Bridge Damage and Repair Costs from Hurricane Katrina

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Abstract: Hurricane Katrina caused significant damage to the transportation system in the Gulf Coast region. The overall cost to repair or replace the bridges damaged during the hurricane is estimated at over $1 billion. This paper describes the observed damage patterns to bridges, including damage attributed to storm surge, wind, impact from debris, scour, and water inundation, as well as examples of repair measures used to quickly restore functionality to the bridges and transportation system. Using the data from the 44 bridges that were damaged, relationships between storm surge elevation, damage level, and repair costs are developed. The analysis reveals that, in general, regions with higher storm surge had more damage, although there were several instances where this was not the case, primarily due to damage resulting from debris impact. It is also shown that a highly nonlinear relationship exists between the normalized repair cost and the damage state. The paper concludes with a brief discussion on the efficacy of using typical seismic design details for mitigating the effects of hurricane loads, and potential design considerations for bridge structures in vulnerable coastal regions.

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Introduction

Hurricane Katrina made landfall on August 29, 2005 providing some of the most plentiful and illustrative empirical evidence of the impact of hurricanes and storm surge on the performance of bridges and the transportation network. Highway bridges are vital components of the transportation system, and their damage can pose a threat to emergency response and recovery efforts and result in severe economic losses for a region. While there have been a number of studies performed to assess the response and performance of bridges subjected to other hazards, such as earthquakes (Basoz et al. 1999), blast (Winget et al. 2005), or impact (Consolazio and Cowan 2005), there has been little work evaluating the potential damage to bridges in hurricane events caused by storm surge. An examination of the highway bridge damage along the Gulf Coast inflicted by Hurricane Katrina is performed in order to better understand the vulnerability of bridges subjected to storm surge and hurricane loading, and ways of protecting these essential lifelines in future hurricane or flood events.

The period following Hurricane Katrina further illustrated the potential economic impacts of a catastrophic event on the transportation system and region. While the regional direct and indirect economic losses are to date unknown (and indeed difficult to quantify), the recovery efforts in terms of repair and restoration of the transportation network have been substantial. The overall cost to repair or replace the bridges damaged during Hurricane Katrina, including emergency repairs, is estimated at over $1 billion based on damage inspection reports and bid estimates (TCLEE 2006). Along the coastal area where storm surge was severe, many roads were heavily damaged and/or had significant deposits of debris, further hindering traffic and recovery efforts for several weeks. The cost for debris removal in the tri-state area is estimated at $200 million. Repair costs and estimated replacement costs for the various types and levels of damage sustained by bridges in the Gulf Coast region are presented to evaluate the direct economic losses resulting from bridge damage.

The assessment of bridge damage and repair costs in the Gulf Coast region as a result of Hurricane Katrina provides empirical evidence that enhances our understanding of the interaction between natural hazards and the built infrastructure. The lessons learned from this event can serve as the foundation for risk assessment and efforts to mitigate the impacts of future events. The following sections describe the damage to highway bridges from Hurricane Katrina, including patterns of damage relative to storm surge, wind loads, and debris impact. Examples of repair and restoration of bridges along with analysis of the cost of repair discriminated by bridge damage state are also presented.

Highway Bridge Damage

Nearly 45 bridges sustained damage in Alabama, Louisiana, and Mississippi during Hurricane Katrina. Most of the damaged

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Fig. 1. US-90 Biloxi-Ocean Springs Bridge showing the primary mode of failure in severely damaged bridges: span unseating due to storm surge-induced loading

(a)

(b)

Fig. 2. Bearing damage that accompanied span shifting or unseating (a); loss of fixed connection (b) in two different bridges

bridges were adjacent to water with damage resulting from storm surge-induced loading. Much of the damage was to the superstructures, where typical damage included unseating or drifting of decks and failure of bridge parapets due to storm surge. Bridge inspections showed that the superstructure damage largely depended upon the connection type between decks and bents. Additionally, several bridges suffered damage due to debris impact in the form of barges, oil rigs, and boats. Other less severe forms of damage were a result of scour, inundation of electrical and/or mechanical equipment, or wind damage. The following sections detail each typical mode of failure, including the nature of the bridge damage as well as a specific example from the Gulf Coast region.

