since such enforcement is critical to ensure the expected level of safety. In many cases, the reconnaissance clearly found that building codes, standards, and practice are adequate to mitigate the types of damage that resulted from the hurricanes. Following good building practices also is critical to better performance of structures during extreme events like hurricanes. Relatively straightforward changes to practice could have reduced the damage that occurred. The best codes and standards cannot protect occupants or buildings unless they are strictly followed. Examples include:

1. Masonry wall failures observed during the reconnaissance may have been prevented had they been properly anchored and reinforced as required by the model codes.

2. Many roofing shingle failures resulted from installers using an inadequate number of fasteners or installing fasteners in the wrong locations. NIST is recommending that states and localities consider licensing roofing contractors, providing continuing education for contractors, and putting in place field inspection programs to monitor roofs being constructed. A licensing program instituted by the state of Florida for roofing contractors may serve as a model for other states to implement licensing programs.

3. Wind-borne gravel from building rooftops caused a great deal of damage to nearby structures. Model building codes do not permit aggregate surface roofs in high wind zones to ensure that the aggregate does not become wind-borne debris and cause damage to windows on nearby buildings.

4. In many instances backup electrical generators, electrical equipment, chillers, and other critical equipment were not placed above the expected flood levels. Model code provisions address the location of critical building equipment to avoid this kind of damage due to surge-induced flooding. This would not have protected all buildings that lost equipment due to the high storm surge, but it would have made a large difference for many critical structures.

Federal agencies, state and local governments, and the private sector already have taken actions that are consistent with NIST's recommendations—in many cases even as the findings were being analyzed and recommendations were being formulated. NIST encourages other organizations with responsibility for implementation to take similar actions. Some of the actions that are already underway include:

<u>Levees and Floodwalls:</u>

- USACE immediately began a major project (Project Guardian) to rebuild the levees and floodwalls where breaches occurred before the start of the hurricane season on June 1, 2006.

- USACE initiated the Interagency Performance Assessment Task Force (IPET) to assess the performance of the New Orleans flood protection system, understand the factors that contributed to failures during Hurricane Katrina, and make recommendations for improvements.

<u>Building Code Adoption and Other Actions:</u>

- Louisiana has adopted the International Building Code (IBC) in the 11 parishes hardest hit by Hurricane Katrina effective immediately for reconstruction. The IBC will become effective statewide for all new construction in 2007.

- The Mississippi Legislature (House Bill 45) amended the Mississippi Code of 1972 to allow the gaming portions of Gulf Coast casinos to be built on land within 800 feet of the high water line or in some cases, as far inland as the southern boundary of the US-90 right-of-way.

- The Department of Housing and Urban Development (HUD) requires that community development block disaster recovery grants not be used for any activity in special flood hazard areas delineated in FEMA's most current flood advisory maps unless it also ensures that the action is designed or modified to minimize development-related harm to or within the flood plain.

<u>Flood Map Modernization and Storm Surge Mapping:</u>

- FEMA, leading the effort in cooperation with USACE, has undertaken a project to update the Flood Insurance Rate Maps for New Orleans and the Gulf Coast areas affected by Hurricane Katrina and Hurricane Rita. Both NOAA and FEMA already are conducting studies to document and assess the storm surge risks posed by Hurricane Katrina in the Gulf Coast region. FEMA has also published a Coastal Construction Manual which provides guidance on building standards and techniques to resist both wind and waves.

- The Federal Coordinator for Gulf Coast Rebuilding, FEMA, and USACE have issued guidelines for rebuilding in New Orleans and surrounding areas based on updated advisory base flood elevations.

- The U.S. Geological Survey (USGS) has initiated a project to map the changes in the coastline due to the effects of storm surge. The agency also plans to study the effects of natural and restored land in mitigating the effects of storm surge.

- NIST has funded a project to develop the methodology for risk-based structural design criteria for coastal structures subjected to both hurricane winds and storm surge that will consider different methods for predicting input hurricane parameters for storm surge and wave models, different storm surge models, and coupling of storm surge models with different wave models. NIST is facilitating coordination and collaboration among relevant federal agencies (e.g., FEMA, USACE, NOAA, USGS, and FHWA) and key private sector organizations in support of FEMA's overall flood map modernization program and under FEMA leadership to ensure that the needs for structural design are adequately met.

<u>Highway Bridges:</u>

- FHWA issued an initial guidance document on "Coastal Bridges and Design Storm Frequency." This document provides a regulatory and engineering rationale for considering both storm surge and wave forces, specifically for those coastal states affected by Hurricane Katrina.

- FHWA is developing a plan of action that will be used to coordinate with the American Association of State Highway and Transportation Officials (AASHTO) and other stakeholders in performing studies and research for coastal bridges vulnerable to scour and hydrodynamic forces.

- FHWA has issued a solicitation for a pooled funds project to develop retrofit strategies and options to mitigate damage to highway bridges subject to coastal storm hydrodynamic factors and recommend improvements for bridges in coastal environments. The objective of this project is to develop solutions that can be immediately implemented by states and bridge owners and adopted into AASHTO standards as appropriate.

Each of the recommendations is stated below within the three groups.

7.1 Group 1: Immediate Impact on Practice for Rebuilding

<u>Recommendation 1.</u> **Improve the design, construction, and performance of the New Orleans levees and floodwalls by: (1) conducting a comprehensive review and upgrade of the design hazard, criteria, and manuals for levees and floodwalls to develop a risk-based approach to design for storm surge that is similar to the current risk-based approach to design for wind; (2) performing a systematic review of the existing, as-constructed levees and floodwalls relative to design requirements in USACE design manuals; and (3) developing methodologies for levee and floodwall design, construction, and repair that allow for overtopping without subsequent failure of the floodwall or levee structures. Major steps are already underway that will fulfill this recommendation. USACE promptly took action (a) to repair damage to the New Orleans flood protection system and (b) to conduct a**

detailed performance evaluation that will provide credible scientific and engineering information for guiding the immediate repair and future upgrade of the system.

Action: USACE immediately began a project to repair the levees and floodwalls in New Orleans before the start of the 2006 Hurricane season (Project Guardian). USACE has also undertaken a detailed performance assessment of the New Orleans flood protection system (IPET). Reports issued by IPET are available at https://ipet.wes.army.mil/

The design hazard for levees and floodwalls is defined by the Standard Project Hurricane (SPH). Current design hazard criteria prescribed by USACE Engineer Manuals (e.g., EM 1110-2-1913, Design & Construction of Levees, EM 1110-2-2502, Retaining and Floodwalls, and EM 1110-2-2504, Design of Sheet Pile Walls) for levee and floodwall design are consistent with a Saffir-Simpson Category 3 hurricane based on wind speed and storm surge height. Wind and storm surge cannot be assumed to be consistent within a single hurricane category. Thus, the required design criteria for levees and floodwalls should be reviewed and upgraded for consistency with a particular return period and safety factors against breaching.

Current USACE Engineer Manuals (e.g., EM 1110-2-301, Landscape Planting, and EM 1110-2-2502, Retaining and Floodwalls) prescribe measures to control overtopping, erosion, scour, and seepage, yet after Hurricane Katrina, erosion, scour, sliding block failures of levees, and complete or partial rotational failures of floodwalls (I-walls) occurred at many locations. Preliminary inspection at these locations indicated that provisions to protect against erosion and scour (such as armoring) and against seepage (95 percent sheet pile penetration of pervious strata), were not always implemented in the construction of the floodwalls. Erosion, caused by water overtopping and flow velocity, was observed to have caused significant loss of embankment material at the toe of the concrete cap wall-steel sheet pile floodwall at many locations, resulting in losses of about one-third to one-half of the embedment depth of the floodwalls at some locations. A systematic review of the floodwall system as constructed is needed to identify inconsistencies with the requirements of the USACE Engineer Manuals and weaknesses in the remaining floodwalls in order to develop proper repair or upgrade methods.

Since it may not be economically feasible to design floodwalls with heights that always prevent overtopping, improved measures for mitigating the potential loss of the embedment depth of the floodwall due to overtopping and erosion induced by the flow velocity need to be integrated as part of the design criteria. This also implies that floodwalls should be designed to resist the hydrodynamic force of flow over the top of the wall in addition to the hydrostatic pressure corresponding to a water level reaching 2 ft below the top of the floodwall (the current design criteria), and below the ground surface where a separation between the levee and the floodwall allows water to apply a hydrostatic pressure to the sheet pile. If the floodwalls had simply been overtopped, the flooding would have been reduced and dewatering would have been completed more quickly. Failure of the levees themselves, however, either due to loss of the surface embankment material through erosion, scouring at gates, failure of the soil substrate, or other reasons resulted in more extensive flooding over a longer period of time and required much more time to repair and dewater. An economically feasible methodology for preventing loss of embankment material due to erosion and scouring should be developed and implemented for the repair and rebuilding phases. The U.S. Army Corps of Engineers is incorporating improvements to levees and floodwalls that are being rebuilt to mitigate the potential for future failures similar to those that occurred during Hurricane Katrina. *Affected Guidance: USACE Engineer Manuals governing the design, construction, and maintenance of levees and floodwalls.*

Primary Interested Government Entities: USACE. Interested Entities: FEMA, local levee districts, ASCE-COPRI

<u>Recommendation 2.</u> **Install mechanical, electrical, and plumbing components, equipment, and systems—including alternative/backup electric power supplies—required for the continued operation of existing critical facilities at a level that is above the design flood elevation by a specified minimum threshold.**

It was observed that mechanical and electrical equipment in a number of critical facilities (those defined as category IV in IBC 2003 Table 1604.5) such as police and fire stations, hospitals, power generation, pumping stations, and waste water treatment facilities were damaged by flooding in Hurricane Katrina, which contributed to these facilities being rendered inoperative. Back up generators, air conditioning equipment, and electrical and communications equipment at many facilities were either located at or below grade level, or not adequately protected, and were subject to damage from flood waters and wind-driven rain. Some of these facilities otherwise sustained minor damage but were out of service for significant periods of time because of flood damage to mechanical and electrical equipment. Major damage agents included saltwater inundation and sediment contamination as well as surge-borne debris impacts.

Equipment being replaced should be placed inside the building at a height above the design flood elevation or outside the building on platforms with appropriate shielding from wind and wind-borne debris. Current provisions in ASCE 24 already require location of such equipment above the design flood elevation. Existing code provisions related to the location of generators, control equipment, transformers and other critical equipment vulnerable to flooding should be investigated and elevation requirements for new designs should be implemented and enforced so that the reliability of the equipment to resist flood damage is at least consistent with the structural reliability of the building the equipment serves. The requirements should be emphasized and disseminated to local authorities and builders by code-writing authorities. *Affected guidance: FEMA Flood Insurance Rate Maps. Affected Codes: International Building Code, NFPA 5000. Affected Standards: ASCE 24.*

Primary Interested Government Entity: FEMA. Interested Entities: ICC, NFPA, BOMA, ASHRAE.

