

Performance of Physical Structures in Hurricane Katrina and Hurricane Rita

Reconnaissance Findings and Recommendations

June 9, 2006

**Building and Fire Research Laboratory
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce**

The Context

- Hurricane Katrina was the deadliest hurricane to strike the United States since 1928.
 - Seven of the 10 most expensive hurricanes in U.S. history occurred in the 14 months from August 2004 to October 2005.
 - Hurricane Katrina appears to have destroyed 10 times as many homes as Hurricane Andrew in 1992 or the 4 storms to hit Florida and the Southeast in 2004.
- Hurricane Katrina and Rita caused significant loss of life and economic losses:
 - Number of deaths: ~1400
 - Estimated economic losses: \$70-130 billion
 - Estimated insured losses: \$45-65 billion
- Extensive damage to physical structures resulted from:
 - Storm surge and wave action; surge-borne debris
 - Flooding due to breaching of levees and floodwalls
 - Extreme winds and wind borne debris

Overall Approach

- Multi-organizational reconnaissance of the performance and damage to physical structures.
 - 26 experts drawn from 16 private sector, academic, and government organizations.
- NIST-led reconnaissance was a cooperative effort from its very launch.
 - Data and information openly shared between NIST, other federal agencies, and private sector participants.
 - While findings and recommendations are those of NIST, the report and its recommendations have been reviewed by the participating organizations.
 - Interagency cooperation is continuing as agencies plan and carry-out follow up actions in response to recommendations.
- Complements other completed and ongoing studies of the performance of structures in the Gulf region.
- Only study to take a broad look at damage to physical structures (major buildings, infrastructure, and residential structures) and its implications for the Gulf Coast and other hurricane-prone regions.

NIST Pre-Reconnaissance Deployments

- NIST began preparation for conducting a reconnaissance on August 29, 2005. Coordinated with FEMA and USACE.
- NIST roofing materials expert deployed with Roofing Industry Committee on Weathering Issues (RICOWI) Sept. 6-10, 2005.
 - Deployment focused on area between Ocean Springs, MS and Pascagoula, MS.
 - Team conducted reconnaissance of roofing damage to essential facilities, schools, hotels, and residences.
- Four NIST structural engineers deployed with the FEMA Mitigation Assessment Team (MAT) Sept. 26-Oct. 1, 2005.
 - NIST staff operated independently but in cooperation with FEMA MAT.
 - Deployment focused on Mississippi Gulf Coast.
 - Team coordinated with U.S. Army Corps of Engineers to visit levee breaches in New Orleans.

Why Reconnaissance?

- Catastrophic events provide an unfortunate but important learning opportunity to improve standards, codes, and practices that will reduce losses in future events.
- **NIST undertook a broad-based reconnaissance rather than a detailed investigation since much has already been learned from past hurricanes.**
- **The reconnaissance was intended to identify new technical issues for:**
 - **Repair and reconstruction in the devastated regions.**
 - **Improving building codes, standards, and practices.**
 - **Further study of specific structures or research and development.**
- The 26 experts were deployed in 3 sub-teams to conduct reconnaissance in:
 - Mississippi Gulf Coast (Hurricane Katrina) – Oct. 17-21, 2005
 - New Orleans (Hurricane Katrina) – Oct. 17-21, 2005
 - Southeast Texas (Hurricane Rita) – Oct. 10-14, 2005
- Each of the three teams was further subdivided to focus on major buildings, infrastructure, residential structures.

Scope of Reconnaissance

- Collect and analyze:
 - Perishable field data (e.g., first-hand observations, photographic data) on performance of physical structures.
 - Environmental data on wind speed, storm surge, and flooding, and relate environmental data to observed structural damage.
- Review and analyze relevant data collected by other sources (e.g., government agencies, academic and research organizations, industry groups).
- Document field observations, environmental conditions, and data gathered from other sources, and make recommendations for:
 - Repair and reconstruction in the devastated regions.
 - Improving building codes, standards, and practices.
 - Further study of specific structures or research and development.

Organizations Participating in NIST Team

- Federal agencies
 - National Institute of Standards and Technology
 - Federal Highway Administration
 - U.S. Army Corps of Engineers
- Private Sector Organizations
 - Applied Technology Council
 - Amtech Roofing Consultants, Inc.
 - Applied Residential Engineering Services
 - ImageCat, Inc.
 - International Code Council, Inc.
 - Scawthorn Porter Associates, LLC
 - Shiner Moseley and Associates, Inc.
 - Smith & Huston, Inc.
- Academic and Research Institutions
 - National Research Council, Canada
 - Texas Tech University
 - University at Buffalo, Multidisciplinary Center for Earthquake Engineering Research
 - University of Puerto Rico

Coordination with Other Agencies

- FEMA Mitigation Assessment Team
 - Damage reconnaissance with focus on mitigation of risks in new or replacement buildings in hurricane-affected areas
 - Coordination and planning of reconnaissance efforts and follow-up work on flood map modernization
 - NIST experts deployed with FEMA MAT
 - FEMA reviewed and commented on final report
- U.S. Army Corps of Engineers
 - Focus on performance evaluation and rebuilding of flood control system in New Orleans
 - USACE staff participated in NIST reconnaissance and provided access to data on flood protection system
 - On-going coordination on flood map modernization
 - USACE reviewed and commented on final report
- Federal Highway Administration
 - Focus on performance of highway structures (roads and bridges)
 - Two FHWA staff participated in NIST reconnaissance
 - FHWA reviewed and commented on final report

Coordination with Other Agencies (2)

- National Science Foundation
 - Three NSF-funded researchers participating on NIST reconnaissance
 - Data from NSF-funded reconnaissance reviewed as part of NIST effort
 - One NSF-funded researcher provided peer review of final report
- National Oceanic and Atmospheric Administration
 - On-going coordination on development of risk-based storm surge maps and evaluation of Saffir-Simpson Hurricane Scale
- Department of Housing and Urban Development
 - Reviewed and provided comments on final report
- U.S. Geological Survey
 - On-going coordination on development of risk-based storm surge maps

External Peer Reviewers of Final Report

- Robert Bea, Ph.D., NAE, University of California, Berkeley
 - NSF SGER Grant Awardee
- Gregory Baecher, Ph.D., NAE, University of Maryland
 - USACE/IPET Team Member
- William Coulbourne, P.E., URS Corporation
 - FEMA/MAT Team Leader
- Robert Hanson, Ph.D., NAE
 - NCST Advisory Committee Member
- James R. Harris, Ph.D., NAE, J. R. Harris and Company
 - ASCE/SEI Codes and Standards
- Timothy Reinhold, Ph.D., Institute for Building and Home Safety
 - Insurance Industry and Wind Industry Expert

Technical Basis of Findings

- Findings are based upon:
 - data collected in the field during the reconnaissance
 - analysis of observations made by other teams
 - analysis of environmental data
 - engineering judgment
- Analytical, numerical, and statistical calculations were outside the scope of this reconnaissance study.

