Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

IMPACT OF 2008 HURRICANE IKE ON BRIDGE INFRASTRUCTURE IN THE HOUSTON/GALVESTON REGION

Matthew Stearns[1], Jamie E. Padgett[2]*

ABSTRACT

The storm surge, wind and waves produced by Hurricane Ike in 2008 caused notable damage to the transportation infrastructure in the Houston/Galveston region of Texas. This paper presents the lessons learned from damage to bridge infrastructure in the Houston/Galveston region observed after Hurricane Ike, with comparisons to empirical evidence from past hurricane events on common failure modes and design details affecting bridge performance under hurricane induced loads. A rich set of damage data is developed drawing upon post event inspections and reconnaissance data to present details such as bridge type, failure mode, and surge elevation for the 53 damaged bridges. Many of the damaged structures in the region were either constructed of timber or were low-clearance water-crossing bridges, and these bridges were often completely destroyed by the storm surge and wave loading. Scour and debris also hampered the performance of both major structures and rural bridges. The evidence from the performance of these structures highlights the need for new design alternatives or retrofits such as the use of shear keys and restrainer cables, grated decks, or replacement of timber bridges with box-culvert structures, among other solutions.

[1] Undergraduate Research Assistant, Department of Civil and Environmental Engineering, Rice University, 6100 Main St., Houston, TX 77005, USA.
[2] Assistant Professor, Department of Civil and Environmental Engineering, Rice University, 6100 Main St., MS-318, Houston, TX 77005, USA.
* Corresponding author: email: jamie.padgett@rice.edu; phone: 713-348-2325

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

INTRODUCTION

The transportation system relies heavily on the performance of regional bridge infrastructure following hurricane events, and is crucial to facilitate post-event response and recovery. When Hurricane Ike made landfall on September 13, 2008, it caused severe damage to the infrastructure of the Houston/Galveston region of Texas. A large number of bridge structures were completely destroyed by the storm surge and wave forces that accompanied the hurricane, though most of these bridges were timber structures in rural areas. Several major bridges were also damaged by debris impact that accompanied the storm surge and wave loading. The damage was largely attributed to inundation of the decks, or superstructures, of the bridges, impact from debris, and erosion of abutment supports and approaches. By compiling and assessing the empirical data from such natural hazard events, lessons are learned that can lead to improved performance of such infrastructure in future events of potentially greater magnitude.

This paper presents a holistic overview of the damage to bridge infrastructure in the Houston and Galveston area caused by the 2008 Hurricane Ike. Using an extensive set of data from post-assessment surveys and reconnaissance reports, failure modes of the structures are evaluated. Included in the assembled data sources are field reconnaissance conducted by the authors, HNTB through the Texas Department of Rural Affairs (TDRA), the Texas Department of Transportation (TXDOT), and interviews with local municipalities or other bridge owners. The performance of rural timber bridges in addition to major highway bridges is assessed, including a discussion of the factors contributing to the damage, the site hazard estimates, repair procedures, and capacity and demand estimates for select water crossing bridges. In addition, the damage witnessed during Hurricane Ike is compared to that observed during past severe hurricane events, including Hurricanes Katrina, Ivan, and Frederick. This paper concludes with a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

summary of lessons learned, recommendations for mitigating future damage, and needed future studies that can benefit from the reconnaissance summarized herein.

OVERVIEW OF HURRICANE IKE AND DAMAGE TO BRIDGE INFRASTRUCTURE

Hurricane Ike originated off the coast of Africa, moving toward the Gulf of Mexico, affecting islands in the Bahamas and Cuba before making landfall in the upper Texas coast on September 13, 2008 as a category 2 hurricane (Berg, 2009). Hurricane Ike reached maximum intensity as a category 4 hurricane while over the open Atlantic Ocean (Berg, 2009). When Ike made landfall in Texas, it had wind speeds of 95 knots, and a peak 1-minute sustained wind speed of 83 knots (Berg, 2009). The pressure at the center of the hurricane upon landfall was 950 mb (Berg, 2009).