Damage due to Surge-Induced Loading

The most common severe failure mode for bridges was the unseating of individual spans, as seen in Fig. 1. This failure often occurred in low elevation spans as a result of excessive longitudinal or transverse motion of the bridge deck. The deck displacement is attributed primarily to the severe storm surge, which led to a combination of buoyant forces and pounding by waves. Similarly, many bridge spans were shifted but did not experience a complete loss of support at the bents or abutments. Bearing damage typically accompanied span unseating or deck displacement, as shown in Fig. 2. The bearings often provided no apparent positive connection between the superstructure and substructure. Some bridge spans, however, which were intended to have a fixed connection through doweling, still experienced complete loss of connectivity. Once the connectivity was lost, lateral wave and wind forces led to displacement of the bridge decks. The shifting of spans sometimes resulted in pounding and excessive transfer of forces to other members in the bridge, which then sustained damage, including the abutments, bent caps, or girders, as illustrated in Fig. 3(a). The loss of, or damage to, parapets on the bridge decks was also a consequence of the storm surge coupled with wave and wind loading [Fig. 3(b)].

Failure modes associated with surge-induced damage occurred in both traditional fixed-type bridges having continuous or simply supported spans, as well as in movable bridges having a swing, lift, or bascule. The traditional nonmovable spans in movable bridges experienced the typical modes of failure presented above that are associated with storm surge-induced loads. In either bridge type, the damaged spans tended to be the low-lying spans of the bridge or approach spans with elevations at or below the estimated peak storm surge level.

The US-90 Bay St. Louis Bridge suffered severe damage due to a combination of surge and wind/wave-induced loading, which led to strong transverse forces, sufficient to unseat a majority of the spans. This bridge is a four-lane, 3.06 km (1.9 mile) long, concrete girder bridge with parallel decks simply supported by high-type steel bearings. The spans are low lying with water navigation permitted through the use of a movable bascule. The bearings were severely damaged due to the surge-induced loading and nearly all connections between the deck and bent caps were lost, resulting in free movement of the decks, as seen in Fig. 4. All of the spans on the western half of the bridge completely unseated and were submerged in the Bay. On the eastern half, the north decks (westbound) were submerged and the south decks (eastbound) had drifted north and were partially submerged.

The damage to the Bay St. Louis Bridge will require complete replacement, which is estimated to cost $267 million. The high-rise replacement bridge will have peak vertical clearances of 25.9 m (85 ft) with approach spans having clearances in excess of 10.7 m (35 ft) to try to avoid future storm-surge issues. The estimated completion date for this project is June 30, 2007—nearly two years after Hurricane Katrina.

Impact Damage

Impact damage also occurred to bridges during Hurricane Katrina. Barges, which are common along the waterways in the Gulf Coast, often impacted bridges, along with oil drilling platforms, tug boats, and other types of debris. The impact damage manifested itself in the form of span misalignment and fascia girder, fender, and pile damage (Fig. 5).

The eastbound I-10 Pascagoula River Bridge was impacted by several objects including a barge and tug boat, which led to ex-

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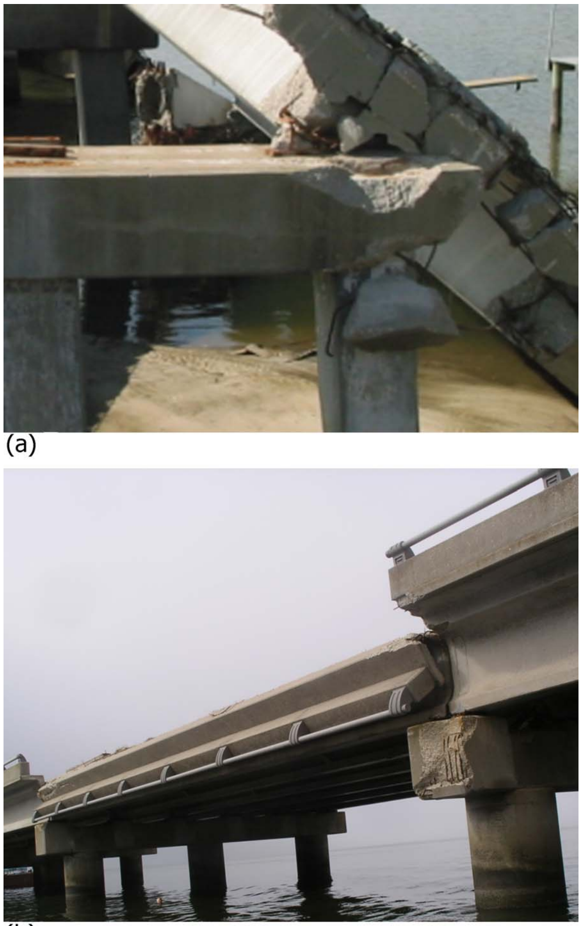

(a)

(b)

Fig. 3. Damage to bent caps (a); bridge parapet (b) due to storm surge

tensive damage to the bridge. This bridge is one of a set of twin-span prestressed concrete girder bridges with over 300 spans that carries I-10 over the Pascagoula River at Moss Point, Miss. The barge impact resulted in over 1.14 m (45 in.) of transverse displacement of a 95.1 m (312 ft) six-span unit, as seen in Fig. 6, and shearing of piles in the bents supporting these spans. Damage to fascia girders including spalling of concrete or exposure and breaking of prestressing strands occurred in other spans due to the tugboat collision.