Key Needs for Detailed Technical Studies

- 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.
- Develop risk-based storm surge maps for use in flood-resistant design of structures.
- Evaluate and, if necessary, modify the Saffir-Simpson hurricane scale's treatment of storm surge effects due to hurricanes.

Key Findings on Codes, Standards, and Practices

- ***Critical importance of state and local entities adopting and then rigorously enforcing building standards, model codes, and practices.***
 - No statewide building code in Louisiana, Mississippi, Alabama, or Texas* at the time the hurricanes struck.
 - The City of New Orleans adopted the 2000 International Building and Residential Codes in January 2004.
 - Louisiana has adopted the International Codes (IBC, IRC, IEBC, and IMC) for the 11 parishes hardest hit by Katrina for rebuilding. The codes go into effect statewide in 2007.
 - The 2003 IBC was adopted statewide in Texas in September 2005 and went into effect statewide in Texas in January 2006.
 - Mississippi does not currently have a statewide building code. Local jurisdictions are permitted to set minimum standards for building construction.
 - Alabama does not currently have a statewide building code. Local jurisdictions are permitted to set minimum standards for building construction.
- The team identified opportunities for improvements in codes, standards, and practices that require no additional study.

* 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.

The Hazard Context

- Hurricane Katrina struck the Gulf Coast as a Category 3 hurricane. The accompanying storm surge reached heights of up to 28 feet in some areas.
 - Hurricane Katrina reached Category 5 in the Gulf of Mexico with max wind of 173 mph.
 - Storm made landfall as a Category 3 hurricane with max wind of 126 mph.
- Hurricane Rita struck the Texas-Louisiana border as a Category 3 hurricane based on winds in a small area in extreme southwest Louisiana. In this small area, the storm surge reached heights of up to 15 feet. Elsewhere, wind speeds were consistent with a Category 1 or 2 hurricane.

Principal Findings: Storm Surge

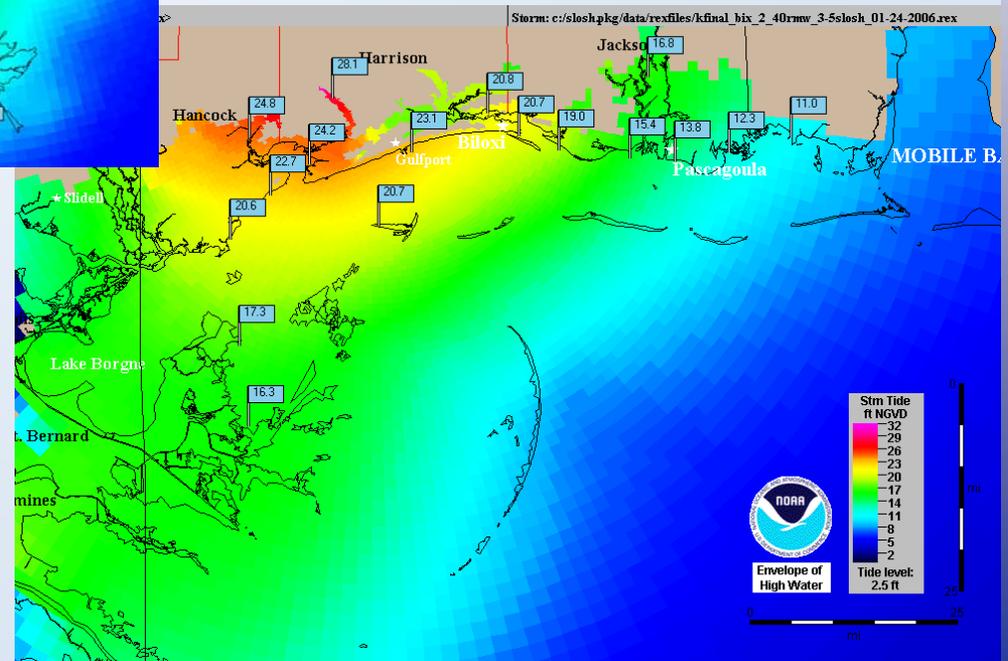
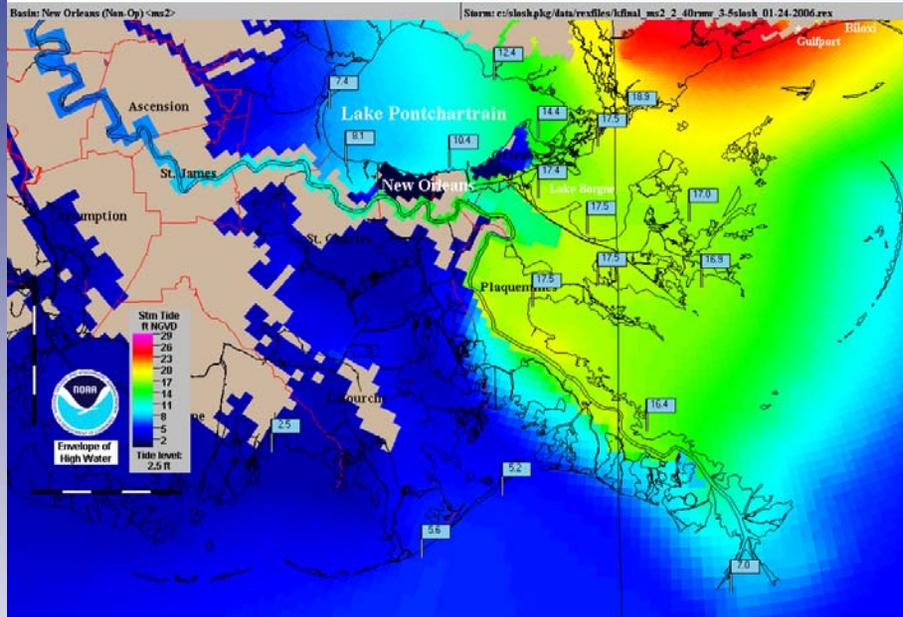
- In coastal areas and in New Orleans, storm surge was the dominant cause of damage.
- Storm surge heights and flooding, in general, exceeded the levels defined by existing flood maps and historical records.
- While design provisions exist to address storm surge and flooding, existing flood hazard maps – 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 hazard from storm surge and coastal flooding is required to appropriately apply existing design provisions and elevation levels for buildings and residences.