Primary hazard parameters of interest when assessing bridge damage under hurricane loads include the generated storm surge and wind waves. Hurricane Ike hindcast data developed by Dawson and Proft (2010) is assessed to identify the surge and wave height at damaged bridge locations. The referenced hindcast data includes SWAN and ADCIRC modeling conducted at the University of Texas at Austin (Dawson and Proft, 2010) in order to evaluate the levels of storm surge and wave heights experienced along the Gulf of Mexico in the Houston/Galveston region. These models revealed that the peak storm surge level was in excess of 14 feet in some locations, while wave heights reached values of over 5 feet near the Rollover Pass coastal region, where some of the most significant bridge damage occurred. Subsequently the bridge damage identified from the post-Ike reconnaissance is evaluated and compared relative to the surge and wave hazard estimates.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Both timber structures as well as major highway bridges are considered in the reconnaissance study herein. A rich dataset regarding damages to bridge infrastructure in the region has been compiled from a number of sources. These sources include inspection reports by the Texas Department of Rural Affairs with HNTB and the Texas Department of Transportation. Additionally, data was obtained through post-event field assessment conducted by the authors and interviews conducted with the infrastructure owners and repair contractors. Much of the damage experienced can be attributed to the storm surge and wave loading on the bridge superstructures, and the damage or destruction of 26 structures were ascribed to these loads. Scour around the abutments and wing walls of the bridges was also common, as 25 structures experienced damage of this type. Impact damage from debris also affected 4 local bridges. The impact damage caused spalling, or the chipping off of portions of concrete, in some of the structures. The damage to bridges surveyed is summarized in Table 1, which includes the type of structure, number of spans, damage state, and cause of damage. The damage states refer to a characterization of the level of damage incurred and are assigned based on the definitions in Table 2. For example, visible repairable damage to the structure that does not affect the structural integrity is deemed *Light damage*. The bridge type noted in Table 1 refers to the substructure material of the bridge. Using data from the referenced Hurricane Ike SWAN and ADCIRC simulations, the maximum storm surges and wave heights were found along the coast and plotted in Figure 1 relative to the damaged bridge locations and their respective damage states. The figure excludes 17 rural bridges located further inland that also experienced damages from Hurricane Ike but were not located in the surge zone. These bridges all experienced a combination of scour or impact damage and all crossed inland waterways or drainage ditches.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

The structures likely experienced damage from the increased flow rate in those waterways as the storm moved inland and from the debris that was carried by the floodwaters.

The following sections provide a summary of the findings of the reconnaissance data assembled with detailed discussion of the failure modes for different bridge types. In order to define the terminology used herein, Figure 2 shows a general bridge layout with the key components and types of damage typical of the bridges studied. The figure illustrates the mean water level prior to the storm, the level of the storm surge, and the level of the accompanying waves in relation to the structure. The hurricane hazard parameters can cause deck uplift, scour, or impact damage, as illustrated in the figure. Further details are provided below to provide insight on mitigating such damage in future events.

DAMAGE TO TIMBER AND LOCAL BRIDGES

A large majority of the bridge structures damaged during Hurricane Ike were small local and timber bridges. These structures suffered from erosion around the substructure due to the storm surge and increased floodwaters at the bridge sites--most of which are water crossing structures. They also suffered impact damage from floating debris. Many post-event inspection reports for the rural structures also noted the deteriorated condition of the bridges. This deterioration cannot be precisely attributed to the storm event and was likely pre-existing and therefore is not included in the report herein. However, it is acknowledged that such pre-event deterioration could render structures more susceptible to damage in extreme events such as hurricanes. Local bridge structures suffered a wide range of damage during Hurricane Ike, and these damage states for the rural and timber bridges are summarized in Figure 3. The

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

subsections below describe the failure modes common to timber bridges and other small local bridge infrastructure, including examples of each type of damage.

Scour

One of the most common forms of damage to local bridges in the area was scour. The combined effect of the storm surge, flooding, increased water levels and flow often led to the deterioration of rip rap by the abutments, undermining of bridge approaches, and damage to the areas behind the wing walls of many structures.