<u>Recommendation 3.</u> **Adopt and enforce model building codes for masonry wall construction to ensure that: (1) load-bearing masonry walls are adequately anchored and reinforced to resist lateral forces; (2) non-load-bearing masonry walls are adequately anchored to the supporting structure; and (3) exterior masonry walls are flood-proofed to the design flood elevation.**

A number of walls constructed of unanchored, ungrouted, and unreinforced concrete masonry units were observed to have collapsed in Hurricane Katrina due to either storm surge effects or wind loads. In particular, roof parapet walls were observed to have blown over, causing the collapse of the exterior wall. Proper anchoring and reinforcement of these walls is specified in model building codes, however, some jurisdictions in the hurricane affected regions did not have building codes in effect at the time of construction. In areas where building codes were in force, some observed damage to reinforced masonry walls was indicative of building code provisions that had not been properly followed during construction.

Buildings should be designed and constructed to ensure a continuous load path to resist wind loads. Code provisions already exist in this area. For example, IBC 2003 sections 1604.8.2 and

2106.2 require all masonry walls to be anchored to floors, roofs, and other structural elements that provide lateral support for the wall (ICC 2003). IBC 2003 section 2304.9.6 requires a continuous load path from sill to roof. IBC 2003 section 1604.8.1 requires anchorage of the roof to walls, and columns, and of walls and columns to foundations, to resist uplift and sliding forces. IBC section 1609.1.3 provides similar requirements for anchorage against overturning, uplift, and sliding due to wind loads. Louisiana has adopted the International Building Code in the 11 parishes hardest hit by Hurricane Katrina effective immediately for reconstruction. The International Building Code becomes effective statewide in 2007 for all new construction.

In flood prone areas, where water velocity is low and there is no significant wave action, buildings should be elevated and the foundation walls flood-proofed as specified in existing guidance. ASCE 24 provides minimum requirements for flood resistant design and construction. Masonry construction should conform to existing standards for construction in flood-prone areas. In V Zones and Coastal A Zones, only open foundations are permitted below the design flood elevation.

Relevant industry and professional organizations should publicize the availability of existing requirements and disseminate information on their use to local authorities and builders, and regulators for enforcement in construction of major buildings. Building codes recognized by HUD also provide a safe harbor for compliance with the accessible design and construction requirements of the Fair Housing Act. *Affected Codes: International Building Code, International Residential Code, NFPA 5000. Affected Standards: ASCE 24, ACI 530 (also published as ASCE 5 and TMS 402), ACI 530.1 (also published as ASCE 6 and TMS 602), and ACI 318*

Primary Interested Government Entity: FEMA. Interested Entities: The Masonry Society (TMS), ASCE, ACI, ICC, NFPA, state and local building authorities.

Recommendation 4. **Adopt and enforce model building codes and the latest standards for roofing systems to: (1) prohibit the use of aggregate surface roofs when re-roofing existing aggregate surface roofs in hurricane-prone regions; and (2) ensure that roofing systems are designed and installed according to standards for roofing in high wind zones. This includes residential steep-sloped asphalt shingle roofs, commercial low-sloped roofs, and mechanically attached metal roofs. Model building codes should be modified to incorporate ASTM D7158, "Wind Resistance of Sealed Asphalt Shingles (Uplift Force/Resistance Method)."**

Glazing damage was observed throughout the study region. In a number of cases where the reconnaissance team observed broken window glass, it also observed the presence of stone matching the aggregate surface observed on upwind roofs. For new buildings, the IBC already prohibits using aggregate surface roofs in such regions (IBC 2004-½, section 1504.8). For existing buildings, local ordinances should be developed to require that roof repairs meet the provisions of the IBC within a reasonable time frame and follow procedures for roof inspection. Aggregate surface roofs on existing buildings should be replaced with an alternative material that, by laboratory tests, is demonstrated not to blow-off at wind speeds consistent with the minimum design wind pressure specified for components and cladding.

Reconnaissance following Hurricanes Katrina and Rita showed also that low-sloped roofing systems experienced three major failure modes, all of which have been observed in past major hurricanes. These are: (1) tear off of perimeter metal flashing, (2) delamination between membranes and insulation, and (3) delamination between bituminous base sheets and decks and other substrates. The following items address these issues:

- Selecting low-sloped roof systems to resist the basic design wind speed as classified according to Factory Mutual and Underwriters Laboratories wind resistance criteria,
- Installing continuous cleats on edge metal and coping details,
- Fastening edge metal flanges adequately in accordance with ANSI/SPRI ES-1 2003, "Wind Design Standard for Edge Systems Used with Low Slope Roofing Systems," and
- Mechanical attachment of base sheets of bituminous systems into nailable decks with more closely-spaced fasteners.

The predominant type of failure observed in residential roofing systems was loss of asphalt shingle roof coverings. In October 2005, ASTM International issued Standard Test Method D 7158, "Wind Resistance of Sealed Asphalt Shingles (Uplift Force/Uplift Resistance Method)," which classifies the wind resistance of asphalt shingles for wind velocities up to and including 242 km/h (150 mph). Repair and reconstruction should reflect this new roofing industry capability for classifying shingle wind resistance. In addition, shingles should be installed according to the most up-to-date practices for proper application in high wind zones. Observations of failed residential pitched roofs after Hurricanes Katrina and Rita provided a number of examples of misapplied asphalt shingles or where proper application of asphalt shingles was not always occurring during repairs and re-installation in the Texas and Louisiana coastal areas. To address the combined need of proper selection and installation of asphalt shingles, shingles should: (1) resist the specified basic wind speed, in accordance with ASTM D 7158, Standard Test Method for Wind Resistance of Sealed Asphalt Shingles (Uplift Force/Uplift Resistance Method), and (2) be installed according to industry guidelines for the proper application of asphalt shingles in high wind zones. *Affected Codes: International Building Code, NFPA 5000. Affected Standards: ASTM D 7158.*

Primary Interested Government Entities: State and local building authorities. Interested Entities: Roofing Industry Committee on Weathering Issues (RICOWI), Asphalt Roofing Manufacturers Association (ARMA), the National Roofing Contractors Association (NRCA), and the Roof Consultants Institute (RCI), ASTM, ICC, NFPA.

Recommendation 5. **States and local jurisdictions should consider (1) licensing of roofing contractors; (2) continuing education of roofing contractors; and (3) field inspection programs to monitor roofs under construction for proper installation, in order to ensure acceptable roofing application.**

Roof installations not in compliance with manufacturers' installation instructions were observed to be a contributing factor to roofing failures. Selection of roof materials and systems classified as having adequate resistance to the design wind speeds will have little impact if such materials and systems are improperly installed. Licensing of roofing contractors under programs that have strict criteria for demonstrating knowledge in roof application is one step toward ensuring proper installation. At the time when Hurricanes Katrina and Rita hit the Gulf Coast, the states of Alabama, Mississippi, Louisiana, and Texas did not have licensing requirements for roofing contractors.

State and local building authorities should initiate extensive educational activities such as workshops, seminars, public awareness announcements, and related campaigns to emphasize to designers, roofing contractors, and building owners the importance of proper shingle selection and proper installation of roofing systems to withstand design wind loads. Replacement roofing should be appropriately designed and installed to withstand future hurricane force winds, individual shingles should be clearly marked to identify the location where fasteners are to be installed, and installation instructions should be printed and distributed to roof mechanics in multi-lingual brochures. Note that steps such as contractor licensing and continuing education requirements have been implemented in South Florida in response to damage suffered in past hurricanes, such as Hurricane Andrew in 1992.

Primary Interested Government Entities: State and local building authorities. Interested Entity: RICOWI.

7.2 Group 2: Standards/Codes/Practice

Recommendation 6. **Evaluate and upgrade mooring system design criteria for floating structures (e.g., casino barges) to be consistent with the wind and storm surge risk including dynamic wave loads.**

Thirteen casino barge structures were in place along the Mississippi coast before Hurricane Katrina, each with its casino structure erected on one or more barges. In most cases, the barges broke free of the moorings and drifted off site. The remaining barges were heavily damaged and sank in place.

Casino barges are permanently moored facilities rather than vessels in service. While their installations are subject to permitting by the U.S. Army Corps of Engineers and limited oversight by the U.S. Coast Guard, neither agency has specific design requirements for the mooring systems. The Mississippi Gaming Commission did, however, require that the mooring system be designed to withstand 155 mph winds and a storm surge height of 15 feet. The design for each casino barge mooring system is unique and it is not within the scope of this reconnaissance to determine what specific design criteria were employed in each case. The Mississippi Gaming Commission reported that post storm investigations showed the mooring systems performed as designed but that actual surge conditions significantly exceeded the design criteria.

Following Hurricane Katrina, the Mississippi Legislature (House Bill 45) amended the Mississippi Code of 1972 to allow the gaming portions of the Gulf coast casinos to be rebuilt on land within 800 feet of the high water line or, in some cases, as far inland as the southern boundary of the U.S. Highway 90 right-of-way. The new legislation allows but does not mandate construction on land. Thus, while some casino operators have expressed the intent to rebuild on land, others have expressed an interest in rebuilding afloat at or near their original locations. Construction of permanently moored facilities presents special engineering challenges that must be considered in design. For that reason, additional investigation into the adequacy of the design criteria applied to the casino barge mooring systems and the technical review of those designs is warranted.

Mooring requirements develop for offshore floating structures developed by the American Petroleum Institute (API) and ISO may provide useful guidance for improvements to mooring standards for floating casino structures.

Primary Interested Government Entities: State and local government agencies (e.g., Mississippi Gaming Commission). Interested Entities: USACE, USCG.

Recommendation 7. **Develop risk-based storm surge maps for several mean recurrence intervals, incorporating storm surge height and current velocity and the associated wave action, to provide a technical basis for the design of coastal structures in storm surge zones – including port facilities, flood protection systems, coastal highway and railroad bridges, and buildings - along the U.S. Atlantic and Gulf Coast regions. The information on storm surge heights, current velocity, and wave characteristics could be provided in separate maps at different mean recurrence intervals (e.g., 10, 50, 100, and 500-yrs)—in addition to the current flood maps which provide total inundation expected from all sources, including storm surge—for use in designing coastal structures.**

Action: FEMA is leading the effort, in cooperation with the USACE, to update the Flood Insurance Rate Maps for New Orleans and Gulf Coast areas through the flood map modernization program. The Flood Insurance Rate Maps include coastal V zones where storm surge and wave actions may occur. The Federal Coordinator for Gulf Coast Rebuilding, FEMA, and USACE have issued guidelines for rebuilding in New Orleans and surrounding areas based on updated advisory base flood elevations. The USGS has initiated a project to map the changes to the coastline due to the effects of storm surge. The agency also plans to study the effects of natural and restored land in mitigating the effects of storm surge. In addition, NIST has funded a project to develop the methodology for risk-based structural design criteria for coastal structures subjected to both hurricane winds and storm surge. NIST is facilitating coordination and collaboration among relevant federal agencies (e.g., FEMA, USACE, NOAA, USGS, and FHWA) and key private sector organizations in support of FEMA's overall flood map modernization program and under FEMA leadership to ensure that the needs for structural design are adequately met.