Principal Findings: Saffir-Simpson Scale

- The Saffir-Simpson Hurricane Intensity Scale – which is used in part by emergency managers for issuing public warnings and making evacuation decisions – specifies hurricane wind speeds and indicates storm surge heights associated with each 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 demonstrated that it is possible for storm surge heights to substantially exceed heights associated with a specific hurricane intensity by the Saffir-Simpson scale.
- NOAA does not rely on the storm surge ranges associated with the Saffir-Simpson hurricane scale. Instead NOAA includes in its advisories storm surge forecasts based upon use of storm surge simulation models.
- 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 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 Hindcasts

- Hindcasts of storm surge due to Hurricane Katrina for Gulf Coast and New Orleans.

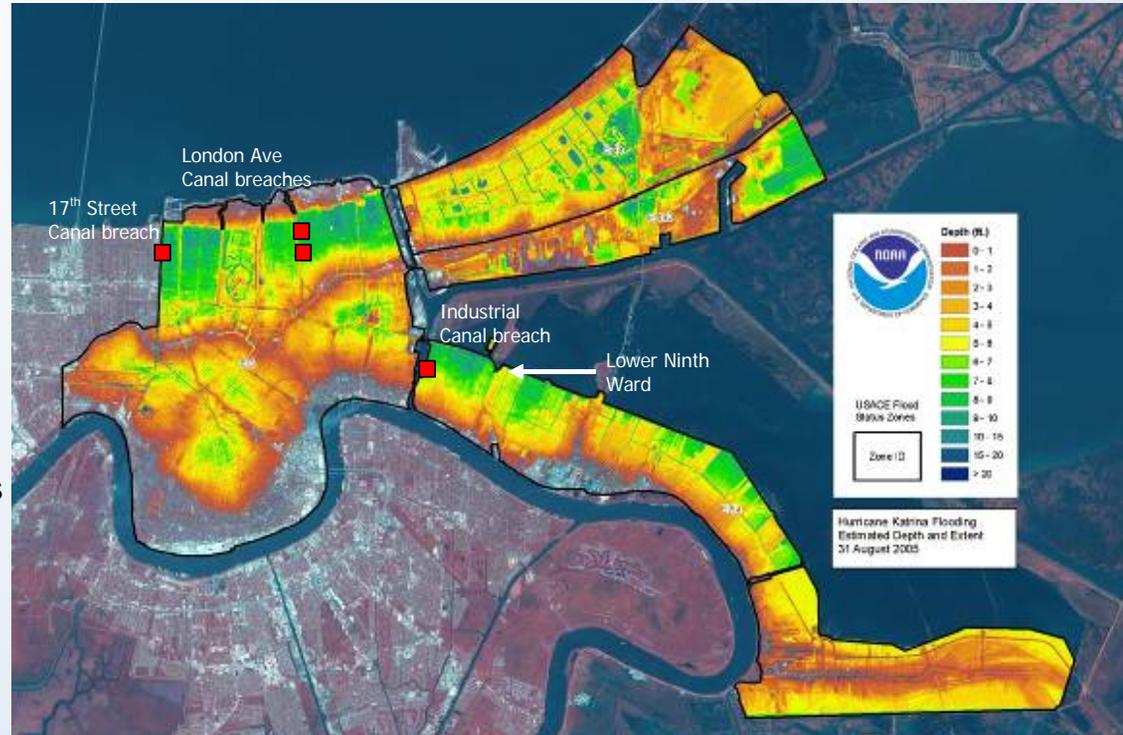


Hurricane Storm Surge

Saffir-Simpson Hurricane Scale		Blue = Hurricane Katrina Red = Hurricane Rita				
Category	Potential Storm Surge (ft above normal)	Location	NIST Observed HWM Relative to Ground Level (ft)	FEMA Storm Surge Contour (estimated) (ft)	Storm Surge Hindcast (ft) ADCIRC/SLOSH	
1	4-5	Port of Mobile, AL	13			
		Port of Pascagoula, MS	20	15-17		
2	6-8	Port of Gulfport, MS	26-28	24-25	23	
		Lake Pont. Causeway		8-9	8-11	
3	9-12	Lake Pont. I-10 Bridge	14		14	
		Waveland City Hall		24-25	23 24-25	
4	13-18	Bay St. Louis City Hall		23-25	25	
		Bay St. Louis, US90 Br.		23-25	26 24-25	
		Pass Christian City Hall		23-25	26 24	
5	Over 18	Long Beach Harbor, MS		24-25	28	
		Gulfport City Hall, MS		24-25	28 24-25	
		Biloxi, MS		21-22	28 21-22	
		Ocean Springs City Hall, MS		21-22	26 19-21	
		Port of Sabine Pass, TX	>5			
		Cameron, LA	12-15			
		Creole, LA	>10			
		Lake Charles, LA		6-10		

New Orleans Flooding

- Major levee breaches in 3 canals
- 80 sq mi, 250,000 acre-feet of water
- 100,000 homes, much of downtown flooded
- Geotechnical movement implicated
- Peak flood depth ~2 ft higher than shown on 2 Sep map
- Many major buildings have basements w/critical equipment, etc.
- Humidity, standing water, and no air conditioning aggravated mold damage



Flooding from Hurricane Rita



Landfall:

September 24

~15 ft storm surge

Storm Surge Damage to Buildings



Damaged school recreational facility, Cameron, LA



Hibernia Bank building, Cameron, LA



Damaged strip mall, Creole, LA

Photo credits: Christopher Letchford, Texas Tech University

Storm Surge Damage to Buildings

- Bay St. Louis, MS



Photo credit: NIST

Storm Surge Damage to Buildings

- Bay St. Louis, MS
- Surge reached second floor of building.