A prime example of scour damage is the CR-3625 Ebenezer Church Road Bridge, which is a two span timber bridge that crosses the Wolf Creek Tributary (State of Texas, 2009). The bridge was classified as heavily damaged, mainly due to the scour of the soil behind one of the wing walls of the bridge. This damage is shown in Figure 4, where the majority of the material behind the wing wall was swept away. To repair this structure, local government officials filled in the void with rock to allow continued use of the structure (State of Texas, 2009). The CR-3400 Rocky Shore Bridge also suffered scour damage, though the damage to this structure was more serious. The bridge is a single-span bridge with steel superstructure and wood decking, and the soil behind the abutment wall eroded, exposing the back side of the wall (State of Texas, 2009).

The Frenchtown Road Bridge is located on the tip of the Bolivar Peninsula, bordering Port Bolivar. The structure is a single-span concrete bridge over steel culverts (State of Texas, 2009). According to the reports by TDRA (2009), the bridge was submerged for an extended period of time, which caused extensive damage to the substructure of the bridge. The bridge was deemed to have heavy damage and was nearly impassible. Both the bridge itself and the

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

approaches to the bridge were undermined by scour, causing the superstructure to displace multiple inches below its original height. Figure 5 shows the entire damaged bridge structure. The approaches to the bridge were severely eroded by the floodwaters, as shown also in Figure 5. The steel culverts were also damaged severely and deemed to need complete replacement by the TDRA (State of Texas, 2009).

Impact Damage

The storm surge and floodwaters from Hurricane Ike often collected large debris, causing a significant amount of damage to local bridges. Many bridges had debris resting against the superstructure which affected post-event functionality, while others suffered visible structural damage due to debris impacts.

The Rice Belt Road Bridge is an example of a bridge that suffered from impact damage. The structure is a double-span timber structure with an asphalt deck and metal guardrails (State of Texas, 2009). One of the guardrails suffered severe damage due to apparent impact of debris during Ike. This damage can be seen in Figure 6, illustrating that the impact bent the guardrail significantly. The Rice Belt Road Bridge was also found to have debris resting against the columns of the support bent, as shown in Figure 6.

The Union Springs Road Bridge, a double-span timber and steel bridge, also suffered impact damage (State of Texas, 2009). A tree trunk was found resting on the middle support bent, indicating that it fell onto the bridge during the storm. This was classified as light damage by TDRA.

Storm Surge Loading

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

When the combined storm surge and waves that accompany storm events such as Hurricane Ike rise to a level at or above the bottom of the bridge deck, the deck is subjected to uplift and transverse forces that can cause severe damage to the structure. The forces acting on the bridge are comprised of both a hydrodynamic and a hydrostatic component. The drag force, inertial force, and buoyancy force make up the hydrostatic component of the force, and the slamming force caused by trapped air effects makes up the hydrodynamic component (Marin and Sheppard, 2009). Given the limited connection capacity provided between many bridge superstructures and substructures, this loading can shift or even completely displace the deck of the bridge. Such damage was frequently observed in rural timber structures during Hurricane Ike.

In Galveston Bay near Port Bolivar, the 7th Street Bridge was completely washed away by the storm surge, which at this location was 12.9 feet with 3.1-foot waves based on hindcast storm data (Dawson and Proft, 2010). The timber-supported bridge deck was displaced completely off the timber support structure, as shown in Figure 7. The bridge deck and the support bent connections were inadequate to resist the uplift forces, and they were ripped from the support columns, detailed in Figure 7.

Multiple bridges on Cane Bayou in Chambers County were also completely displaced by the storm surge loading. The storm surge in this location was 14.2 feet with 5.5-foot waves. Figure 8 shows the remaining support piers from the structure, indicating that the connections between the support bents and the columns were not strong enough to resist the uplift forces from the surge and waves. Many of the bridges with decks that were displaced by the storm surge similarly failed at the connection between the support bents and the columns, indicating that this is the weakest joint of the timber structures.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

DAMAGE TO MAJOR BRIDGE STRUCTURES

Many of the failure modes suffered by the smaller local bridges were also exhibited by the major bridge structures and roadways. Bridges with more than five spans that were constructed of steel and concrete are considered here to be major bridge structures. Three major bridge structures will be used to demonstrate the damage to major structures in the Houston/Galveston region from Hurricane Ike. The Humble Camp Bridge at Hildebrandt Bayou and Rollover Pass Bridge both suffered damage from coupled storm surge and wave loading, along with potential impact contributing to the damage. The Pelican Island Bridge experienced scour on the approach to the bridge that made the roadway impassible and exposed the abutment of the bridge.