Storm surge and associated wave action, rather than wind, was the most destructive force associated with Hurricanes Katrina and Rita in coastal areas. The storm surge, which in some locations reached 25 feet or more above mean sea level, along with saltwater inundation of coastal areas, caused widespread damage to highway bridges, inland and coastal flood protection systems in New Orleans, and buildings and facilities in coastal areas. Sites and elevations for many coastal facilities and bridges had been selected on the basis of observed surge levels associated with past events (Hurricane Camille in 1969) or other flood events. The potential for damage associated with storm surge effects should be assessed on the basis of the potential surge height and the dynamic forces imposed by storm surge and wave action, the compounding effects of receding water as the surge dissipates, and the effects of surge-borne debris on structures. Information such as FEMA's National Flood Insurance Program (NFIP) maps and estimates developed using existing storm surge models such as SLOSH and ADCIRC and wave models such as SWAN, STWAVE, and WAVEWATCH will be useful for the development of risk-based storm surge maps that identify risk over several mean recurrence intervals. Making storm surge-related data widely accessible and in user-friendly formats will promote a higher level of awareness and enhance pre-event planning and mitigation actions.

From observations in Hurricane Katrina, it appears that the risk of structural damage due to storm surge effects in coastal flood zones exceeds the risk of structural damage implied in modern building codes and engineering standards. Coastal buildings designed and constructed to resist wind damage may more likely[17] be damaged or destroyed by storm surge. There appears to be an imbalance in risk objectives between policies and design practices for wind hazards and those for storm surge hazards. A study of observed or recorded storm surge elevations from Hurricane Katrina along the Mississippi and Alabama coastlines should be conducted to better characterize the event in terms of storm surge probability. Such a study would provide a critical review of the accuracy and applicability of existing storm surge maps and the flood boundaries and building elevations based on those maps. Such a study would also help to define uncertainty in the assignment of probabilistic storm surge elevations and improve coastal storm surge risk modeling. Both NOAA and FEMA already are conducting studies to document and assess the storm surge risks posed by Hurricane Katrina in the Gulf Coast region. FEMA has also published a Coastal Construction Manual which provides guidance on building standards and techniques to resist both wind and waves.

Highest priority should be assigned—and is being assigned by federal agencies—to update storm surge information in current flood maps for the Gulf Coast regions affected by Hurricane Katrina considering factors such as changes in topography over the past three decades, the updated historical database of hurricanes, advances in computer simulation models and risk analysis methods, and the inclusion of current velocity and wave characteristics (height and period). The adequacy of the storm surge information in existing flood maps for other hurricane-prone Gulf and Atlantic coast regions should be evaluated considering these same factors. If the storm surge information is found to be deficient in other regions, then updated flood maps should be developed for such other regions as well. The findings contained in this report do not apply to flooding in inland water basins.

Examples of how the updated flood maps with storm surge, current velocity, and wave information might be used are provided below:

1. To determine the height to which residential (non-engineered) structures should be elevated so that they remain above the surge-induced flood level. Current velocity and wind-induced wave characteristics are needed to design the supports for the elevated structures.

2. To determine the height to which the bridge decks should be elevated so that they either (a) remain above the surge-induced flood level or (b) are adequately restrained from being dislodged by uplift and lateral wave forces. Current velocity and wind-induced wave characteristics are needed to design the piers supporting the bridge decks.

3. To determine the height of the floodwalls and levees to prevent overtopping under the 100-year surge-induced floods in combination with wind-induced wave heights. Also, the floodwalls and levees will need to be designed to resist hydrodynamic forces induced by waves.

Further, it is important to study the sensitivity of the surge-induced flood and wind-induced wave characteristics to the mean recurrence interval (100 year versus other intervals) to develop confidence in the choice of the recurrence interval. For example, a large variation in flood levels for small changes in recurrence interval could raise significant design issues. *Affected Standards:* ASCE 7, ASCE 24.

Primary Interested Government Entities: FEMA, NOAA, USACE, NIST. Interested Entities: USGS, NSF, FHWA, ASCE

Recommendation 8. **Evaluate and, if necessary, modify the Saffir-Simpson hurricane scale's treatment of storm surge effects due to hurricanes. The results of the evaluation should be broadly discussed by experts before changes, if needed, are considered for implementation.**

The Saffir-Simpson hurricane scale assigns a Category (1-5) to hurricanes based upon maximum sustained wind speeds. The scale also gives a range of storm surge heights that can be expected from a hurricane of a given category. A storm surge component was added to the hurricane scale but since storm surge is a function of local ocean bathymetry the scale's simplified treatment of storm surge has significant limitations. NOAA does not rely on the storm surge ranges associated with the Saffir-Simpson hurricane scale in its hurricane advisories. Instead, NOAA includes in its advisories storm surge forecasts based upon use of storm surge simulation models.

Hurricane Katrina, due to its large horizontal size and the local ocean bathymetry, produced exceptionally large storm surge. NOAA, using the SLOSH program, predicted in their advisories for Hurricane Katrina storm surge elevations on the order of those observed in coastal areas. At the time of landfall, Hurricane Katrina was a Category 3 hurricane on the Saffir-Simpson hurricane scale based on 1-minute average wind speed. This behavior suggests a possible need for evaluation and, if necessary, modification of the scale.

It is recommended that research be conducted with a view to ascertaining whether the scale should be modified by developing risk-based estimates of storm surge for specific geographic areas along the U.S. Atlantic and Gulf Coasts (see Recommendation #7) and comparing them with wind-speed based hurricane categories. Possible modifications that may be considered include complete decoupling of storm surge from the wind-speed based Saffir-Simpson scale or accounting for the coupling between wind speed and surge heights based on site-specific joint probabilities.

Primary Interested Government Entities: NOAA, NIST. Interested Entities: FEMA, NSF

Recommendation 9. **Develop design requirements for improved structural integrity of precast reinforced concrete structures subject to storm surge loadings.**

Many parking garages that were associated with casino hotels in the Hurricane Katrina storm surge region from Biloxi to Gulfport were built with precast concrete beams and girders, supported by reinforced concrete columns. Most decks consisted of double-tee beams, usually prestressed, topped with thin cast-in-place slabs. Connections of beams and girders to supporting elements were for gravity loads only, with very little lateral load resisting capacity. In several of the garages surveyed, double-tee beam decks at the first level above ground collapsed. Storm surge-induced lateral and uplift forces and possible combination of these forces with the pre-tension loads in the beams were the cause of failure. Minimum lateral and uplift load provisions applicable to new construction, and retrofit details for existing construction should be implemented to ensure the structural integrity of precast concrete structures in storm surge regions. Existing provisions for design of connections to resist seismic loads should be evaluated for applicability to structures that may be subject to storm surge. *Affected Standards: ACI 318. Model Building Codes: International Building Code, NFPA 5000.*

Primary Interested Government Entities: NIST, FEMA. Interested Entities: American Concrete Institute (ACI), Portland Cement Association (PCA), Prestressed Concrete Institute (PCI), Construction Technology Laboratories (CTL Group), ICC, NFPA 5000.

Recommendation 10. **Establish risk-based design methodologies for: (1) coastal bridges, (2) communication systems, (3) electricity, water, and gas distribution systems, and (4) roadside signs to resist flooding, storm surge, debris impact, and wind.**

The difference between the storm surge heights observed in Hurricane Katrina and the range estimated for a Category 3 hurricane according to the Saffir-Simpson scale demonstrates the need to develop risk-consistent design methodologies for critical structures exposed to multiple natural hazards. Risk-based methodologies, based upon an expected return period for an event of a particular magnitude, would provide a consistent basis for design of structures and infrastructure systems. Such structures include bridges, roadside signs, communication systems, individual structures and complete networks in electricity, water, sewage, and gas distribution. Furthermore, codes and standards should incorporate a probability-based, all-hazards design process to ensure a comprehensive approach to risk evaluation. *Affected Standards: AASHTO's "LRFD Bridge Design Specification" and "Standard Specifications for Structural Supports for Highway Signs, Luminaries and Traffic Signals;" ASME/ANSI B31.3; API 620 and 650; AWWA D; RUS 1742e-200 and -300; ASCE 7 and 10, Manual 72, 74, and 91, Concrete Poles; IEEE; NESC; TIA/EIA 222F and G; Bell Core.*

Primary Interested Government Entities: ASCE, FHWA. Interested Entities: FEMA, AASHTO, EPRI, IEEE, Railroad Industry.

Recommendation 11. **Evaluate the adequacy of restraining systems for large cargo cranes in port facilities.**

Restraining system design and securing practices for large cargo handling cranes should be reevaluated based on the observed failures of restraining systems due to storm surge and extreme winds in Hurricane Katrina. Damage to container handling cranes located at the Port of Gulfport, Mississippi and the Port of New Orleans apparently[25] stemmed from vibration or rocking motions from extreme winds and storm surge and involved the rupture of either the threaded bars that anchor the crane to the concrete wharf or the connecting pin that is part of the hurricane tie-down system. Marine organizations such as the American Association of Port Authorities should be included in design standard evaluations. Domestic efforts should be coordinated with international efforts.

Primary Interested Government Entities: OSHA; State Port Authorities in coastal areas. Interested Entities: American Association of Port Authorities; Port Authorities at Mobile, Pascagoula, Biloxi and New Orleans; National Maritime Safety Association (NMSA); International Longshoremen's Association (ILA)

Recommendation 12. **Adopt and implement existing model code provisions for providing alternative/backup electric power supplies for all critical facilities and equipment.**

Observations following Hurricanes Katrina and Rita noted many critical facilities and equipment failing operationally because of inadequate alternative electric power. Emergency facilities such as hospitals, fire stations, police stations, water and sewage treatment plants, and communication systems either did not have sufficient backup electrical power capability or sufficient fuel reserves for the duration of utility electric power outage.

In many cases, facilities that could be made operational after the storm remained out of service because electric power had not been restored. Where generators were provided, they did not have automatic start-up and/or remote activation capabilities. Water treatment facilities rendered inoperable by lack of electric power were unable to provide minimum required levels of treatment. At many wastewater treatment plants, the inflow of sewage from outside the storm surge impact zone continued even though the plants were inoperable, resulting in direct flows of

[25] The terms *possible, apparently,* and *likely* refer to increasing levels of supporting observations or technical certainty in the findings. These determinations are made based on visual observations and engineering judgment, and not on the basis of analytical, numerical, or statistical calculations.

untreated sewage into the environment. Delayed return of service was also observed because of limited availability of technical personnel and replacement parts for equipment. Responsible authorities should make it a priority to ascertain supply of replacement equipment and labor for critical needs such as backup electric power. *Affected Codes: International Building Code, NFPA 5000. Affected Standards: ASCE 24.*

Primary Interested Government Entities: State and local governments. Interested Entities: ICC, NFPA, APWA, AWWA, utility and telecommunication companies.

Recommendation 13. **Install isolation valves in water and gas distribution systems in areas susceptible to damage.**

The preponderance of damage to potable water and natural gas systems was to distribution piping at the end user level. Massive damage to homes and businesses resulted in the unrestricted flow of water and gas into the environment and the resultant degradation of system pressure affected users system-wide, including those well outside the direct damage zone. In most areas, fire main systems and domestic potable service systems are fed from common mains. Many fire hydrants were sheared off due to storm surge, contributing to the service losses. System restoration was hampered by the inability to reach isolation valves in areas with heavy debris accumulations. Utility providers should be encouraged to install isolation valves at key locations selected on the basis of the potential for major damage. Fire main systems that represent the potential for major pressure losses should have provisions for being separated from potable water service systems to minimize overall losses and allow restoration of fire services even in the event of damage to end user facilities. *Affected Standards: AWWA Standards for Valves and Hydrants; ASME/ANSI B16.33, B16.34, B16.38.*

Primary Interested Government Entities: State and local governments. Interested Entities: NFPA, APWA, AWWA.