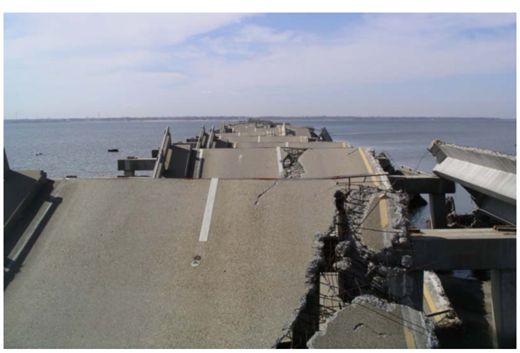

Fig. 4. Loss of bearing connectivity and span unseating on the US-90 Bay St. Louis Bridge. Estimated cost for replacement of this bridge is $267 million.

(a)

(b)

Fig. 5. Damage to girders (a); piers (b) due to impact from tugboat and barge (courtesy of MDOT)

The impact damage required repair or replacement of some girders, replacement of the six-span unit, bent cap repair or replacement, and installation of new precast piling. Extensive work was also performed to excavate, pump, and remove the barge. Because a crossover was built 8 days after bridge closure, traffic was maintained in both directions using the westbound bridge during the repair of the eastbound structure. The subsequent repairs were performed in 20 days at a total cost of $5.8 million.

Damage Resulting from Scour

Another failure mode was due primarily to scour. Observations revealed that this damage type may or may not accompany the other damage modes inherent to storm-surge loads. The scour damage that was readily visible to inspectors included scour and erosion of the abutment, slope failure, and undermining of the approach (Fig. 7).

The Chef Menteur Bridge, which carries US-90 over Chef Menteur Pass in Orleans Parish, is one of the bridges that suffered severe damage from scour (Fig. 8). Although this bridge is a movable bridge and suffered damage to the electrical and mechanical systems in the movable span, the most significant damage to the bridge structure was in the simply-supported concrete approach spans. The estimated total cost of repairs is $3.6 million. A large portion of the emergency repair budget for the Chef Menteur Bridge was devoted to removal of five north approach spans, which were affected by slope failure attributed to scour. This repair includes removal of the supporting bents whose foundation has been compromised, replacement of the bents with piles driven to a depth 12.2 m (40 ft) below the original piles, and

(a)

(b)

Fig. 6. Misaligned span due to barge impact on the I-10 Bridge at Pascagoula, Miss. (a); resulting pier damage (b) (courtesy of MDOT)

replacement of the five 6 m (20 ft) spans with a single, 61 m (200 ft) girder-supported span to place the bent beyond the projected failure plane (Gautreau 2006).

Damage due to Water Inundation

Movable bridges suffered damage to submerged electrical and mechanical equipment. Debris accumulation also affected the functioning of the mechanical gears along with some cases of bent pivots, fractured mechanical parts, or damaged traffic control gates. Although most systems are designed for temporary wetting or submersion, extended submersion and rushing flood waters often destroyed bridge electronics. In many cases, water inundation destroyed lift motors and electrical systems, rendering otherwise structurally sound bridges immovable. Damage to these electrical and mechanically-dependent systems hindered marine and highway traffic, and several of the damaged movable spans were forced open to allow marine traffic to pass in support of the regional shipping industry and transport of goods for disaster relief and recovery.

The Yscloskey Bridge on Route LA 46 in St. Bernard Parish, Louisiana is a lift bridge that sustained damage due to water inundation (Fig. 9). Lift bridges are one of three typical movable bridges found in the Gulf Coast region that permit channel navigation by vertically lifting a central deck by mechanical systems on two supporting towers. The high waters at the location of the bridge submerged the electrical and control systems in the operator house and completely damaged the system. In addition, the surge itself elevated the movable deck approximately 2.4 m (8 ft) and caused it to be skewed and stuck in the lifted position. Emergency repairs of the Yscloskey Bridge cost $900,000—80% of which was for the replacement of electronics damaged by water inundation. Other repairs included resurfacing the road, replacing electronic traffic control gates, and repairing barriers and the operator house.