Rollover Pass Bridge

The bridge carrying State Highway 87 across Rollover Pass on Bolivar Peninsula was one of the most severely damaged bridge structures from Hurricane Ike. Rollover Pass Bridge is located in the thinnest portion of the Bolivar Peninsula, adjacent to Rollover Bay, and it crosses the man-made Rollover Pass channel. The structure, constructed in 1984, was a concrete box-girder bridge with five spans on concrete pile substructure. The bridge deck, 72.5 feet wide, consisted of 18 pre-stressed concrete box girders, each 1.67 feet thick with a 3-inch finish grade of asphalt on top. The end spans of the bridge were 45 feet long, and the middle three spans were 50 feet long. The support bents and abutments for the structure rested on 12 spiral-bound concrete piles. Prior to Hurricane Ike, the structure was given National Bridge Inventory

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

condition ratings of “good” for the superstructure and substructure, “very good” for the deck, and “satisfactory” for the channel in 2008 (FHWA). It had a deck clearance of approximately 5.3 feet over mean water elevation, and during Hurricane Ike the bridge was subjected to a 15-foot surge with 5-foot waves. The bridge suffered major shifting of many of the sections of the bridge and complete loss of some of the sections, yielding displacement in four of the five spans. Site visits indicated that minimal spalling occurred on the bent beams along with complete loss of most connections between superstructure and substructure. These visits also confirmed deterioration in the post-tensioning cables that were present in the bridge. Overall, the abutments and support bents of the bridge suffered little to no damage, according to TXDOT reports (Merrill, 2008), and were salvaged for the repair and restoration of the bridge.

Figure 9 summarizes the shifting and unseating of the spans and their box-girder subcomponents under the surge and wave loading, which can be attributed primarily to limited continuity and connectivity. Adjacent bridge spans responded in a non-continuous manner and box-girders of the same span were shifted independently. While in many cases, bridge spans shift as a single unit or resist surge wave loading, the post tensioning cables between adjacent girders failed under the hurricane loads permitting shifting of individual girders. It is worth noting that corrosion of these cables was visible from field assessment. Furthermore, only limited connectivity was provided between the superstructure and substructure by dowels that suffered pullout. These #9 size dowels were embedded approximately 18 inches into the bridge substructure and superstructure. Figure 10 shows the extent of the damage to the structure, including the missing and shifted spans, and failed connections. Initially, one lane was opened to restricted traffic and emergency repair were conducted using a combination of new and salvaged girders to restore functionality of the bridge.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Using the AASHTO *Guide Specifications for Bridges Vulnerable to Coastal Storms* (AASHTO, 2008), the uplift forces on Rollover Pass Bridge are estimated and compared to the resistance to uplift of the structure. Appendix A provides a summary of the equations used to estimate the uplift forces on the bridge deck. The surge and wave parameters from the SWAN and ADCIRC modeling (Dawson and Proft, 2010), summarized in Table 3, are used to estimate the uplift forces that acted on Rollover Pass Bridge. The uplift forces are approximated by treating the superstructure as a slab for the purposes of force estimation, to reflect the lack of girders that otherwise entrap air. The maximum total uplift force on each span of the bridge is estimated to be approximately 825 kips. The total resistance to uplift is estimated as the sum of the deck weight and connection resistance between the deck and support bents, approximated based on the as-built plans for the bridge. The connection resistance is estimated as the pullout strength of the concrete embedded dowels (ACI, 2008).