Recommendation 14. **Develop and implement special inspection requirements for connection and cladding attachments in pre-engineered metal buildings within model codes for hurricane prone regions.**

The NIST-led reconnaissance observed a considerable amount of damage to engineered metal buildings throughout the region affected by Hurricane Katrina and Rita. In many cases damage consisted of cladding that had been removed from the building due to wind pressure and in other cases, damage to the structural members was observed. The Structural Engineers Association of Washington (SEAW) submitted a code change proposal in March 2006 to the International Code Council to add special inspection requirements for pre-engineered metal buildings located in hurricane-prone regions to the IBC. *Affected Codes: International Building Code, NFPA 5000.*

Primary Interested Government Entities: NIST. Interested Entities: ICC, NFPA.

7.3 Group 3: Further Study

Recommendation 15. **Conduct detailed performance assessments of coastal highway and railroad bridges to fully understand and document the factors that contributed to their failure or survival and make recommendations for improvements to future designs. This work should include: (1) evaluation of design methods and connection details to improve the resistance to storm surge-induced uplift and lateral forces; (2) development of measures**

to prevent widespread loss of functionality of moveable bridges following a hurricane due to inundation of electrical and mechanical equipment; (3) development of means to mitigate the impacts of debris and massive objects carried by storm surge on the performance and functionality of bridges; and (4) development of methods for armoring bridge approaches against scour and erosion to avoid losing the use of a bridge.

Action: FHWA has issued an initial guidance document on "Coastal Bridges and Design Storm Frequency." This initial guidance provided regulatory and engineering rationale for considering both surge and wave forces, specifically for those coastal States affected by Katrina. Further, FHWA is developing a Plan of Action that will be used to coordinate with AASHTO and other stakeholders in performing studies and research for coastal bridges vulnerable to scour and hydrodynamic forces. Additionally, FHWA has issued a solicitation for a pooled funds project to develop retrofit strategies and options to mitigate damage to highway bridges subject to coastal storm hydrodynamic factors, and recommend improvements for bridges in coastal environments. The objective of this project is to develop solutions that can be immediately implemented by states and bridge owners and that can be adopted into AASHTO standards as appropriate.

The damage to railroad and highway bridges needs to be further investigated. For example, two or more bridges at the same general location (Biloxi Bay, Lake Pontchartrain) and subjected to essentially the same loading conditions responded differently, where one bridge survived and the other(s) sustained major structural damage. Field observations were able to reveal a few important distinctions, such as the presence of shear blocks on the pier caps, which provided lateral restraint and kept deck spans from being laterally displaced, thus helping one bridge survive while the deck spans of another nearby bridge collapsed into the water. Ballast used on railroad bridges may have reduced the buoyancy of the decks and contributed positively to the performance of railroad bridges subjected to storm surge. A detailed performance assessment would yield valuable information about how to protect bridges in the future. This would provide a technical basis for the development of specifications for the design of new bridges and retrofit approaches to protect the bridges that are still in service or which will be rebuilt.

Much research has been conducted on hydraulic scour around bridges due to river flows. Predictive models exist to determine the depth of potential scour and the necessary depth of piles. The understanding of tidal scour is not so well understood. A comparison of the designs and site conditions might provide some clues as to what factors are significant. Mapping the current contours of the bay bottom may also give an indication of how the surge affected soil conditions and the structures' foundations.

<u>Design methods and connection details</u>

Hurricane Katrina's storm surge dislodged many bridge spans from their piers due to a combination of uplift and lateral forces. Scour around bridge approaches was also observed and in some cases was extensive enough to prevent vehicular access to the bridge. Current design criteria include minimum requirements for lateral loads but do not consider storm surge loads. Design criteria considering lateral and uplift forces on bridge decks and scour around bridge approaches due to storm surge should be developed to improve the performance of coastal bridges that may be subjected to such loads. This guidance should also provide bridge designers with risk-based storm surge maps (refer to Recommendation 7) that provide the basis for determining minimum design loads for bridges located in storm surge-prone regions. FHWA, in conjunction with AASHTO, is already conducting work in this area, including development of preliminary vulnerability assessment criteria, quantification of surge and uplift forces for these assessments, and development of cost-effective retrofit techniques for existing coastal bridges.

Since the structural damage resulting from hurricanes is sometimes similar to that caused by earthquakes, seismic design and retrofit details may be applicable to structures exposed to hurricanes. Some of these measures might be implemented to retrofit existing bridges to resist hurricanes in the near term. Repairs already made or planned should be checked to ensure to mitigate the potential for the same failure to recur in future hurricanes. Bridge pier foundations should also be checked to ensure that uplift and lateral forces transmitted by improved connections can be resisted.

Moveable bridges:
Many moveable bridges became inoperable after the hurricanes, primarily because electrical and mechanical systems were damaged by storm surge flooding and surge-borne debris. Many moveable bridges malfunctioned after electrical enclosures and equipment rooms flooded with highly conductive and corrosive saltwater that also carried sand and sediment. In other cases, the loss of function was due to debris lodged in operating mechanisms. Elevated, fixed (non-mechanical) bridges were not similarly affected and even with minor structural damage still allowed passage of both marine and highway traffic. In contrast, immobilized moveable bridges either cut off vehicular traffic or restricted marine traffic. There are many moveable bridges in Mississippi, Alabama, and Louisiana. The loss of functionality caused severe disruption of the transportation network, which was vital not only during evacuation of the area but also during recovery operations. One possible solution is to replace these bridges with elevated structures that are less susceptible to flooding and debris impact, however, this is often not feasible due to approach grade issues, and significantly greater cost.

Surge-borne debris impact on bridges:
The impact of surge-borne debris, sometimes consisting of massive objects, contributed significantly to bridge damage. Field observations showed evidence of collision from barges, boats, tanks and vehicles as well as blockage caused by the accumulation of smaller debris. Current design requirements specify impact criteria for bridges located in shipping channels, but do not specifically consider impacts from surge-borne debris. A study of this information will help determine if current design practices and codes adequately capture the risks to bridges from surge-borne debris. The AASHTO-sponsored National Cooperative Highway Research Program (NCHRP) previously conducted a study to quantify the loads that should be used in design to account for impact of debris on bridges during major river flooding.

Erosion and scouring of bridge approaches:
Numerous bridges that weathered the storms without substantial damage were unusable immediately after the storm because they were not accessible from the roadway. The principal problem was erosion at the ends of the bridges where the approach pavement joined the bridge structure. Some of this damage might have been prevented by providing improved armoring of the bank areas adjacent to the bridge abutments. The relative contributions of tidal scour, storm surge related scour, and the lateral forces applied to the piers by the storm surge need to be better understood so that appropriate design criteria for bridge approaches in storm surge-prone regions can be developed.

Affected Standard: AASHTO *LRFD Bridge Design Specification*.

Primary Interested Government Entity: FHWA. Responsible Entities: AASHTO, AREMA, NSF, Railroad Industry

Recommendation 16. **Conduct detailed studies to identify mechanisms for water ingress into buildings during hurricanes and to develop improved building envelope construction and cladding systems that are resistant to water ingress.**

Many buildings in the areas affected by Hurricanes Katrina and Rita, including critical hospital facilities, sustained little or no structural damage but had significant water ingress due to penetration of wind-driven rain around windows, through walls, damaged roofs, or displaced ductwork or equipment on roofs. Water ingress often led to complete shut down and loss of operation of the building for an extended period of time. Specific vulnerabilities identified in the Orange, Beaumont, Gulfport, Biloxi and Port Arthur areas are permeability of masonry cladding, weather tightness of hurricane-rated windows, and susceptibility of roof-mounted ductwork and vent covers to damage. A detailed performance assessment on the integrity of the envelope of major buildings is recommended to identify strategies to mitigate water ingress into buildings and dwellings during hurricanes.

Research in this area should be focused on providing guidance on the design, selection, and installation of cladding that considers the risk from wind-driven rain. Research should also consider accessibility requirements as specified by Fair Housing Act, Americans with Disabilities Act, and Section 504 of the Rehabilitation Act as appropriate. Results should be implemented in U.S. model building codes, ASCE and ASTM engineering standards. *Affected Standards: ASTM E-96; Affected Codes: International Building Code; International Residential Code; NFPA 5000.*

Primary Interested Government Entities: DOE. Interested Entities: HUD, FEMA, ASCE, ASTM, ICC, NFPA, and state and local building authorities.

Recommendation 17. **Conduct an evaluation of the application of seismic design methods and retrofit details to improve the resistance of existing unreinforced masonry construction to extreme wind loading.**

Older masonry buildings in the areas affected by Hurricanes Katrina and Rita exhibited a range of performance from collapse to no apparent structural damage. The vulnerability of older unreinforced masonry construction to extreme loading is not a new lesson; however, some of these buildings were able to survive while others were not. It appears that many of the types of detailing commonly used to retrofit masonry buildings for seismic loads could have mitigated the collapses observed in Hurricanes Katrina and Rita. Further study is recommended to investigate the details present in buildings that did not collapse, and to correlate the level of resistance provided relative to the magnitude of the wind loading. A possible outcome of this study would be recommendations for retrofit of existing unreinforced masonry buildings that are tailored to the hurricane design problem and preventing collapse due extreme wind loads. *Affected Standards: ACI 530 (also published as ASCE 6 and TMS 402).*

Primary Interested Government Entity: FEMA. Interested Entities: ACI, ASCE, TMS, state and local building authorities.

Recommendation 18. **Conduct detailed performance assessments of the wharfs in the Gulf States that were exposed to uplift and lateral forces due to storm surge to fully understand and document the factors that contributed to their performance during Hurricane Katrina or Rita and make recommendations for improvements to future designs.**

The reconnaissance team observed damage to ports throughout the study region. Ports in Mobile, Alabama and Pascagoula and Gulfport, Mississippi were all subjected to storm surge and wave action during Hurricane Katrina. While the ports at Mobile, Alabama and Pascagoula, Mississippi showed evidence of flooding as a result of storm surge, the wharves at the Port of Gulfport suffered significant structural damage due to storm surge and associated wave action. The factors that contributed to the performance of wharves exposed to storm surge and wave action need to be better understood for subsequent design and reconstruction.

Primary Interested Government Entities: State and local port authorities. Interested Entity: ASCE-COPRI.

Recommendation 19. **Conduct detailed performance assessments of the portable classrooms (manufactured houses) in Port Arthur, TX, to fully understand and document the factors that contributed to their survival and make recommendations for improvements to future designs.**

The Port Arthur, Texas school system had a large number of portable classrooms (manufactured homes), including one campus that consisted entirely of portables. The City of Port Arthur has strict requirements governing the installation of such units. Port Arthur's portable classrooms sustained no damage due to wind or wind borne debris, and the anchorages of these buildings were intact after the storm. A detailed understanding of the actual wind loads experienced, local requirements and actual practice could lead to recommendations for model code provisions to improve the performance and safety of similar structures (portable classrooms, office units, and manufactured housing) in other hurricane prone regions. Research should also consider accessibility requirements as specified by Fair Housing Act, Americans with Disabilities Act, and Section 504 of the Rehabilitation Act as appropriate. *Affected Codes: HUD Manufactured Home Construction and Safety Standards*.