(a)

(b)

Fig. 7. Abutment and approach damage from scour and erosion [(a) courtesy of MDOT; (b) courtesy of LADOT]

Wind Damage

The high winds from the Hurricane may contribute to the other modes of failure described in past sections by increasing the potential for impact and debris, and facilitating large surges, waves, and horizontal pounding. Additionally, there were several ex-

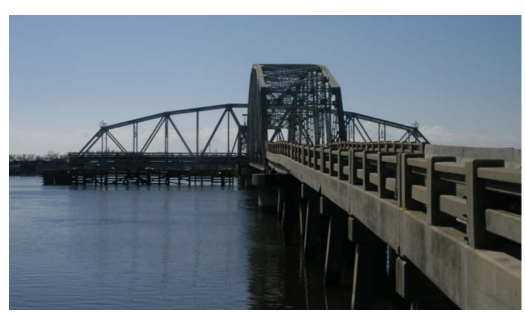

Fig. 8. Chef Menteur Bridge with fixed spans compromised by scour and slope failure at the foundations

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(a)

(b)

Fig. 9. Yscloskey Bridge damaged by water inundation: movable span immobile (a) due to elevation from surge and submersion of mechanical system; damaged operator house (b)

Table 1. Qualitative Damage State Descriptions Defined by Amending HAZUS for Typical Hurricane-Induced Bridge Damage (FEMA 2003)

Damage state	Description
Slight	Minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column (damage requires no more than cosmetic repair), minor cracking to the deck, or slight damage to operator house.
Moderate	Any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment (<2 in.), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, moderate settlement of the approach, moderate scour of the abutment or approach, damage to guardrails, wind and/or water damage to operator house resulting in switchboard or content damage.
Extensive	Any column degrading without collapse—shear failure (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, shear key failure at abutments, extensive scour of abutments, or submerged electrical or mechanical equipment.
Complete	Any column collapsing or connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure.

amples of structural damage to operator houses or machinery housing on movable bridges, and damage to electrical cables on some towers, which have been attributed to wind damage. The houses and control rooms, however, often suffered a combination of damage resulting from water inundation, impact, or debris. The operator house on the West Pearl River Bridge in St. Tammany Parish, La. suffered wind damage where the roof was blown off. This subsequently led to destruction of the contents, including the electrical/mechanical systems, resulting in repair costs of nearly $350,000.

Summary of Bridge Damage and Storm Surge Elevations

Damage States and Bridge Damage Summary

As a result of the ASCE TCLEE (Technical Council on Lifeline Earthquake Engineering) reconnaissance and communication with state DOTs, it is determined that 44 highway bridges were damaged along the Gulf Coast region during Hurricane Katrina (TCLEE 2006). Seven bridges were damaged in Mississippi, including two major water crossings of US-90, which require complete replacement. In Louisiana, 33 bridges were damaged—most of which are movable bridges that sustained damage to submerged mechanical and electric systems. Four bridges suffered damage in Alabama; however, none of them had complete span unseating as was the case with several bridges in the other two states.

The 44 highway bridges were classified according to the observed state of damage. Because little past work has investigated the damage to bridges from hurricanes or flood events, damage state definitions traditionally developed for earthquake damage are used as a baseline for this categorization. The qualitative descriptions used for discriminating slight, moderate, extensive, and complete damage for bridges presented in HAZUS from seismic events are used in this study with additional descriptions included for more hurricane-specific damage (FEMA 2003). These additional types and levels of bridge damage are assigned to one of the four traditional damage-state definitions based on the judgment of the writers, with the aim that the damage similarly impacts the functionality of the bridge and necessary repair efforts. Table 1 presents the qualitative damage state descriptions for classifying the level of bridge damage sustained in Hurricane Katrina.

Table 2 lists the 44 highway bridges damaged in Alabama, Louisiana, and Mississippi during Katrina, including the type of bridge, damage state, and estimated repair or replacement cost. Fig. 10 tabulates the total number of bridges in each damage state, and breaks down the contribution of fixed and movable bridges to the number of bridges suffering each level of damage. In total there were 9, 10, 20, and 5 bridges in the slight, moderate, extensive, and complete damage states, respectively. As indicated in Fig. 10, there is a predominance of damaged movable bridges in the Gulf Coast. However, one should note that movable bridges may have suffered damage to either the movable or fixed spans (recall the example of the Bay St. Louis Bridge which has a movable span, but suffered complete damage due to unseating of the fixed spans). It is estimated that over one-third of the damaged

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Table 2. Bridges Damaged in Hurricane Katrina