$$l_d = \frac{\varphi_s f_y}{20\sqrt{f_c'}} d_b \tag{1}$$

$$F_d = \frac{l_e}{l_d} f_y A \tag{2}$$

Where l_d is the development length, φ_s is the bar size factor, f_y is the yield strength of steel, d_b is the diameter of the rebar, f_c' is the strength of concrete, F_d is the pullout force, l_e is the embedment length, and A is the area of the rebar. Assuming a weight of reinforced concrete of 150 pcf (Wang and Salmon, 1992), the total uplift resistance of the structure is estimated as 560 kips per span for the Rollover Pass Bridge considering the deck weight and connection resistance. This indicates that the uplift forces experienced during hurricane Ike surpassed the resistance to uplift by approximately 265 kips per span--enough force to fail the connections and cause the displacement of the spans that occurred during Ike.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

The roadway adjacent to the Rollover Pass Bridge, State Highway 87, in Bolivar also suffered extensive damage from inundation and flooding due to the storm surge of Hurricane Ike. The Texas Department of Transportation reported that the road had many sections that were undermined by the water and completely swept away. TXDOT used local supplies of milled asphalt to fill in the damaged areas to allow transportation of goods over the roadway following the event. The highway also had extensive amounts of debris from the surge, including approximately 10,000 pounds of hazardous materials, 250 cars, boats and golf carts, and 40,000 cubic yards of sand that had to be removed to restore functionality (Kerry Kipp, personal communication, February 23, 2010).

Humble Camp Bridge at Hildebrandt Bayou

The Humble Camp Bridge is a concrete and timber bridge with twenty-four spans that cross Hildebrandt Bayou (State of Texas, 2008). Nine spans on the northwest end of the bridge are steel girders with a concrete slab, while the remaining 15 spans are timber girders with a concrete slab. The bridge, which had a deck elevation of approximately 4.5 feet over mean water elevation, was overtopped during the storm by a 13-foot surge coupled with 3.3-foot waves, and the timber-supported spans slightly shifted in the transverse direction as a result. The failure observed indicates potential damage to the vertical and transverse restraints in the bridge, without complete loss of the superstructure. This structure, however, included shear key, or shear links, in the form of steel plates bolted between the bridge deck and bent beam, as shown in Figure 11, where it is possible to see that multiple spans have shifted as a result of the storm surge wave loading. The shear keys of the bridge bent on some spans but did not fail completely,

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

and it is likely due to these shear key details that the bridge was able to remain intact without span unseating.

The approach previously detailed is applied to the Humble Camp Bridge to estimate the uplift forces due to surge and wave loading. The surge and wave parameters used for the demand estimates are listed in Table 3. Field investigations were conducted to find the dimensions of the bridge to estimate the resistance to uplift. The bridge consisted of 24 spans that were each 28 feet wide and 15 feet long. The slab of the bridge had a thickness of 0.9 feet, and it rested on concrete support bents, which rested on support piers. The support piers were steel for 9 spans of the bridge and timber for the remaining 15 spans. The uplift loads of 317 kips per span are estimated based on the AASHTO Specifications. The estimated resistance to uplift of Humble Camp Bridge is 87 kips per span, based on weight of superstructure alone. Therefore, the bridge was subjected to uplift forces that exceeded the resistance by 230 kips per span, resulting in the observed shifting of spans of the bridge. However, the supplemental shear links provided additional resistance, and full span unseating was not observed for Humble Camp as seen in other structures. Plans were not available for this "off system" bridge, so exact plate or bolt dimensions and embedment lengths were not known to determine the capacity of the links.

Pelican Island Bridge

The Pelican Island Bridge is a concrete slab bridge with a movable bascule section in the main span to allow for ship navigation between the Gulf of Mexico and Galveston Bay. The bridge was constructed in 1960, and prior to Hurricane Ike, the bridge was given NBI condition ratings of “satisfactory” for the deck, “fair” for the superstructure, and “poor” for the substructure and channel. The poor channel rating indicates that the banks have been severely

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

undermined, and large deposits of debris are in the river even prior to the storm. Despite the questionable condition of the bridge, limited structural damage occurred during Hurricane Ike and the majority of the damage to the bridge was to the approaches, according to reports by the Texas Department of Transportation. Site visits and reports from Sullivan Brothers Builders revealed that the Southwest approach of the bridge was undermined by erosion, as shown in Figure 12. Sections of the approaching roadway and the rip rap that was designed to protect the roadway were also eroded. This erosion completely exposed the tops of the abutment cap, as seen in Figure 12. The concrete slab portion of the bridge superstructure did not suffer any damage due to Hurricane Ike. The bascule section of the bridge had severe damage to the fender systems, which were in need of repair, as they offered minimal protection to either side of the bridge. Severe erosion occurred around the support columns of the concrete section of the bridge, amplifying the already-present erosion problem with the bridge (Les Jarosz, personal communication, February 16, 2010).