Primary Interested Government Entity: HUD. Interested Entities: MHI, NAHB, state and local building authorities.

Recommendation 20. **Conduct detailed studies of the performance of metal buildings subjected to hurricane force winds to fully understand and document the factors that contributed to their performance and make recommendations for improvements to future designs.**

A large number of steel buildings were affected by Hurricanes Katrina and Rita. These buildings exhibited a wide range of performance from minimal damage to significant damage to the cladding and/or the structure as a result of wind and impact of wind-borne debris. The construction of steel buildings and components is often proprietary and uses standard details and rules of thumb that have worked successfully in the past. Further study is recommended to investigate the connection details present in the buildings that did not collapse and to establish the ultimate strength of buildings relative to wind loading, taking into account wind directionality and the dynamical, stochastic nature of the load.

Primary Interested Government Entities: NIST. Interested Entity: Metal Building Manufacturers Association (MBMA)

Recommendation 21. **Conduct detailed studies of the performance of residential asphalt shingle roofing, metal roofing on both residential and commercial buildings, and low-rise membrane roofs on commercial buildings to identify factors that affected performance and provide the technical basis for improved guidance on the use of these roofing systems in high wind zones.**

Asphalt Shingle Roofs:
The performance of asphalt shingles in Hurricanes Katrina and Rita was observed to be quite variable. Field observations were made to determine how dwellings in general performed during the hurricane; however the reconnaissance was not designed to gather data elucidating factors affecting the performance of asphalt shingles in high winds such as the adequacy of the installation, shingle age, and wind resistance classification. Differences in shingle performance may result from differences in wind fields, inherent shingle uplift resistance including self-sealing capability, application techniques, shingle age, or combinations of these and other factors. Knowledge of factors affecting wind performance would be beneficial in specifying and installing shingles that provide improved wind resistance for hurricane regions while eliminating those that are not suitable for such regions. Research is needed to quantify factors affecting performance and to provide the technical basis for the development of improved guidance on the selection and installation of asphalt shingles in hurricane-prone regions. *Affected Standards*: *ASTM D 7158.*

Primary Interested Government Entities: HUD, DOE. Interested Entities: Asphalt Roofing Manufacturers Association (ARMA), National Roofing Contractors Association, RICOWI, Roof Consultants Institute.

Metal Roofs:
Observations of residential pitched roofing in the Gulf Coast zones struck by Hurricane Rita suggest that metal standing-seam roofing may offer improved roofing performance in high winds. Traditionally, in the United States, metal roofing has been used to a limited extent for residential construction. Consistent with this fact, the number of houses observed to have standing-seam metal roofing in the Texas and Louisiana Gulf Coast areas was small. Nevertheless, for the most part, those observed appeared to be damage-free. Where damage attributed to direct wind force was seen, it was generally limited to a relatively small area of the roof.

A large number of metal roofs were present on low-sloped commercial and industrial buildings in the affected areas. Observations of standing-seam metal roofing indicated that many of these systems performed well, although a limited number of buildings with standing-seam roof damage were seen. Examples of damage included loss of metal panels and, in cases where panel fasteners performed adequately, wind-induced buckling of truss members and compromising of truss welds. In addition to standing-seam roofing, metal roofs consisting of metal decking attached to support trusses and steel frames were observed on a number of large commercial facilities and airport hangars. Extensive damage to many of these metal roofs was observed in all areas affected by Hurricane Rita. In most instances, the buildings had no structural damage to the steel frame but lost metal roof panels through tearing out of the fasteners. For both types of metal roofing, a detailed assessment of installation specifications and practices is recommended. Further study of the performance of metal roofing systems subjected to hurricane force winds is also recommended to identify strategies to mitigate tear-out through the fasteners and detrimental effects from uplift forces.

One of the barriers to installing metal standing-seam roofing is economic: metal roofing is more expensive than asphalt shingle roofing on a first cost basis. However, on a life cycle cost basis, this may not be the case. Economic analysis to quantify the lifecycle costs for metal roofing systems, as well as other systems such as asphalt shingles, should be conducted and the results publicized to provide additional information to homeowners and building owners when selecting a roofing system. *Affected Codes: International Building Code, International Residential Code*

Primary Interested Government Entities: HUD, DOE. Interested Entities: Metal Construction Association, Metal Building Manufacturers Association, NAHB

Low-slope Membrane Roofs

Significant failures of low-slope membrane roofs were observed throughout the Hurricanes Katrina and Rita damage zones. The failures were primarily due to wind-induced uplift that, for some buildings, may have been accompanied by pressurization of the underside of the system. Two major factors contributing to the failures were inadequate performance of perimeter flashing systems in the hurricane-force winds, and improper installation of the membrane system and/or perimeter flashings. In almost all cases, the failed roofing membrane system separated from or within an insulation component or from the roof deck. The result was that the membrane peeled back, exposing the building to extensive water entry. In at least one case, the roof membrane remained in place, although ripples in the membrane surface, reportedly not present before the hurricane, were evidence that the membrane had separated from its substrate. Further performance assessments of these roofs can shed additional light on the factors that affect performance and advance the technical basis for improved installation procedures and practices for membrane roofing systems applied in hurricane and other high wind zones. *Affected Codes: International Building Code.*

Primary Interested Government Entity: DOE. Interested Entities: National Roofing Contractors Association, RICOWI.

Recommendation 22. **Conducting detailed studies to: (1) evaluate and quantify the effects of corrosion, decay, and other aging factors on the service life performance of residential buildings and components; and (2) evaluate and improve performance criteria and installation practice for anchorage systems for manufactured homes.**

Corrosion, decay, and other prevalent aging factors on the performance of residential buildings and components

Numerous instances of corrosion (e.g., corroded brick ties and connectors) and decay (e.g., rot of wood sheathing often in combination with termite damage to framing) were noted in structures damaged by hurricane winds and surge. In general, such effects and their impacts on the performance and safety of buildings are not well understood or addressed in building codes and engineering standards. Instead, judgment is applied through terms such as “corrosion resistant” or “decay resistant” with little knowledge of performance effects over time in actual construction. Other aging effects, such as deterioration of roof shingles, also affect the nature and extent of observed damage, especially in high wind hazard areas and residential developments where roof shingle pieces are often primary components of the wind debris field. Research in this area will provide an objective basis for including durability guidance in model building codes. *Affected Code: International Residential Code.*

Primary Interested Government Entities: HUD. Interested Entity: NAHB.

Anchorage systems for manufactured homes

Following Hurricane Katrina, manufactured homes anchored to the ground were observed to have moved off of their foundations even though wind loads were, for the most part, below design levels (especially considering wooded exposures. HUD noted in its report following Hurricane Charley that, “Newer foundation installations installed under Florida’s revised (1999) Installation Standards typically performed with a relatively low level of damage. However, post 1999 installations were not flawless and about 40 percent experienced some level of damage.” In Hurricane Charley, wind loads were, for the most part, at or slightly below design levels, thus the anchors did not reach their ultimate design load before failure. The amount of drift/uplift at the design load on these systems is in the range of 2 inches or more, which precipitates failure of the foundations or sliding of the unit off of the foundations. Furthermore, corrosion of these systems is a major issue (refer to previous paragraph). Additional performance studies of these systems are required to understand the factors affecting their performance and to provide the basis for improvements to the performance criteria for ground anchor systems. *Affected Code: HUD Manufactured Home Construction and Safety Standards.*

Primary Interested Government Entities: HUD, FEMA. Interested Entities: NAHB, MHI.

Recommendation 23. **Evaluate the effects of shielded (e.g., wooded or wooded/suburban) exposures and their potential for reducing the wind loads on nearby residential structures and better explaining the variation in observed damage.**

Residential structures in wooded or wooded/suburban exposures may be exposed to lower drag and uplift forces during high wind events than is currently required in ASCE 7. Current provisions in the ASCE 7 standard permit design using Exposure Category B loads fro components and cladding as well as MWFRS. Preliminary results of field data from instrumented houses exposed to hurricane winds and wind tunnel tests suggest much less reduction in component and cladding loads than allowed by code unless the structure is located in a heavily forested area. For clear cut, suburban areas, Exposure Category C yields better results for component and cladding loads. Recent research results, however, indicate that shielding due to trees or other nearby structures significantly reduces the drag and uplift forces on residential structures.

The effects of shielding have been addressed in the Australian Wind Code for Housing, which includes simplified reduction factors to account for two categories of shielding in suburban exposures (Exposure Category B). Greater reductions are permitted if the more detailed methods of the Australian Wind Code are used. Additional research is needed to quantify the shielding effects provided by wooded areas and nearby structures (Exposure Category B) and the reduction in wind loads on shielded structures. Such research may involve use of boundary layer wind tunnel facilities as well as facilities that are already active in monitoring of near ground wind conditions in extreme wind events. *Affected Standard: ASCE 7.*

Primary Interested Government Entities: HUD, NIST. Interested Entities: NAHB, ASCE, AAWE.

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Appendix A
TEAM ORGANIZATION

This appendix provides the organization, affiliation, and roles of the NIST reconnaissance team members and partners.

The deployment strategy was to send three separate teams to Louisiana, Mississippi and Texas, to cover a fairly large area in a short period of time. Each team was further broken into three sub-groups: major buildings, infrastructure and lifelines, and residential construction. After each day of investigation, the sub-groups were brought together to share observations and findings with other members of the team. In addition, summary reports were prepared by each team that were delivered to NIST for internal distribution.

A.1 TEAM MEMBERS

A list of all team members that deployed on this reconnaissance is provided below, with contact information.