Bridge name	Carried	Bridge type	Damage state	Damage source	Cost estimate	Surge elevation (m)
Alabama						
Bayou La Batre	Hwy. 188	Fix.	Moderate	SC	$10,000	—
Dauphin Island Parkway	193	Fix.	Moderate	I,SC	$6 million	—
Cochrane Africatown USA	US-90	Fix.	Extensive	I	$1 million	—
Mobile Delta Causeway	I-10	Fix.	Extensive	D	$1.14 million	—
Louisiana						
Bayou Des Allemands	LA-631	Mov.	Slight	W	$3,000	0.98
Bayou Dulac	LA-57	Mov.	Slight	W	$1,000	1.16
Country Club	LA-3127	Mov.	Slight	W	$1,000	0.91
Galliano	LA-308	Mov.	Slight	W	$5,000	1.95
Golden Meadow	LA-308	Mov.	Slight	W	$9,000	1.95
Harvey Canal	LA-18	Mov.	Slight	W	$2,000	3.54
Houma Navigation Canal	LA-661	Mov.	Slight	W	$1,000	0.91
Lockport Company Canal	LA-1	Mov.	Slight	W	$2,000	0.91
Presque Isle @ Bayou Petite Caillou	LA-24	Mov.	Slight	W	$1,000	—
Belle Chase	LA-23	Mov.	Moderate	W	$200,000	4.08
Claiborne	LA-39	Mov.	Moderate	W	$40,000	—
Intracoastal Waterway @ Larose	LA-1	Mov.	Moderate	W	$170,000	1.34
Perez	LA-23	Mov.	Moderate	W	$200,000	—
Seabrook	Local Road	Mov.	Moderate	W	$25,000	3.11
St. Bernard Canal	LA-46	Mov.	Moderate	W	$40,000	—
West Pearl River	US-90	Mov.	Moderate	EM,SC,W	$350,000	4.60
Bayou Barataria	LA-302	Mov.	Extensive	EM	$50,000	1.16
Bayou Lafourche @ Leeville	LA-1	Mov.	Extensive	SC, W	$1.6 million	2.13
Bayou Liberty	LA-433	Mov.	Extensive	EM,W	$1.5 million	3.47
Bonfouca	LA-433	Mov.	Extensive	EM,W	$200,000	3.57
Caminada Bay	LA-1	Fix.	Extensive	D, SC	$500,000	2.44
Chef Menteur	US-90	Mov.	Extensive	EM, SC	$3.6 million	3.96
Doullut Canal	LA-11	Mov.	Extensive	EM, W	$700,000	3.44
East Pearl River	US-90	Mov.	Extensive	EM,SC,W	$400,000	4.60
Inner Harbor Navigation Canal	Florida Ave.	Mov.	Extensive	EM,I,W	$500,000	1.01
North Draw—Lake Pontchartrain	US-11	Mov.	Extensive	EM	$50,000	4.02
Rigolets Pass	US-90	Mov.	Extensive	EM,SC,W	$2 million	4.60
Rigolets Pass–Under Construction	US-90	Mov.	Extensive	I,W	$1.7 million	4.60
Tchefuncte River Madisonville	LA-22	Mov.	Extensive	EM,SC,W	$25,000	2.32
US 11 @ Lake Pontchartrain	US-11	Mov.	Extensive	EM,SC,W	$6 million	4.02
Yscloskey	LA-46	Mov.	Extensive	EM,SC,W	$900,000	5.12
Lake Pontchartrain	I-10	Fix.	Complete	D, SC	$30 million	4.02
Pontchartrain Causeway	LA-Causeway	Fix.	Complete	D, SC	$1.5 million	2.77
Mississippi						
David V. LaRosa	W. Wittman Rd.	Fix.	Moderate	D	$60,000	7.50
Biloxi Back Bay	I-110	Mov.	Extensive	I	$2.5 million	6.22
I-10 Pascagoula River	I-10	Fix.	Extensive	D,I	$5.8 million	4.57
Popps Ferry	Popps Ferry Rd.	Mov.	Extensive	D,EM	$7.7 million	5.82
Biloxi-Ocean Springs	US-90	Mov.	Complete	D,EM	$275 million	6.58
US-90 Bay St. Louis	US-90	Mov.	Complete	D,EM	$276 million	5.58
US-90 Henderson Point	US-90	Fix.	Complete	D	$1.9 million	7.01

Note: — indicates no available surge estimate. Bridge type key: Mov.=movable, Fix.=fixed. Damage key: D=deck movement, EM=electrical/mechanical, I=impact, SC=scour, W=wind.