After the event, emergency repairs to the approach were conducted in six days by filling in the scoured areas to allow traffic to pass over the bridge (John Sullivan, personal communication, June 3, 2010). These initial repairs cost $400,000, and TXDOT bid out the final repairs to bring the approach back to its original condition. The final repair costs for the bridge were $6.5 million (Elder 2010).

COMPARISON TO PAST EVENTS

To provide context to the lessons learned or reinforced regarding bridge vulnerability and potential improved design details illuminated in Hurricane Ike, comparisons are made to bridge infrastructure performance in past hurricane events. Due to the fact that Hurricane Katrina

(2005) provided the most plentiful empirical evidence of bridge damage data of past events, a dedicated discussion is provided for that event, followed by several other cases. These comparisons coupled with the assessment of empirical evidence from Hurricane Ike will form the foundation for the concluding summary of damage mitigation strategies for new design or retrofit of existing structures, along with areas ripe for future investigation.

Hurricane Katrina

In 2005, Hurricane Katrina made landfall on the Gulf Coast as the sixth-strongest Atlantic hurricane on record to that date and affected bridge and roadway infrastructure along coastal Alabama, Mississippi, and Louisiana (DesRoches et al., 2006). The storm generated one-minute sustained wind speeds of 125 miles per hour at landfall, and was classified as a Category 3 hurricane. However, the high storm surge, in excess of 28 feet in some areas (Mosqueda et al., 2007)--significantly higher than that observed in Hurricane Ike--was the major contributing factor to severe bridge damage in the region. A total of 44 highway bridges sustained damage in Hurricane Katrina, in addition to a number of railway bridges (DesRoches, et al., 2006).

Typical modes of failure in the coastal bridges included damage attributed to storm surge; impact from debris, loose barges or oil rigs; and scour. The storm proved the significance of span elevation and resistance to uplift in structural response to storm surge and wave loading, which was also observed in Hurricane Ike. One of the most heavily-damaged bridges during the storm was the US-90 bridge across St. Louis Bay, where nearly all spans of the bridge were unseated, and many of the substructure support piers were compromised by scour (Okeil and Cai, 2008). In total, nearly 1000 bridge spans in the tri-state region either shifted off of their supports or unseated falling into the water below (Padgett et al., 2009). As a result of the Katrina

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

observations, recommendations for retrofits or improved design details included the use of air vents in bridge diaphragms, improved connectivity or vertical restraining elements, transverse shear keys to prevent lateral shifting, as well as increased span elevation (AASHTO, 2008; DesRoches, et al., 2006; Padgett et al., 2008; Sawyer, 2008).

There are several notable similarities and differences between the damage observed from Hurricane Katrina and those during Hurricane Ike. The reported bridge damage from Katrina was mainly to highway bridges, without investigation of damaged timber structures. Hurricane Ike resulted in only three severely-damaged major bridges, but extensive reports of timber bridge damage. Hence, a comparison of total number of bridges damaged is irrelevant, yet the failure modes are comparable for both the highway and rural timber structures. The most common type of damage from both storms was movement of bridge decks and the scour of abutments and approaches. The extent of the damage was very different, however, as many major water crossings needed complete replacement after Katrina, yet only a couple major bridge structures were impassable after Ike, with only one needing complete replacement. The difference in type, or route carried by, the damaged bridges also affected the down time of the major transportation networks after the events in dissimilar ways. After Hurricane Katrina, many major transportation arteries were completely inaccessible, but only a few county roads were deemed impassible after Hurricane Ike.