National Institute of Standards and Technology (NIST)

1. S. Shyam Sunder, Sc.D. — **Technical and Management Oversight** (did not deploy)
   Deputy Director, Building and Fire Research Laboratory, NIST

2. James St. Pierre — **Management Oversight** (did not deploy)
   Chief, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

3. Stephen A. Cauffman — **NIST Reconnaissance Team Leader**
   Leader Structures Group, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

4. Emil Simiu, Ph.D., P.E. — NIST Fellow (did not deploy), Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

5. Long T. Phan, Ph.D, P.E. — Research Structural Engineer, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

6. Fahim Sadek, Ph.D. — Research Structural Engineer, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

7.	William Fritz, Ph.D.	Research Structural Engineer, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST
8.	Walter J. Rossiter, Ph.D.	Research Chemist, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST
9.	Dat Duthinh, Ph.D.	Research Structural Engineer, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

Applied Technology Council (ATC)

1.	Thomas R. McLane	**ATC Project Coordinator**, Director of Business Development Applied Technology Council

SUB-TEAM 1 Mississippi/Alabama (Biloxi, MS)
Deployment: October 17-21, 2005

1.	Captain Thomas B. Rodino	**Sub-Team 1 Coordinator,** Senior Maritime Consultant, Shiner Moseley and Associates, Inc. U.S. Coast Guard (Retired)
2.	Jay H. Crandell, P.E.	Owner, Applied Residential Engineering Services (ARES)
3.	Fahim Sadek, Ph.D.	Research Structural Engineer, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST
4.	Habib Rahman, Ph.D.	Research Officer, Institute for Research in Construction National Research Council of Canada
5.	Jerome S. O'Connor	Senior Program Officer, Transportation Research Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo
6.	John R. Hayes, Jr., Ph.D.	Leader, Seismic and Structural Engineering Group, Construction Engineering Research Laboratory US Army Corps of Engineers
7.	Rebecca Paulsen Edwards	NSF IGERT Fellow, Wind Science and Engineering Texas Tech University
8.	Ricardo R. Lopez, Ph.D.	Professor and Associate Director, Department of Civil Engineering and Surveying University of Puerto Rico

SUB-TEAM 2 New Orleans, LA
Deployment: October 17-21, 2005

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2.	Ronald T. Eguchi	**Technical Coordinator** President and CEO, ImageCat, Inc.
3.	Shubharoop Ghosh	Transportation Systems Analyst, ImageCat, Inc.
4.	Edwin T. Huston, P.E.	Principal, Smith & Huston Inc.
5.	Long T. Phan, Ph.D., P.E.	Research Structural Engineer, NIST
6.	Douglas Edwards, P.E.	Senior Structural Engineer, FHWA
7.	James Wilcoski, P.E.	Project Manager and Research Structural Engineer, USACE
8.	Ali Saffar, Ph.D., P.E.	Professor, Department of Civil Engineering and Surveying University of Puerto Rico
9.	Robb G. Smith	Senior Consultant Amtech Roofing Consultants, Inc.
10.	Stephen A. Cauffman	Leader Structures Group, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

SUB-TEAM 3 Eastern Texas/Western Louisiana (Houston, TX/Baton Rouge, LA)
Deployment: October 10-14, 2005

1.	Christopher W. Letchford, Ph.D.	**Sub-Team 3 Coordinator**, Professor, Department of Civil Engineering Texas Tech University
2.	Jon A. Heintz, P.E.	Director of Projects, Applied Technology Council
3.	William Fritz, Ph.D.	Research Structural Engineer, NIST
4.	Sheila Rimal Duwadi, P.E.	Team Leader, Bridge Safety, Reliability and Security, Office of Infrastructure R&D, FHWA
5.	Dominic Sims	Deputy Chief Operating Officer, International Code Council (ICC)
6.	Walter J. Rossiter, Ph.D.	Research Chemist, NIST
7.	Dat Duthinh, Ph.D.	Research Structural Engineer, NIST

8.	Luis A. Godoy, Ph.D.	Professor and Associate Director for Research, Department of Civil Engineering and Surveying, University of Puerto Rico at Mayaguez
9.	Stephen A. Cauffman	Leader Structures Group, Materials and Construction Research Division, Building and Fire Research Laboratory, NIST

A.2 ROLES OF KEY FEDERAL AGENCIES IN DEPLOYMENT

NIST was responsible for defining the objectives, scope, and schedule for this deployment. NIST approved all members of the reconnaissance team. Members of NIST also participated in the reconnaissance and provided technical expertise in the assessment of performance of structures in the affected regions. Logistics with outside organizations was arranged by NIST management. Final approval of the reconnaissance report is also the responsibility of NIST.

U.S. Army Corps of Engineers provided technical information, coordination, and access, with special attention given to the assessment of the levee and floodwall system in New Orleans, for this reconnaissance effort. Members of the Army Corps of Engineers also deployed as members of the reconnaissance team.

Federal Highway Administration assisted in providing technical information and expertise in the assessment of highway and railroad bridges. Members of FHWA also deployed as members of the reconnaissance team.

A.3 ROLES OF PRIVATE INDUSTRY AND ACADEMIC INSTITUTIONS

ATC was responsible for assembling the reconnaissance team, selecting team coordinators, coordinating the travel and deployment arrangements for all non-NIST team members, and preparing a draft report for the NIST-led reconnaissance.

The role of private industry and academic institutions is to bring technical expertise to the reconnaissance team in the areas of structural engineering, transportation engineering, bridge design and analysis, lifeline engineering, risk analysis, geographic information systems, remote sensing, and report preparation and development.

Appendix B
List of Organizations Surveyed for Post-Hurricane Studies

American Petroleum Institute (API)

American Public Transportation Association (APTA)

American Railroad & Engineering & Maintenance of Way Association (AREMA)

American Society for Testing and Materials (ASTM)

American Society of Civil Engineers (ASCE)

Applied Technology Council (ATC)

Architectural Engineering Institute (AEI)

Centers for Disease Control (CDC)

Coasts, Oceans, Ports, and Rivers Institute (COPRI)

Council on Disaster Reduction (CDR)

Department of Homeland Security (DHS)

Electric Power Research Institute (EPRI)

Environmental and Water Resources Institute (EWRI)

Environmental Protection Agency (EPA)

Federal Aviation Administration (FAA)

Federal Emergency Management Agency (FEMA)

Federal Highway Administration (FHWA)

Federal Railroad Administration (FRA)

Federal Transit Administration (FTA)

GeoInstitute (GI)

Geospatial One Stop

Gulf Coast Housing Initiative

Hurricane Insurance Information Center

Institute for Business and Home Safety (IBHS)

International Hurricane Research Center

Liberty Mutual

Louisiana Hospital Association (LHA)

Louisiana State University Hurricane Center

Manufactured Housing Institute (MHI)

Multidisciplinary Center for Earthquake Engineering Research (MCEER)

Munich Re

National Academy of Sciences (NAS)

National Aeronautics and Space Administration (NASA)

National Association of Home Builders (NAHB)

National Conference of States on Building Codes and Standards (NCSBCS)

National Institute of Standards and Technology (NIST)

National Institutes of Health (NIH)

National Oceanic and Atmospheric Administration (NOAA)

National Science Foundation (NSF)

Naval Facilities Engineering Command (NAVFAC)

Office of Science and Technology Policy (OSTP)

Pipeline and Hazardous Materials Safety Administration (PHMSA)

Software Engineering International (SEI)

Structural Engineers Association of Central California (SEAOCC)

Technical Council on Forensic Engineering (TCFE)

Technical Council on Lifeline Earthquake Engineering (TCLEE)

The Infrastructure Security Partnership (TISP)

Transportation and Development Institute (T&DI)

U.S. Army Corps of Engineers (USACE)

U.S. Census Bureau

U.S. Department of Housing and Urban Development (HUD)

U.S. Department of Transportation (DOT)

U.S. General Services Administration (GSA)

U.S. Geological Survey (USGS)

U.S. Government Accountability Office (GAO)

Appendix C
OTHER RELATED STUDIES

To understand what knowledge or information had already been developed or collected prior to the deployment of the NIST reconnaissance teams, NIST approved that the Information Services Department of the Multidisciplinary Center for Earthquake Engineering Research (MCEER) develop a web-based search tool that surveyed data and reports from over 50 organizations or groups. A list of these organizations is provided in Appendix A. Because post-Katrina and post-Rita studies cover a broad range of subjects, this survey only covered those topics that were relevant to the structural performance of major buildings, lifelines and dwellings in these two events, as well as topics that helped to define the severity of the environmental factors that caused damage to these facilities. Short descriptions of key efforts are described in Appendix C.

The information gleaned from this review were used in 1) establishing the priorities for reconnaissance for all three deployments, but especially for New Orleans; 2) filling in information gaps for this report; and 3) providing a broader context for the recommendations contained in Chapter 7. The focus of the NIST-ATC report is described in Chapter 1 and essentially defines a broader, more comprehensive study which eventually identifies implementation or research needs with regard to improvements in design and construction codes.

American Petroleum Institute. The American Petroleum Institute launched a study to assess hurricane impacts on oil and gas operations in the Gulf of Mexico. Specifically, this study is examining impacts to crude oil, natural gas, refinery, and pipeline systems, in addition to impacts to the Louisiana Offshore Oil Port (LOOP). For more information, see www.api.org.

American Society for Testing and Materials. In the aftermath of Hurricane Katrina, the U.S. Public Health Service contacted ASTM International and requested its hospital preparedness standard. The purpose of E 2413 is to provide the minimal levels of preparedness needed for hospitals to deal with a large-scale terrorist attack or other serious emergency. The standard deals with issues such as the process of organizing and planning a hospital response plan, the nature of supplies that hospitals need to make available, and an acceptable means to protect facilities for usual operation, patients, and staff while still providing an effective response. It also deals with the coordination of operations with community assets, including local emergency planning committees.
www.astm.org/cgibin/SoftCart.exe/SNEWS/NOVEMBER_2005/plaintalk_nov05.html?L+mystore+iauf2689

American Society of Civil Engineers. In collaboration with the University of California, Berkeley and the U.S. Army Corps of Engineers, the American Society of Civil Engineers (ASCE) is conducting a study of the regional flood protection systems in the New Orleans area. The initial focus is to capture perishable data and observations related to the performance of the levee system in New Orleans in the aftermath of Hurricane Katrina. The initial field observations occurred over a span of two and a half weeks, between September 28 and October 15, 2005. A preliminary report has been published that contains assessments of likely causes of failures and/or significant damage to levees and floodwalls at many sites within the New Orleans flood protection system. See www.asce.org/files/pdf/katrina/teamdatareport1121.pdf

American Society of Civil Engineers. In October 2005, the Department of Defense authorized the American Society of Civil Engineers (ASCE) to convene an external review panel to conduct continuing expert review of the work performed by the federal government's Interagency Performance Evaluation Task Force (IPET). Organized by the U.S. Army Corps of Engineers, the IPET's mission is to obtain the facts by collecting, analyzing, testing, and modeling data and information on the performance of the New Orleans hurricane protection system during Hurricane Katrina. The IPET study is expected to be released in June 2006. www.asce.org/static/hurricane/whitehouse.cfm

Federal Emergency Management Agency. FEMA's Hazard Mitigation Assessment Teams (MATs) are conducting engineering analyses of structures damaged by Hurricane Katrina to determine the causes of structural failures and successes. Facility types that are being assessed include government facilities, homes, businesses, and other structures. The teams include representatives from FEMA, NIST, state and local agencies, and a range of private sector specialists in structural and civil engineering, architecture, building construction, floodplain management, and building code development and enforcement. Based on a comprehensive analysis of the data, the teams are preparing recommendations regarding construction codes and standards, building design issues, and best practices that communities and the construction industry can use to reduce damage from future disasters. See http://www.fema.gov/pdf/rebuild/mitigation_assessment_team.pdf

Louisiana State University. Louisiana State University (LSU) is preparing a report for the State of Louisiana to help explain the levee failures at the 17th Street and London Avenue Canals. The team is led by Ivor van Heerden, Deputy Director of the LSU Hurricane Center. The team is using computer models to examine various design scenarios to better understand those factors that led to the failure of the levees at these two locations. See: www.cnn.com/2005/TECH/science/12/01/new.orleans.levees.ap/

Manufactured Housing Institute. The National Modular Housing Council (NMHC) and the Manufactured Housing Institute (MHI) have teamed up to launch a new initiative to help rebuild homes in the hurricane-devastated areas of the Gulf Coast. "The Gulf Coast Housing Initiative: Factory Building the American Dream" will focus on demonstrating how both modular and manufactured homes can play a vital role in rebuilding permanent homes for the thousands of people displaced by Hurricanes Katrina and Rita.