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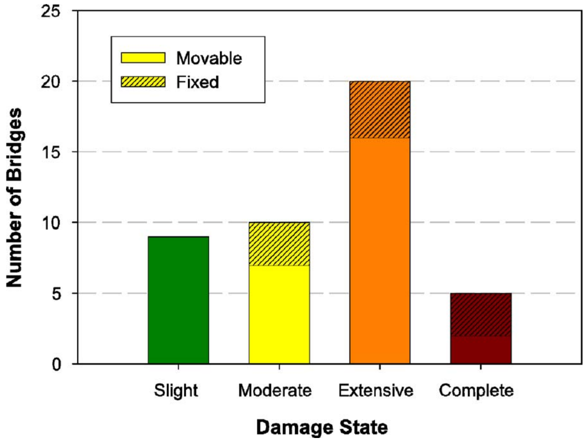


Fig. 10. Distribution of damaged bridges by bridge type and damage state

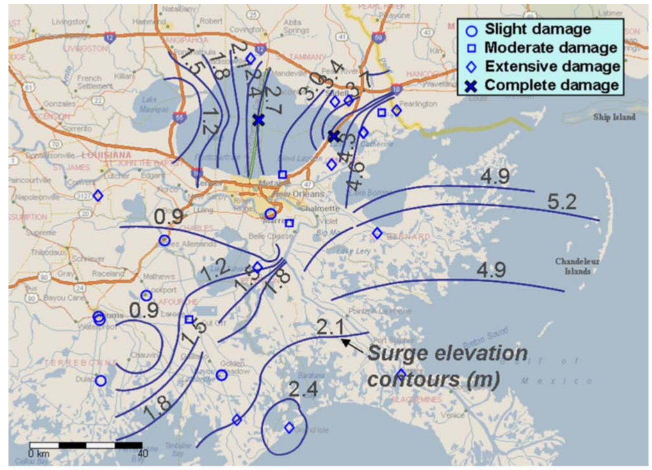
movable bridges experienced a significant amount of damage to bridge components not associated with the movable spans.

Storm Surge

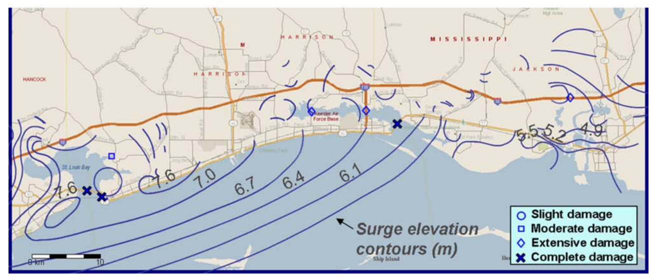
The estimated storm surge is evaluated at the location of each damaged bridge in order to assess the relationship between the state of damage to bridges and level of storm surge produced during the hurricane event. At its peak intensity, Hurricane Katrina was a Category 5 storm, and upon landfall was a Category 3, with winds in excess of 201 km/hr (125 mph) (NOAA 2005). Surges exceeding 7.6 m (25 ft) were induced by the storm in some areas. FEMA has developed maps of the hurricane surge elevation contours based on engineering judgment and empirical data from the event using coastal high water marks (FEMA 2006). Data describing the geographic variation in surge elevation were used to estimate the surge heights at the locations of the damaged bridges along the Gulf Coast, as shown in Figs. 11(a and b) for Louisiana and Mississippi, respectively. In general, this figure indicates that most of the slightly damaged bridges were in regions of relatively low storm surge. The completely damaged bridges tended to have surges on the order of 6.1 m (20 ft). However, there is a significant amount of variation in the surge elevation at the locations of the moderate and extensively-damaged bridges. It is noted that the relative elevation of the bridge decks or electrical/mechanical equipment to the storm surge also could have an impact on the realized relationship between the damage and surge. The estimated storm surge elevations are also presented in Table 2 alongside the level of damage and repair cost.

Repair and Replacement Cost Estimates

Estimates of downtime and repair cost are important factors for loss modeling of natural hazard events. As indicated by Comario (2006), documentation of empirical data regarding repair and recovery along with associated costs is essential to refine loss models to assess the consequences and impacts of natural hazard events to communities and regions. The data provided in Hurricane Katrina further support such efforts. In the case of Katrina, inspection teams were often able to mobilize within a couple of days following the storm to perform evaluation of the bridge damage and provide initial recommendations on closure, repair, and restoration. In many cases, emergency repairs were performed in order to provide quick restoration of functionality, and typically resulted in higher costs or bonus incentives. Most states' immediate efforts were to restore interstates such as I-10, which are a part of the national defense network, followed by addressing local traffic issues. Minor damage was often repaired in house, while major damage and replacement contracts were let outside of the state DOTs.