Other Events

Although Hurricane Katrina provided a wealth of damage data for comparison with Hurricane Ike, evidence of bridge infrastructure vulnerability has also been observed in many past hurricane or typhoon events worldwide. For example, Hurricane Ivan made landfall near

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Mobile, Alabama on September 16, 2004 as a Category 3 storm (State of Florida, 2004). The storm surge height with associated wave action reached levels of 15 to 20 feet in certain areas along the coast (State of Florida, 2004). This high storm surge, combined with the 130 mph wind speeds led to extensive erosion and debris damage of coastal bridge structures (State of Florida, 2004). On the Escambia Bay Bridge, 58 spans were completely unseated into the water, and 66 spans were displaced (Huang and Xiao, 2009). Many roadways and bridge approaches were covered in sand or eroded due to the wave run-up. Fishing piers, like the one at Pensacola Beach, were destroyed, and their decks were completely displaced off the supports (State of Florida, 2004). Many retaining walls were also destroyed. This event proved the dangerous potential for scour, erosion and debris damage associated with storm surges during hurricane events and the need for strong retaining walls, rip rap, or other counter measures to prevent such damage. It is possible that the use of one of these erosion protection measures may not be sufficient, as was observed at Pelican Island Bridge, in which case multiple erosion protection measures may be needed.

Coastal bridge infrastructure susceptibility to hurricanes was revealed decades ago, on September 12, 1979 when Hurricane Frederick made landfall at Dauphin Island, Alabama. It generated storm surges of 6 to 15 feet and peak gusts of over 145 mph (Sawyer, 2008). The hurricane severely damaged several bridge structures in Alabama, including the Dauphin Island Bridge, where 135 spans were completely unseated into the ocean and the remaining spans were damaged beyond repair (Sawyer, 2008). At the I-10 bridge over Mobile Bay, the storm surge reached a height of 11.7 feet, and this resulted in the displacement of multiple approach spans (Sawyer, 2008). Other examples of unseating of low elevation simply supported bridge spans can be found from Hurricane Camille (1969) (Douglass et al., 2004), and in Hokkaido, Japan during

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

the Songda Typhoon (2004) (Okada et al., 2006). These storms provide further evidence of the power of storm surge and wave forces and the need for positive reinforcement in the vertical direction to restrain bridge decks from displacement if immediate functionality is required following the event.

LESSONS LEARNED FROM IKE BRIDGE DAMAGE AND CONCLUSIONS

The assessment of the post event reconnaissance reveals that the combination of storm surge and wave loading caused severe damages to the bridge infrastructure in the Houston/Galveston region during Hurricane Ike. The rich data set assembled indicates that approximately 53 bridges in the area sustained damage, although many of these structures were rural timber bridges. The performance of timber structures under storm surge and wave loading has not historically been extensively available in the literature. However, the thorough reports of the extensive damage in Ike reveals that these timber structures are extremely vulnerable to extreme storm events. This demonstrates the need for retrofits or replacement of such structures to ensure the safety and longevity of the timber bridges in regions susceptible to extreme storm events. Additionally, the damage reconnaissance from Hurricane Ike also reveals lessons regarding major highway bridges with steel or concrete superstructures. Empirical evidence from past hurricane events confirms the findings in Hurricane Ike regarding bridge failure modes and potential retrofit options. These include damage attributed to storm surge and wave loading, impact from debris, and scour or erosion of abutments and foundations. These lessons could prove critical in the Houston and Galveston region of Texas, especially in the consideration of repair and retrofit options, given the potential for hurricanes with even higher storm surge across the area depending upon the strength of storm and angle of incidence along the coast.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Many of the reports issued by the Texas Department of Rural Affairs (TDRA) suggest that the existing timber structures be replaced with concrete structures with increased capacity and clearance. This might also be accomplished with grated replacement bridge decks with reduced surface area in addition to erosion mitigation at the bridge approaches and abutments. As was witnessed at Rollover Pass and at many rural timber structures, numerous water-crossing bridges were uplifted from their support and displaced due to low elevation, little or no continuity between adjacent spans, and limited connectivity to the substructure. Hence for new structures, continuous superstructures with increased clearance level over the water could further protect the structure from damage during extreme storm events. However, for retrofit of existing structures or design of approach spans that tie into the roadway, simple design details such as transverse shear keys or restrainer cables may be viable options. It is necessary to ensure that the forces transferred to the piers or foundations do not require additional upgrading of those components. Alternatively, a fuse in the strengthened connection between superstructure and substructure may be provided so that uplift of the deck is avoided in moderate events up until the force transferred to the substructure exceeds a fraction of the substructure capacity. At that point deck unseating may be deemed an acceptable alternative as long as the costly pier and foundation substructure may be salvaged. While this alternative is not ideal to promote immediate post-event functionality in extreme events, it may mitigate the cost of repair in severe cases.