Photo Credits: NIST

Storm Surge Damage to Buildings

Lakefront Airport, New Orleans, LA



- Grouted, reinforced masonry wall 20 ft from seawall.
- Short lap splice observed at fracture, consequent frame collapse

Photo credit: Ed Huston, Smith and Huston, Inc.

Storm Surge Damage to Buildings

Venetian Isles fire station



Photo credit: Keith Porter, Scawthorn Porter Associates

Principal Findings: New Orleans Flood Protection System

- Storm surge and associated wave action led to breaches in the flood protection in New Orleans. This resulted in:
 - Significant damage to and destruction of adjacent residential structures due to high velocity water flow
 - Flooding in approximately 75 percent of the city
- The NIST-led team observed failures of the levees and floodwalls due to four different mechanisms:
 - Rotational failure of the floodwall-sheetpile system triggered by soil erosion (due to overtopping)
 - Massive erosion and scour of the earthen levee at the levee/floodwall junction (with overtopping)
 - Sliding instability of the floodwall-levee system due to foundation failure (without overtopping)

Rotational Failure of Floodwall-Sheetpile due to Scour (Overtopping)

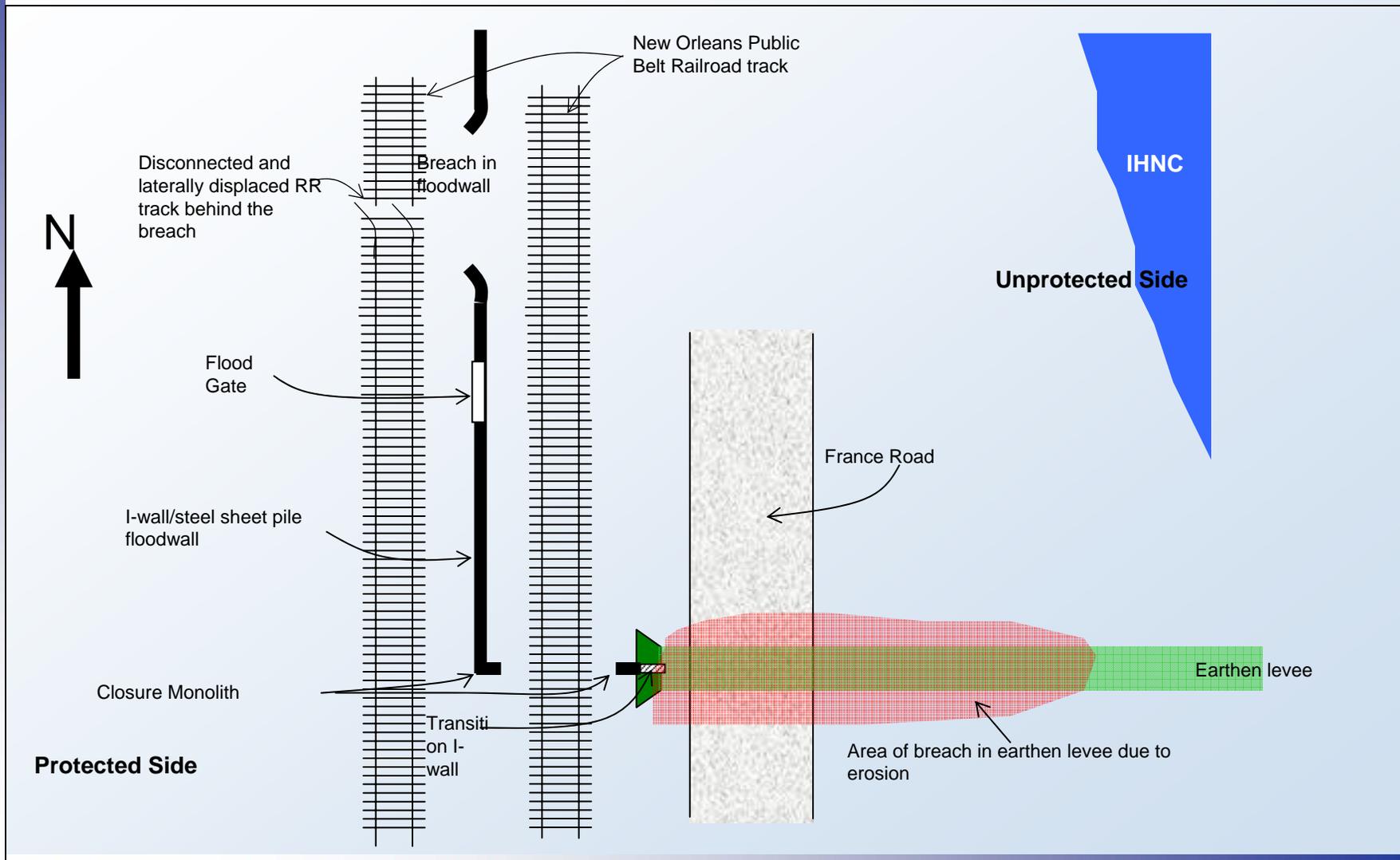
Inner Harbor Navigation Canal (Lower Ninth Ward)



- Rotational failure of floodwall-sheetpile due to overtopping and scour on protected side of levee.

Photo credits: NIST

Massive Erosion and Scour of Earthen Levee (Overtopping)



Massive Erosion and Scour of Earthen Levee (Overtopping)



- Failure of pavement and subsoil due to scour



- Levee breach due to erosion on water side

Photo credit: NIST

Sliding Instability of Floodwall-Levee System Due to Foundation Failure (No Overtopping)

17th St Canal Outfall Canal



Credit: Keith Porter, Scawthorn Porter Associates

- Foundation failure likely caused by shear failure within the clay in the foundation beneath the levee and floodwall, according to IPET Study.