(a)



(b)

Fig. 11. Damaged bridges relative to storm surge contours in (a) Louisiana; (b) Mississippi (adapted from FEMA 2006)

Repair costs ranged from an estimated $275 million for replacement of the Biloxi-Ocean Springs Bridge carrying US-90 in Mississippi, to less than $1,000 for minor repairs of damaged operator houses on movable bridges in Louisiana, as listed in Table 2. The cost estimates are assumed based on the findings of the TCLEE (2006) reconnaissance using preliminary DOT inspection reports and estimates, costs of work completed to date, and bid estimates. Fig. 12 shows a plot of the number of bridges in each damage state that fell into a given range of estimated repair or replacement cost. This plot indicates that all of the slightly damaged bridges had repair costs of less than $10,000. These bridges were all movable bridges found in Louisiana that typically suffered slight damage to the operator house and to gates and signals, often as a result of wind and rain. However, there is significant variation in the repair cost for bridges that were in the extensive damage state, ranging from $25,000 to nearly $7.7 million. Many of these bridges had repair costs between $1 million and $5 million and were typically movable bridges. The repair costs, therefore, were highly dependent upon the level of damage to and cost for repair of the submerged electrical and mechanical systems in these movable bridges. The completely damaged bridge repair or replacement costs ranged from $1.9–275 million, depending upon the size of the bridge, how many of the spans

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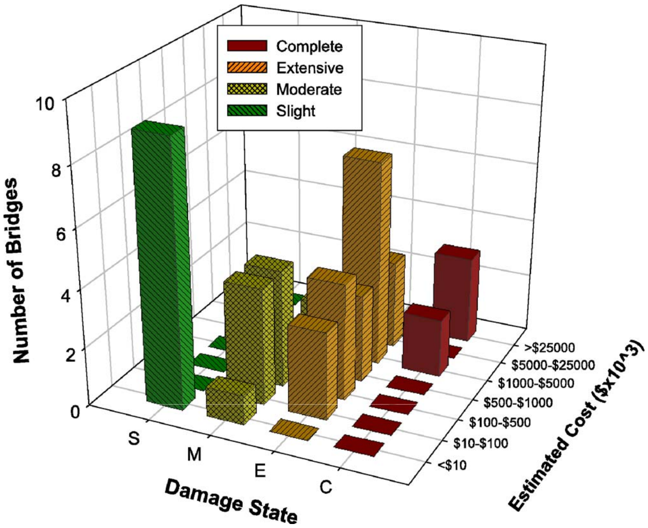

Fig. 12. Distribution of damaged bridges by damage state and estimated repair or replacement cost

were completely collapsed, and whether or not the bridge was salvageable or required replacement. All of the completely damaged bridges suffered span unseating to the fixed spans, regardless of whether or not they are classified as a movable bridge.

In an effort to reduce the apparent variability in costs that may be dependent upon the size of the bridge, the repair costs are normalized by the deck area to assess potential trends in the average repair cost per ft^2. Fig. 13 presents a bar chart of cost per ft^2 of repair to bridges in each damage state, where the mean and mean plus 1 standard deviation are plotted. In general, this chart allows for a comparison of the increasing trend of repair cost per ft^2 with increasing damage state, where the estimated means are $\$0.25/ft^2$, $\$6.28/ft^2$, $\$53.05/ft^2$, and $\$189.43/ft^2$ for slight, moderate, extensive, and complete damage, respectively. It is interesting to note that the estimates above, when normalized by the typical replacement costs, show similar trends to the damage ratio values used for earthquake damage in HAZUS (FEMA 2003). Also, Fig. 13 reiterates that there is more variability in the estimated repair cost per ft^2 for the higher damage states. Relative to the other completely damaged bridges, the estimate in cost per ft^2 is considerably higher for the bridges that require total replacement (often replaced with newly designed high-rise bridges). One should note, however, that the slightly and extensively damaged movable bridges that experienced damage to the operator houses and/or electrical/mechanical systems, may have repair costs that have little dependence on the total deck area.