Multidisciplinary Center for Earthquake Engineering Research (NSF-sponsored). Within days after Hurricane Katrina made landfall, the Multidisciplinary Center for Earthquake Engineering Research (MCEER) dispatched a reconnaissance team to rapidly investigate damage from the disaster and file real-time reports, posted daily on the MCEER web site. Two additional teams were deployed within weeks for further investigations. Members of the NIST team that deployed with MCEER include Keith Porter, Jerry O'Connor, and Shubharoop Ghosh. Sponsored principally by the National Science Foundation (NSF), the MCEER reconnaissance team used remote sensing technologies, in-field investigations, and on-site interviews to rapidly collect data, including visual images of damage, over large geographical areas. The focus of these investigations was to collect information and data on the performance of buildings and lifeline facilities, and to deploy several advanced technologies (remote sensing, GPS-based data collection systems) to collect data for a very large region. Preliminary reports are available on MCEER's website (http://mceer.buffalo.edu/); a series of three reports will be available that summarizes the findings and conclusions from these deployments in early February 2006.

National Aeronautics and Space Administration. The National Aeronautics and Space Administration (NASA) has produced a series of images that document the effects of Hurricanes Katrina and Rita. Using a variety of sensors, NASA has delineated areas of flooding and wind damage at different stages of these events. In addition to still images, animation is used to display the severity of damage and flooding in the New Orleans area. See http://www.nasa.gov/vision/earth/lookingatearth/h2005_katrina.html

National Oceanic and Atmospheric Administration. The day after Hurricane Katrina made landfall on the U.S. Gulf Coast, the National Oceanic and Atmospheric Administration (NOAA) began aerial photography flights of the affected areas. For nine days, the NOAA Cessna Citation aircraft flew two to three missions each day. Nearly 7,000 aerial images were produced from these missions. Similar missions were completed after Hurricanes Rita and Wilma. See the following website for more information: http://www.noaanews.noaa.gov/stories2005/s2500.htm

National Research Council. In October (2005), the Department of Defense announced the creation of an independent panel of national experts under the direction of the National Academies of Science to evaluate the performance of the hurricane protection systems in New Orleans and the surrounding areas. Under the National Academies, the National Research Council (NRC) will assemble a multi-disciplinary, independent panel of experts to perform a high-level review and issue a final set of findings based primarily on the data gathered by IPET. The ASCE external review panel (described above) will also report its findings directly to NRC. The report is expected to be released in July 2006. See: www.asce.org/static/hurricane/whitehouse.cfm.

Naval Facilities Engineering Command (NAVFAC). Immediately following Hurricane Katrina, the Naval Facilities Engineering Command deployed damage assessment teams (DATs) from around the country to provide immediate damage assessment for all Gulf Coast naval installations. These teams were composed of structural and mechanical engineers, architects, roofing specialists, and contracting specialists from various NAVFAC facilities. See the following website for more information on this deployment. https://portal.navfac.navy.mil/pls/portal/docs/PAGE/NAVFAC/NAVFAC_FORMEDIA_PP/NAVFAC_PUBLICATIONS_PP/CEC%20BIWEEKLY/BIWEEKLY%20ARCHIVE/2005SEPTEMBER22/050922_BIWEEKLY.PDF

Office of Science and Technology Policy. Federal research agencies, the Office of Management and Budget (OMB), and the Office of Science and Technology Policy (OSTP) are coordinating activities with institutions and individuals in the Gulf region to restore the high quality of research, research training, and science education supported by Federal grants and other assistance awards. Some of the most important actions that can be taken to address resumption of research activities and to address critical research resources are being dealt with on a project by project basis. See the following website for more details. http://www.ostp.gov/html/Hurricane%20relief1.pdf

U.S. Army Corps of Engineers. A comprehensive analysis to determine exactly what happened in the New Orleans flood protection system during Hurricane Katrina is the mission of the Interagency Performance Evaluation Task Force (IPET). Established by the Chief of the U.S. Army Corps of Engineers, the IPET is comprised of some of the nation's leading engineers and scientists from government (federal, state and local agencies), academia and private industry. The IPET analysis teams are all co-led by representatives from independent organizations and personnel from the Corps. NIST is on the IPET, providing technical review, and USACE staff is on the NIST recon team. While the IPET's primary focus is investigating the levees and floodwalls that overtopped or breached in order to help provide answers for use in future New

Orleans protection project designs, the task force is also providing preliminary observations from its own team members and from other engineering organizations for possible use in the rapid-paced repairs of Hurricane Katrina damage. These observations are being provided to the Corps' Task Force Guardian, which is managing the repair of damaged levees and floodwalls, for possible inclusion in repair designs. As part of this process, the IPET has reviewed the "Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005" that was prepared jointly by an American Society of Civil Engineers (ASCE) team and a National Science Foundation (NSF) team, which was primarily from the University of California at Berkeley. See https://ipet.wes.army.mil/

U.S. Environmental Protection Agency. The Environmental Protection Agency is providing a website for users to obtain information on Flood Water Sampling Locations. This map displays the States impacted by the Hurricane Katrina (Louisiana, Mississippi and Alabama) and by Hurricane Rita. However, sampling of flood water and sediment has occurred only in Louisiana in the following parishes: Jefferson, Orleans, Plaquemines, St. Bernard, and St. Tammany. See the following website for more information: http://www.epa.gov/enviro/katrina/instruction.html

U.S. Geological Survey. The U.S. Geological Survey (USGS), NASA, the U.S. Army Corps of Engineers, and the University of New Orleans are cooperating in a research project investigating coastal change that occurred as a result of Hurricane Katrina. Aerial video, still photography, and laser altimetry surveys of post-storm beach conditions were collected August 31 and September 1, 2005 for comparison with earlier data. The comparisons will show the nature, magnitude, and spatial variability of coastal changes such as beach erosion, overwash deposition, and island breaching. These data will also be used to further refine predictive models of coastal impacts from severe storms. The data are being made available to local, state, and federal agencies for purposes of disaster recovery and erosion mitigation. See the following website: http://coastal.er.usgs.gov/hurricanes/katrina/

U.S. Government Accountability Office (GAO). The federal government relies on partnerships across the public and private sectors to achieve critical results in preparing for and responding to natural disasters, with an increasing reliance on contractors to carry out specific aspects of its missions. At the same time, the acquisition functions at several agencies are on GAO's high risk list, indicating a vulnerability to fraud, waste, abuse, and mismanagement. GAO was asked to provide an overview of (1) its role in evaluating the contracting community with regard to disaster preparedness and response; (2) GAO's plans for reviewing the performance of the federal government and its contractors in preparing for and responding to the hurricanes; and (3) what GAO has learned so far about the performance of the federal government and its contractors in preparing for and responding to the hurricanes. See: http://www.gao.gov/new.items/d06235t.pdf

University of California at Berkeley (NSF-sponsored). Civil engineers from the University of California, Berkeley (UCB), are part of an independent team of researchers investigating levee failures in the wake of Hurricane Katrina. The research team is funded by the National Science Foundation (NSF) and is led by Ray Seed, UC Berkeley professor of civil engineering and principal investigator of the NSF grant. The team is collaborating closely with groups from the U.S. Army Corps of Engineers and the American Society of Civil Engineers (ASCE), sharing data and resources. Each team's findings, however, are being developed independently. The researchers studying the levee failures are expected to identify and prioritize the steps needed to restore critical infrastructure and to extend lessons learned to other regions of the United States.

Appendix D
CONVERSION OF 1-MINUTE “SUSTAINED” WIND TO 3-SECOND GUST OR “PEAK GUST”

V_3 = Wind velocity for 3-second gust or “Peak Gust”
V_{60} = Wind velocity for 1-minute “Sustained”
V_{3600} = Wind velocity for 1-hour (used for conversion)

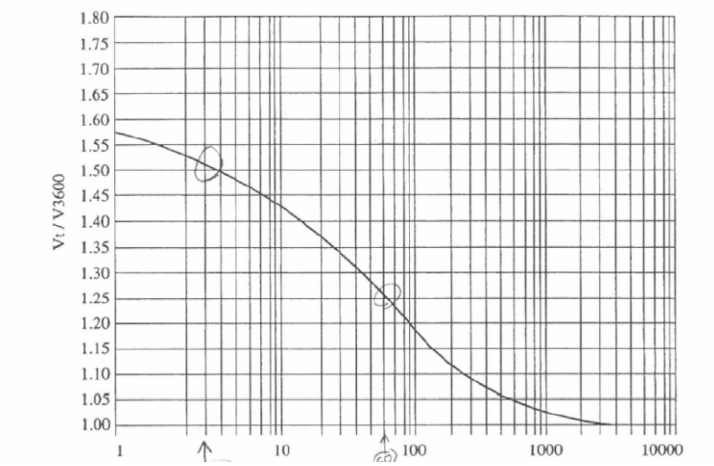

Figure A-1 ASCE 7-05 Commentary (Fig. C6-4) Curve

Applying a two-step conversion process using the ASCE 7-05 Commentary (p. 308, Fig. C6-4) curve:

Step 1: Using the curve, convert 1-minute “Sustained” to 1-Hour:

$(V_{60} / V_{3600}) = 1.26$

$\rightarrow V_{60} = 1.26 * (V_{3600})$ (a)

Then convert 1-Hour speed to peak 3-sec gust:

$(V_3 / V_{3600}) = 1.52$

$\rightarrow V_3 = 1.52 * (V_{3600})$ (b)

Step 2: Convert 1-minute “Sustained” speed to peak 3-sec gust:

Dividing equation (b) by equation (a):

$(V_3 / V_{3600}) / (V_{60} / V_{3600}) = [1.52 * (V_{3600})] / [1.26 * (V_{3600})]$

$\rightarrow (V_3 / V_{60}) = 1.52 / 1.26 = 1.21$

$\rightarrow$ **$V_3 = 1.21 * (V_{60})$**

Therefore, in accordance with the ASCE 7-05 Commentary, the peak 3-s gust is 21 % higher than the 1-minute “Sustained” wind speed.
Note that the ASCE 7-05 Commentary (Table C6-4) conversion factors between wind speeds with various averaging times are nominal values used for structural engineering purposes, and

that those factors are currently regarded by some experts as inappropriate. In fact, the conversion factors, rather than being deterministic, exhibit random variability around a mean value.

Appendix E
DESIGN AND CONSTRUCTION CODES IN AFFECTED AREAS

BUILDINGS

In August and September of 2005, when Hurricanes Katrina and Rita made landfall, there were no statewide building codes in effect in Louisiana, Texas, Mississippi, and Alabama. Local jurisdictions at the city, county, or parish levels were permitted to set and enforce minimum standards for building construction. As such, the basis for building codes in the regions affected by the hurricanes varies, and buildings that experienced wind, storm surge, and flood loading as a result of Hurricanes Katrina and Rita were built to a variety of construction standards.

The Southern Building Code Congress International (SBCCI) Standard Building Code has been the historical basis for building codes in the Southeastern United States. With some exceptions, most jurisdictions had adopted the 1997 edition of this code in 1997, or shortly thereafter. With the formation of the International Code Council (ICC), and the publication of the 2000 International Building Code (IBC) and 2000 International Residential Code (IRC), some jurisdictions began adopting the I-codes as the basis for their building codes. By 2005, before the hurricanes hit, many jurisdictions had adopted the 2000, or later, editions of the IBC and IRC. This includes Texas, which adopted the 2003 IBC as the basis for a statewide building code in September 2005, although this adoption did not take effect until January 2006.