Sliding Instability of Floodwall-Levee System Due to Foundation Failure (No Overtopping)

London Avenue Outfall Canal



Photo credits: NIST



- Failure was likely triggered by erosion and piping of soil due to underseepage according to IPET study.

Overtopping and Scour Without Failure



- Evidence of overtopping at this location.
- Scour on protected side of levee due to overtopping.
- Floodwall remained in place.



Photo credits: NIST

Principal Findings: Flooding of Residential Structures

- Many houses in the immediate vicinity of levee breaches were severely damaged or destroyed as a result of high velocity water flow and flooding.
- 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.
- 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.

Damage and Destruction of Residential Structures



Photo credit: Keith Porter Scawthorn Porter Associates

- **Damage to residential structures adjacent to levee breaches**



Photo credit: Edwin T. Huston, Smith and Huston, Inc.



Principal Findings: Bridges and Parking Structures

- Many bridges in coastal areas were damaged due to 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 surges were in many cases rendered inoperable due to inundation of mechanical and electrical equipment.
- Failures of precast concrete 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.

Damage to Bridges Due to Storm Surge

- Deck sections lifted and displaced by storm surge and wave action.
- Decks were simply connected to bridge piers (no shear key present).



Photo credit: J. O'Connor, MCEER

Damage to Bridges Due to Storm Surge

- Failure due to uplift and lateral displacement from storm surge and wave action.



Photo credit: NIST

Damage to Bridges Due to Storm Surge

- Bridge deck sections lifted and displaced by storm surge.
- Displaced deck sections lifted above the height of concrete shear keys.

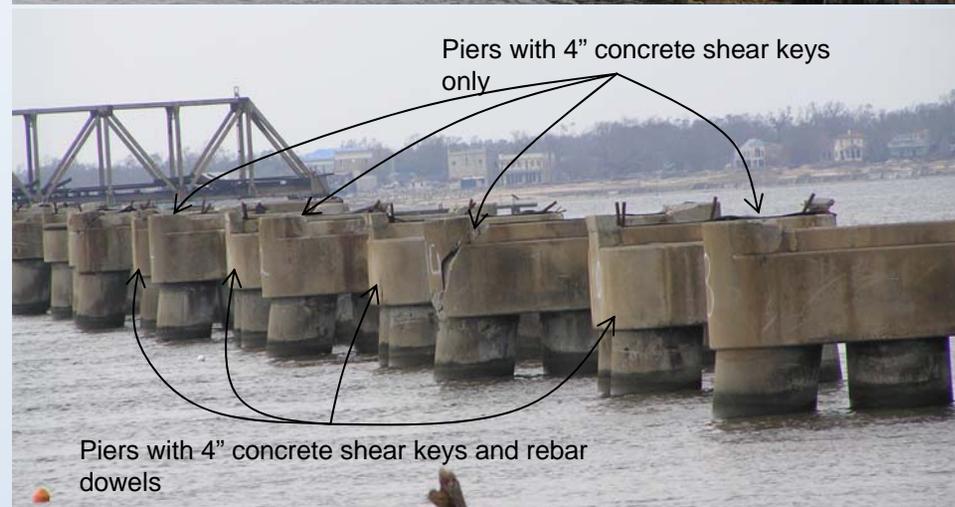


Photo credits: NIST

Example of Good Performance of a Bridge Exposed to Storm Surge

- Bridge subjected to storm surge.
- Deck sections were not lifted above the height of shear key and remained in place.