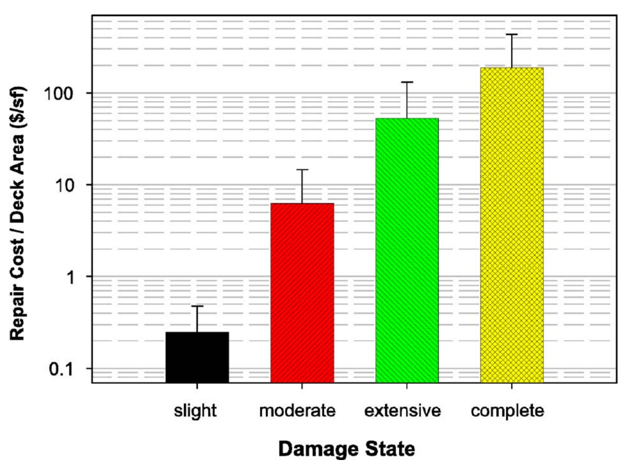

Fig. 13. Mean and mean+σ repair cost normalized by deck area for each damage state

(a)

(b)

Fig. 14. (a) Unseating of spans from an earthquake (a) (NISEE 2006); (b) damage during hurricane Katrina (b). Note distant railroad bridge with shear keys is still intact.

Comparison of Hurricane and Earthquake Damage

While the nature of the loading and load transfer mechanisms in hurricanes and earthquakes are considerably different, the observations from Hurricane Katrina indicate that there are similarities in the types and patterns of bridge damage resulting from the two hazards. The unseating of bridge spans during Katrina, which resulted in a considerable amount of damage, disruption, and losses, has been a common problem in earthquake events (Jennings 1971; Moehle 1995; Comartin et al. 1995). During a seismic event, superstructure displacements are induced by inertial loads from the earthquake. Collapse of the deck spans occurs if the seat width is not adequate to accommodate the excessive displacements, as shown in Fig. 14(a). During a hurricane, the loads from storm surge and/or wind results in forces that could displace the bridge deck, both longitudinal and transverse to the bridge centerline [Fig. 14(b)].

In the seismic design or retrofit of bridges, shear keys are often used to limit the transverse displacement of the decks. As evidenced in Hurricane Katrina, bridges with adequate shear keys were often spared the level of damage suffered by neighboring bridges without such details. For example, the CSXT Biloxi Bay railroad bridge having 38.1 cm (15 in.) high shear keys had no unseated spans, while the adjacent Biloxi-Ocean Springs Bridge carrying US-90 had little transverse restraint and suffered complete damage [Fig. 14(b)]. Other superstructure retrofits, which are common in seismic zones, include the use of vertical tie downs or longitudinal restrainers (Saiidi et al. 1996; DesRoches and Fenves 2000) to limit deck movement. The use of such design or retrofit techniques, which have traditionally been used for earthquake design, may be potentially viable to improve the performance of bridges in hurricane or storm-surge events, and are being considered by transportation officials in these regions.

Conclusions and Recommendations

The combination of high winds, rain, and storm surge in Hurricane Katrina led to significant damage to highway bridges along the coastal region. Examples of five different typical modes of failure are presented. A considerable amount of bridge damage is attributed to storm surge resulting in submersion of mechanical and electrical equipment on movable bridges, as well as displacement of bridge decks in traditional fixed spans, from a combination of buoyant forces and horizontal pounding by waves. Analysis of the data shows there is some correlation between damage state and storm-surge elevation. However, some bridges located a considerable distance from the coast were still severely damaged due to impact with loose barges or other debris. The data presented summarize the state of damage, repair cost, and estimated storm-surge elevation at the location of the 44 bridges damaged in the Gulf Coast region. In general, analysis of the data indicates a relationship between the surge elevation, damage state, and resulting repair costs. Bridges that were located in areas of higher storm surge typically had more damage, and subsequently had higher repair costs. It was also shown that the normalized repair cost (repair cost/deck area) was typically highly nonlinear, as a function of damage state. For example, the normalized repair cost increased by a factor of 25 when going from slight to moderate, and a factor of 8.5 when going from moderate to extensive. As experienced in other natural hazards, the consequences associated with such damage and loss of functionality indeed extend beyond these direct losses and are difficult to quantify. However, having a better understanding of the modes of failure and empirical evidence of the repair costs will serve to support future loss assessments and risk mitigation efforts.

The nature of the damage reveals some of the potential vulnerabilities of bridges subjected to hurricane or storm surge. It also indicates that designing to higher elevations or using simple details, such as transverse shear keys, could help to mitigate damage and costs. To this end, the reconstructed bridges are being designed as high-rise structures, and states are considering implementing new design details and retrofit measures. These include methods for anchoring the superstructure of bridges in coastal regions (such as those traditionally used in seismic zones), and approaches to reduce the uplift forces placed on bridge decks including providing air vents or elevating the bridges. Further investigation on potential design and retrofit details is needed and would help support the protection of highway bridges and transportation networks in such natural hazard events.

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