As a result of the hurricanes, the State of Louisiana and selected cities in Texas and Alabama moved toward adoption of the 2003 IBC and 2003 IRC in 2005. Building industry groups are currently lobbying for adoption of a statewide building code in Mississippi.

Building codes in effect in the areas investigated by the NIST reconnaissance team are summarized below.

Louisiana. In November 2005, Louisiana adopted the full suite of the ICC International Codes including the 2003 IBC, IRC, IEBC, IMC. This adoption is immediately applicable to buildings being rebuilt as a result of the hurricanes, and to home repairs if repair costs are more than 50% of the pre-storm valuation. These codes will first take effect in the 11 coastal parishes most affected by the hurricanes, and then statewide for all new construction on January 1, 2007. Prior to this adoption, cities and parishes in Louisiana were permitted to set minimum standards for building construction, and enforcement occurred at either the city or the parish level. At the time of the hurricanes, there was a variety of codes in effect in Louisiana.

> **New Orleans.** In January 2004, the city of New Orleans adopted the 2000 IBC and 2000 IRC, which were in effect at the time of the hurricane. Between 1985 and 1997, the codes were based on the SBCCI Standard Building Code, most recently the 1997 edition. Prior to that, New Orleans drafted its own building standards.
>
> **Lake Charles**. In January 2004, the city of Lake Charles adopted the 2000 IBC and 2000 IRC, which were in effect at the time of the hurricane. Prior to that, the codes were based on the SBCCI Standard Building Code, most recently the 1999 edition.

Plaquemines Parish. In Plaquemines Parish, building codes are enforced at the parish level. In December 2005, Plaquemines Parish adopted the 2003 IBC and 2003 IRC. At the time of the hurricane, the 1997 edition of the SBCCI Standard Building Code was in effect.

Jefferson Parish. Jefferson Parish maintains a building code, but cities located within the parish have not been required to follow parish construction standards. In August 1998, Jefferson Parish adopted the 1997 edition of the SBCCI Standard Building Code, which was the code in effect at the time of the hurricane. Between 1991 and 1997, the code was based on the 1991 edition. Prior to that, Jefferson Parish drafted its own building standards, modeled after the New Orleans Building Code and the Uniform Building Code. Adoption of the 2003 IBC and 2003 IRC is expected to occur by March 2006.

Texas. In September 2005, the State of Texas adopted the 2003 IBC, but this adoption did not take effect until January 2006. Prior to this adoption, local city and county jurisdictions in Texas were permitted to set minimum standards for building construction. In addition, in order to be eligible for windstorm insurance, homeowners were required to comply with the Texas Windstorm Code, published by the Texas Department of Insurance. The Texas Department of Insurance put into effect the 2000 IBC and IRC with Texas revisions on February 1, 2003 for the fourteen counties on the Texas Gulf Coast. The Texas Department of Insurance put into effect the 2003 IBC and IRC on January 1, 2005 for these counties. The 2003 IBC and 2000 IRC are effective statewide in Texas but local jurisdictions are authorized by state law to adopt later editions of the IBC, IRC, and other International Codes.

Beaumont. In January 2004, the city of Beaumont adopted the 2003 IBC and 2000 IRC, which were in effect at the time of the hurricane. Prior to that, Beaumont building codes were based on the SBCCI Standard Building Code, most recently the 1997 edition.

Orange. In January 2005, the city of Orange adopted the 2003 IBC and 2003 IRC, which were in effect at the time of the hurricane. Prior to that, Orange building codes were based on the SBCCI Standard Building Code, most recently the 1997 edition.

Port Arthur. In December 2005, the city of Port Arthur adopted the 2003 IBC. At the time of the hurricane, the 2000 IBC, and the 2000 IRC were in effect. Prior to that, Port Arthur building codes were based on the SBCCI Standard Building Code, most recently the 1997 edition.

Mississippi. Currently, there is no statewide building code in Mississippi. Local city and county jurisdictions are permitted to set minimum standards for building construction. As a result of Hurricane Katrina, however, Mississippi building groups are lobbying for statewide adoption of the IBC. The Mississippi Construction Industry Coalition sponsored a workshop in December 2005 to prepare key decision makers for future hurricanes and to discuss the potential for a statewide minimum building code in Mississippi.

Bay St. Louis. The city of Bay St. Louis in Hancock County is currently using the 2003 IBC and 2003 IRC, which were in effect at the time of the hurricane.

Biloxi. The city of Biloxi in Harrison County is currently using the 1997 SBCCI Standard Building Code, which was the code in effect at the time of the hurricane.

Gulfport. The city of Gulfport in Harrison County is currently using the 1995 Council of American Building Officials (CABO) One and Two Family Dwelling Code, which was the code in effect at the time of the hurricane.

Ocean Springs. In August 2003, the city of Ocean Springs in Jackson County adopted the 2003 IBC and 2003 IRC, which were the codes in effect at the time of the hurricane. Between 2000 and 2003, the codes were based on the 2000 IBC and IRC. Prior to that, Ocean Springs building codes were based on the SBCCI Standard Building Code, most recently the 1997 edition.

Alabama. Currently there is no statewide building code in Alabama. Local city and county jurisdictions are permitted to set minimum standards for building construction.

Bayou La Batre. The city of Bayou La Batre in Mobile County adopted the 2003 IBC and 2003 IRC in October 2005, in direct response to hurricane damage. Prior to that, Bayou La Batre building codes were based on the SBCCI Standard Building Code, most recently the 1997 edition.

INFRASTRUCTURES and LIFELINES

Lifeline Facilities. Guidelines, codes and standards for the design of lifeline facilities are varied and numerous. Table E-1 is a listing of the design guidelines and standards for oil product, natural gas, water, wastewater, electric power, and telecommunication systems, and for port and inland waterway facilities referenced by this report, and derived from the matrix developed by the American Lifeline Alliance [10]. Since adoption of these guidelines and standards is completely voluntary at present, it is not known whether they have been adopted by the various lifeline operators in the Gulf Coast region at this time.

Floodwalls and Levees. Five Engineer Manuals of the US Army Corps of Engineers relate to the design and construction of floodwalls and levees. USACE [13] presents basic principles used in the design and construction of earth levees. Among other features, this document specifies procedures for field investigations, laboratory tests, stability and settlement analysis, and levee construction. USACE [11] reviews principal classes of flood analyses and estimates involved in the planning and design of flood control and multiple-purpose projects, with the primary objective of indicating the general application and purposes of Standard Project Flood Estimates. USACE [12] provides guidance to Corps of Engineers personnel responsible for monitoring and analyzing embankment dams and levees. USACE [14] provides criteria for the design of landscape plantings and vegetation maintenance at floodwalls, levees, and embankment dams. None of these documents specify how the design flood elevation is to be established. None address probabilistic risk of levee or floodwall overtopping, surface erosion, internal erosion, slides, or other failure modes, although USACE [13] specifies some factors of safety, which provide an unspecified non-exceedance probability of various failure modes given the design flood.

Highway Bridges. The American Association of State Highway and Transportation Officials (AASHTO) is a nonprofit, nonpartisan association representing highway and transportation departments in the 50 states, the District of Columbia, and Puerto Rico. It represents five transportation modes: air, highways, public transportation, rail, and water.

AASHTO's primary goal is to foster the development, operation, and maintenance of an integrated national transportation system. It funds the necessary research, code writing, and continual refinement of technical issues involved in the design of highways and bridges. These are adopted into practice after thorough deliberation and a vote by members. FHWA does not have the authority to exert direct control of AASHTO activities but is a valuable partner that provides additional resources and advice.

AASHTO issues publications on geometric design of streets and highways, and virtually any bridge designed in the past 50 years was done according to the version of AASHTO's Standard Specification for Highway Bridges that was applicable at the time. This code gives very specific design criteria on bridge design loads. For live loads (i.e. traffic), it provides design vehicle configurations with axle weights and spacing. It also gives guidance on wind, thermal, braking, and earthquake loads. For river bridges, it also gives a basis for design of hydraulic capacity. Although the potential for other forces such as wave action and uplift from surge is acknowledged, specific procedures for design of bridges to resist such loads is not currently available.

AASHTO is in the midst of conversion to a newer Load and Resistance Factor Design (LRFD) Bridge Design Specification that is based on reliability theory. It has been used for the design of very few bridges to date, but is expected to be the principal AASHTO code for bridge design by 2007. This document advances the understanding of multiple load combinations and special limit states, providing factors for certain combinations of hazards that should be accounted for during design. This design approach was not in practice when the bridges in the Gulf Coast region were built.

Table E-1 Natural Hazards Design Matrix for Lifeline Systems

American Society of Mechanical Engineers

ASME/ANSI B16.33 - Manually Operated Metallic Gas Valves for Use in Gas Piping Systems up to 125 psig
ASME/ANSI B16.34 - Valves – Flanged, Threaded, and Welding End
ASME/ANSI B16.38 - Large Metallic Valves for Gas Distribution
ASME/ANSI B31.3 - Process Piping

American Petroleum Institute

API 620 - Recommended Rules for Design and Construction of Large, Welded, Low-Pressure Storage Tanks

API 650 - Welded Steel Tanks for Oil Storage

American Water Works Association

AWWA Standards for Valves and Hydrants
AWWA D100 - Welded Steel Tanks for Water Storage
AWWA D103 - Factory-Coated Bolted Steel Tanks for Water Storage
AWWA D110 - Wire- and Strand-Wound Circular Prestressed Concrete Water Tanks
AWWA D115 - Circular Prestressed Concrete Tanks with Circumferential Tendons
AWWA D120 - Plastic Storage Tanks

U.S. Department of Agriculture/Rural Utilities Service

RUS 1742e-200 - Design Manual for High Voltage Transmission Lines
RUS 1742e -300 - Design Guide for Rural Substations

American Society of Civil Engineers

ASCE 7 - Minimum Design Loads for Buildings and Other Structures
ASCE 10 - Design of Latticed Transmission Structures
ASCE Manual 72 - Tubular Pole Design Standard
ASCE Manual 74 – Guidelines for Electrical Transmission Line Structural Loading
ASCE Manual 91 – The Design of Guyed Electrical Transmission Structures
ASCE/PCI Joint Committee on Concrete Poles - Guide for the Design of Prestressed Concrete Poles

Institute of Electrical and Electronics Engineers

IEEE 691 - Guide for Transmission Structure Foundation Design and Testing
IEEE 693 - IEEE Recommended Practice for the Seismic Design of Substations
NESC - National Electrical Safety Code

Telecommunications Industry Association/Electronic Industry Alliance

TIA/EIA 222F - Structural Standards for Steel Antenna Towers and Antenna Supporting Structures

TIA/EIA 222G - Steel Antenna Towers and Antenna Supporting Structures

Bell Communications Research (Bellcore)

Bellcore has produced proprietary telecommunication systems guidelines for Buried Cables, Aboveground Cables, and Switching Equipment which were not produced by a consensus process as defined for Standards Developing Organization's approved by the American National Standards Institute.