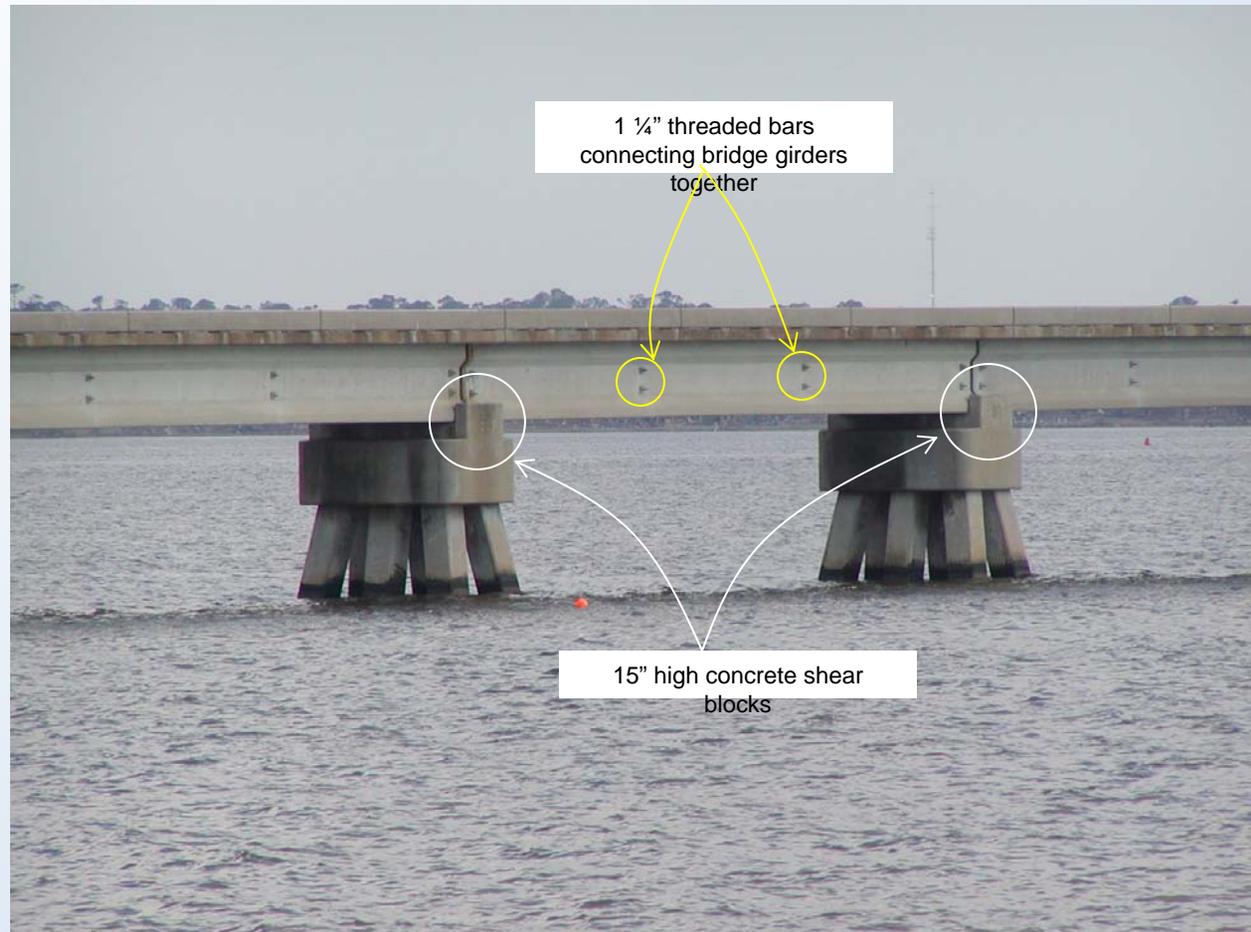


Photo credit: LA DOTD

Damage to Swing Span Bridges

- Swing span bridge in open position.
- Electrical and mechanical equipment damaged due to inundation.
- Debris accumulation due in bridge mechanism due to inundation.



Photo credit: LA DOTD, provided by J. O'Connor, MCEER



Photo credit: NIST

Damage to Parking Garages due to Storm Surge

- Failure of first level deck of pre-cast concrete parking garage due to storm surge.
- Storm surge lifted and displaced simply supported deck.



Photo credit: NIST

Principal Findings: Moored Casino Barges

- 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 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.

Failure of Casino Barge Moorings Due to Storm Surge



- Casino barge that broke free of moorings and floated inland.



- Casino barge impacted parking garage causing partial collapse of parking structure.
- Casino barge sank in place.

Photo credits: NIST

Principal Findings: Damage to Industrial Facilities Due to Storm Surge

- 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.

Damage to Seaports Due to Storm Surge



- Failure of concrete wharf at Port of Gulfport due to uplift from storm surge.

- Collapse of wharf at Port of Gulfport due to pile failure.



Photo credits: Thomas B. Rodino, Shiner Moseley and Associates, Inc.

Principal Findings: Operation of Critical Equipment

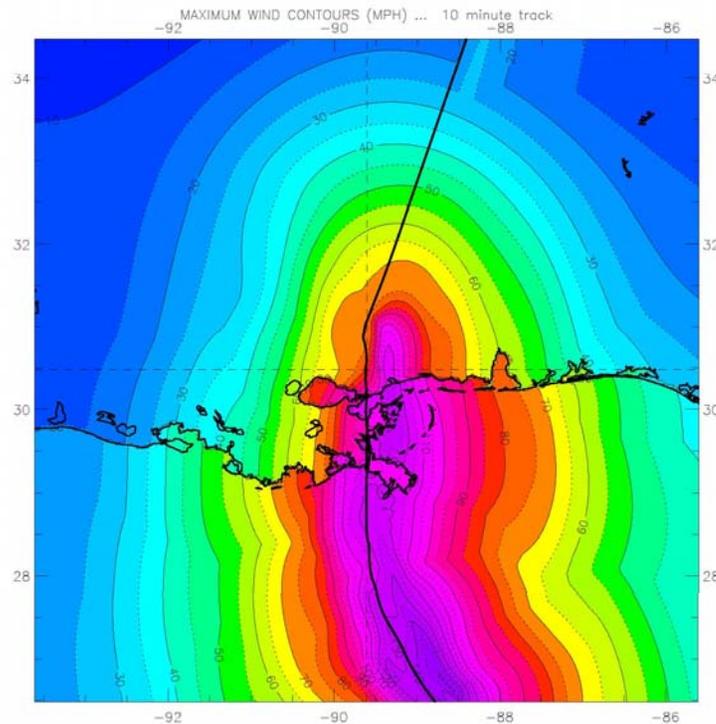
- Several buildings were rendered inoperable because critical equipment, such as backup generators, electrical equipment, and chiller plants, were located at or below grade and damaged due to inundation by floodwaters.
- Current model codes and standards contain provisions for the design of structures and location of equipment to account for flooding and storm surge.

Principal Findings: Wind and Wind-Induced Damage to Structures

- 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 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.

Environmental Conditions – Wind Speed Data

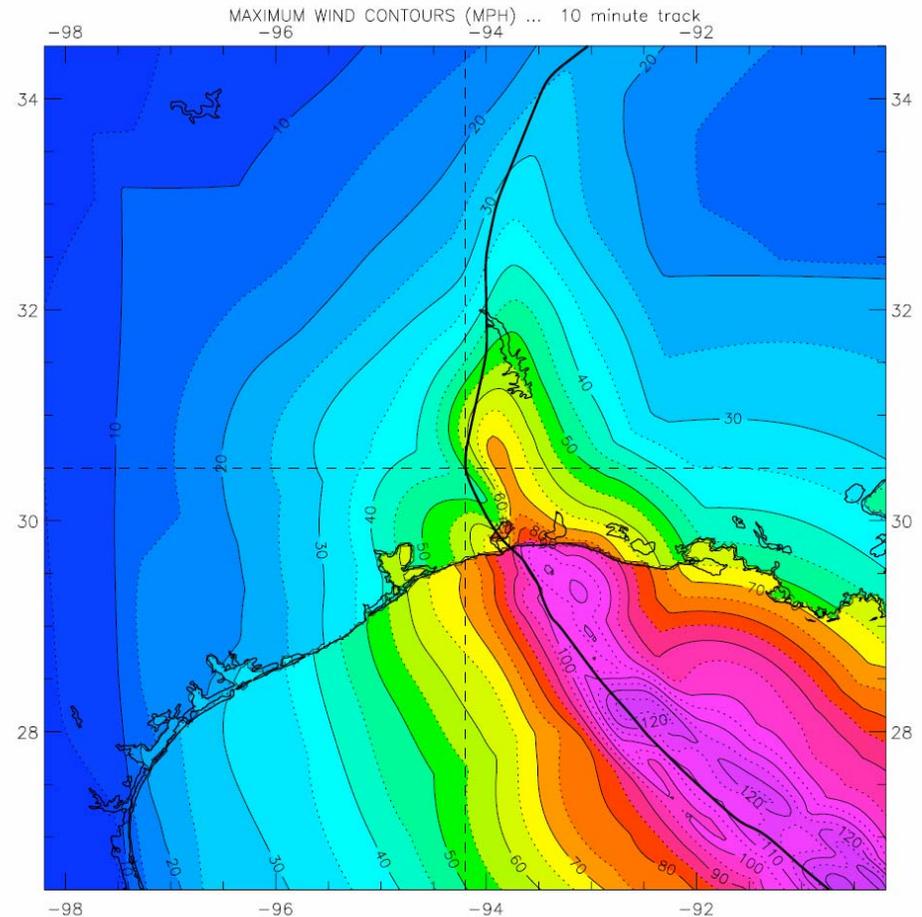
Katrina



- Wind speeds in affected areas were at or below design wind speeds.

- Wind speeds diminish rapidly as hurricane passes over land.

Rita



3-s gust speeds are 20 to 25 percent greater than the 1 min averages shown

Hurricane Wind

Saffir-Simpson Hurricane Scale			Location	Observed 3-sec Gust Wind Speed (mph)	Modeled 3-sec Gust Wind Speed (mph) NOAA/ARA	
Category	Sustained Wind Speed (mph)	Equivalent 3-sec Gust Wind Speed (mph)				
1	74-95	82-108	Mobile, AL	91	70	90
			Pascagoula, MS	93	117	100
2	96-110	109-130	Nederland, TX	93	71	110
			Orange, TX	98	88	120
3	111-130	131-156	Dauphin Island, AL	101	92	91
			Stennis Airport, MS	105	116	133
4	131-155	157-191	Bay St. Louis, MS		116	120
			Belle Chasse, MS		91	109
5	Over 155	Over 191	Port Arthur, TX	116	91	120

Blue = Hurricane Katrina

Red = Hurricane Rita

Wind-Induced Roofing Failure



- Failure of roofing membrane on Superdome



Wind-Induced Roofing Failure

- Failure of bituminous roofing membrane.
- Roof failure precipitated by failure of metal edge flashing allowing wind under roof membrane.



Photo credit: NIST

Wind-Damage to Rooftop Equipment



Photo credit: Keith Porter, Scawthorn Porter Associates

- Wind-induced damage to rooftop equipment.
- Missing vent covers provide path for water ingress.



Photo credits: NIST

Principal Findings: Wind and Wind-Borne Debris Damage to Major Buildings

- Major buildings suffered wind-induced damage to glazing (windows) as a result of debris from:
 - Aggregate surface roofs on adjacent buildings
 - Damaged equipment screens on top of buildings
 - Damaged façade or structure of adjacent buildings
- In many cases, buildings that suffered structural damage 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.

Wind-Borne Debris Damage to Windows



Photo credit: Keith Porter, Scawthorn Porter Associates

Wind-Borne Debris Damage to Windows

- Wind damage to low-rise unreinforced masonry building in foreground.
- Hancock Bank building in background damaged by wind-borne debris.
- Low-rise building likely source of wind-borne debris.



Photo credit: NIST

Structural Failure Due to Wind

- **Gulfport, MS**
- **Collapse of community center building due to wind.**
- **Engineered metal building with masonry in-fill walls.**



Photo credit: NIST

Building Envelope Failure Due to Wind

- Wind damage to aircraft hangar at Stennis Airport, MS.



Photo credit: NIST

Building Envelope Failures Due to Wind

- Metal roof and wall cladding
- Brick veneer
- Membrane roofing



Photo Credits: NIST



Principal Findings: Roofing Systems

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

Wind-Induced Failure of Roofing

- Loss of metal roof panels and supporting structure due to wind
- Joists supporting roof have been replaced with larger members.

Photo credit: NIST

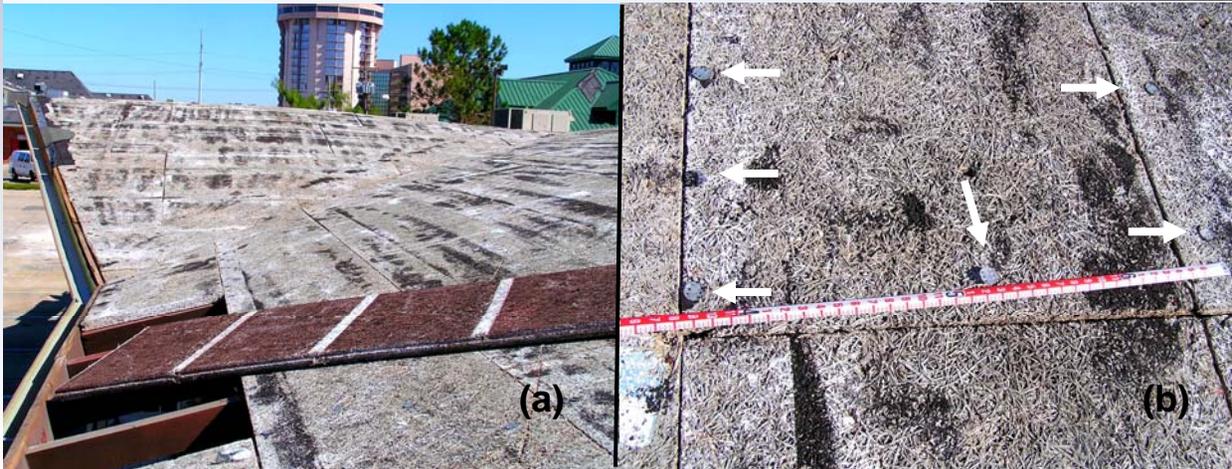


Photo credit: Robb Smith, Amtech Roofing Consultants

- Failure of bituminous membrane from wood fiber cementitious panel.
- An insufficient number of fasteners had been installed.

Examples of Good Performance of Metal Roofing



- Undamaged metal roof on school building in Pass Christian, Mississippi.

Photo credit: NIST

- Limited damage to metal roof on a house.



Photo credit: Dominic Sims, International Code Council

Wind-Induced Damage to Shingle Roofs



Photo credit: NIST

- Wind-induced failure of three-tab shingles on residential roof.

- Wind damage to roof of an apartment building.
- Plywood sheathing lost and roof trusses damaged.



Photo credit: NIST

- Typical example of improper installation of three-tab shingle.
- Number of fasteners is insufficient.
- Fasteners not properly located.

Photo credit: Robb Smith, Amtech Roofing Consultants



Principal Findings: Wind Damage to Industrial Facilities

- Industrial facilities outside the surge and flood zones 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.

Damage to Cargo Handling Cranes



- Wind-induced failure of restraint.
- Carriage damage visible in background.



- Storm surge-induced failure of restraint.
- Three of four restraints failed.
- Crane remained in-place on rails.

Photo Credits: NIST

Damage to Utilities due to Flooding and Wind



Photo Credit: Ron T. Eguchi, ImageCat

- **Water inundation damage to equipment at wastewater treatment facility.**
- **Facility was underwater for three weeks.**



Photo Credit: Christopher Letchford, Texas Tech University

- **Wind-induced failure of roller door led to damage of transformer shutdown of backup generator at wastewater treatment plant.**

Failure of Transmission Towers Due to Wind

- ~300 towers, steel poles lost
- Many cascade failures
- Failures caused by wind



Photo Credits: NIST



Damage to Electric Power Lines

~1,000,000 poles lost as a result of both hurricanes



Photo credits: NIST



Communication Towers/Failures Due to Wind



Photo credit: Christopher Letchford,
Texas Tech University

Cell tower failure, Route 82, coastal
LA



Photo credit: Christopher Letchford, Texas Tech University
Sabine Pass tower failure



Photo credit: NIST Orange cell tower failure

Damage to Petrochemical Plants

- Oil storage tanks shifted due to flooding.



Photo Credit: D. Fratta, U. of Milwaukee

- Buckled oil storage tank. Failure due to wind loads.



Photo Credit: Keith Porter, Scawthorn Porter Associates

- Damaged cooling tower shroud



Photo credit: Christopher Letchford, Texas Tech University

- Insulation damage due to wind



Photo Credit: NIST

Recommendations

- As a part of its reconnaissance, NIST is making 23 recommendations for specific improvements in the way buildings, physical infrastructure, and residential structures are designed, constructed, maintained, and operated in hurricane-prone regions.
- These recommendations are grouped as follows:
 - Immediate impact on practice for rebuilding (5)
 - Standards, codes, and practices (9)
 - Further study and research and development (9)
- 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.

Recommendations (2)

- ***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 does not prescribe specific systems, materials, or technologies.** Instead, NIST encourages competition among alternatives that meet performance requirements.
- **The recommendations 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.

Adoption and Enforcement of Codes and Standards

- ***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 is critical to better performance of structures during extreme events such as hurricanes.*** Relatively straightforward changes to practice could have reduced the damaged that occurred.
- The best codes and standards cannot protect occupants 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 model codes.
 - Many roofing shingle failures resulted from installers using an inadequate number of fasteners or installing fasteners in the wrong locations.
 - Wind-borne gravel from building rooftops caused a great deal of damage to windows on nearby structures.
 - In many instances, backup electrical generators, electrical equipment, chillers and other equipment were not placed above the expected flood levels.

Actions Already Underway

- Federal agencies, state and local governments, and the private sector have already taken actions that are consistent with NIST's recommendations. NIST encourages other organizations with responsibility for implementation to take similar actions.
- 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 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.

Actions Already Underway (2)

- 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 Office of the Federal Coordinator for Gulf Coast Rebuilding, FEMA and USACE have issued guidelines for rebuilding in New Orleans and the surrounding areas.
 - The USGS have 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.

Actions Already Underway (3)

- 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 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 quickly implemented by states and bridge owners and adopted into AASHTO standards as appropriate.

Recommendations

Group 1: Immediate Impact on Practice for Rebuilding

These recommendations (1-5) have immediate implications for the repair and reconstruction of buildings, physical structures, and associated equipment, damaged or destroyed by Hurricanes Katrina and Rita.

Immediate Impact on Practice for Rebuilding

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 for storm surge that is similar to risk-based 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. #1

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 above the design flood elevation by a specified minimum threshold. #2

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. #3

Immediate Impact on Practice for Rebuilding (2)

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).” #4

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. #5

Group 2: Standards, Codes, and Practices

These recommendations (6-14) 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.

Standards, Codes, and Practices

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. #6

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. #7

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. #8

Develop design requirements for improved structural integrity of **precast reinforced concrete structures** subject to storm surge loadings. #9

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. #10

Standards, Codes, and Practices (2)

Evaluate the adequacy of restraining systems for **large cargo cranes** in port facilities. #11

Adopt and implement existing model code provisions for providing **alternative/backup electric power supplies** for all critical facilities and equipment. #12

Install isolation valves in **water and gas distribution systems** in areas susceptible to damage. #13

Develop and implement special inspection requirements for connection and cladding attachments in **pre-engineered metal buildings** within model codes for hurricane prone regions. #14

Group 3: Further Study of Specific Structures or Research and Development

These recommendations (15-23) 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.

Further Study or Research and Development

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. #15

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. #16

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. #17

Conduct detailed performance assessments of the **wharves** 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. #18

Further Study or Research and Development (2)

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. #19

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. #20

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. #21

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**. # 22

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. #23

NIST's Next Steps

- Briefings for state and local entities
 - Joint briefings with FEMA in each state for building officials (June 19-21, 2006)
 - Coordinating briefings with national and state associations of building officials
- Briefings for the Office of the Federal Coordinator for Gulf Coast Rebuilding
- Broad dissemination of report and outreach to:
 - Standards and codes organizations
 - Other federal agencies
 - State and local entities
 - Practicing professionals
 - Industry associations
- Collaborative R&D with other agencies (e.g., FEMA, NOAA, USACE, FHWA, USGS) and the private sector on risk-based storm surge maps and evaluation of Saffir-Simpson Scale

Thank you

<http://www.bfrl.nist.gov/investigations/investigations.htm>