The reconnaissance also revealed the vulnerability of the approaches, abutments, and foundations to erosion and scour caused by the flooding that accompanied Hurricane Ike. Many of the damaged bridges had timber or nonexistent wing walls, which highlighted the need for improved wing walls or rip rap at the pier foundations and abutments to protect them from scour

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

and erosion. Additionally, land barriers could also serve as protection to approach spans. For example, reports and site visits revealed that the one area of the Pelican Island Bridge approach that was not severely damaged in Hurricane Ike was protected by a thin plot of land that extends into the Galveston Bay. While the sections of the approach on either side of this land barrier were completely destroyed, the small strip of land was enough to protect that section of the approach from any damage.

Hurricane Ike devastated the Houston/Galveston region, and it revealed vulnerability of coastal bridge infrastructure and potential retrofits and design improvements for coastal bridges nationwide. Although similar failure modes have been observed in past storm events, the post-event reconnaissance data assembled from Hurricane Ike provides some of the richest empirical evidence of the performance of bridge infrastructure for major bridges as well as rural timber structures relative to hazard estimates at the sites. These factors contributing to the damage were indicated and can be used to screen existing bridges in vulnerable or high-priority regions. While a number of options for improved design details are highlighted and supported with empirical evidence, further research is required to analytically and experimentally assess the viability of many of these strategies. The continued development of such improved retrofit and design details, coupled with the ongoing development of reliability based vulnerability models (Padgett et al, 2009), will help to improve the safety of bridge infrastructure in hurricane exposed regions.

ACKNOWLEDGEMENTS

This study was supported by Houston Endowment under the SSPEED Grant entitled "Hurricane Ike: Lessons Learned and Steps for the Future." The authors would like to express their gratitude to the Texas Department of Transportation, HNTB and the Texas Department of Rural

Affairs for providing access to structures and inspection data. The authors would also like to thank Sullivan Brothers Builders and its owners William, Todd, and John Sullivan for their assistance in reconnaissance for the Pelican Island Bridge.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). *Guide Specifications for Bridges Vulnerable to Coastal Storms. Washington, D.C.: AASHTO, 2008.*

American Concrete Institute (ACI) Committee 318. *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary.* ACI, 2008.

Berg, R. "Tropical Cyclone Report: Hurricane Ike." National Hurricane Center, 23 January, 2009.

Dawson, C. and Proft, J.. *Hurricane Ike ADCIRC and SWAN Data.* University of Texas at Austin. Files sent to author. 23 June 2010.

DesRoches et al. H*urricane Katrina: Performance of Transportation Systems.* Technical Council on Lifeline Earthquake Engineering. ASCE, 2006.

Douglass, S., Hughes, S., Rogers, S., and Chen, Q., "The impact of Hurricane Ivan on the coastal roads of Florida and Alabama: A preliminary report," Coastal Transportation Engineering Research and Education Center 2004.

Elder, L. "Feds commit $6.5M to Pelican Island Bridge repairs." *The Galveston County Daily News.* 2 May 2010. Web.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Federal Highway Administration (FHWA) (2008). "2008 National Bridge Inventory ASCII Files: Texas." *NBI ASCII Files.* <http://www.fhwa.dot.gov/bridge/nbi/2008/TX08.txt> (Jan 13, 2011).

Huang, W. and Xiao, H.. "Numerical modeling of dynamic wave force acting on Escambia bay bridge deck during Hurricane Ivan," *Journal of Waterway, Port, Coastal and Ocean Engineering*, 2009. Vol. 135, No. 4, pp. 164-175.

Marin, J. and Sheppard, D. M.. *Storm Surge and Wave Loading on Bridge Superstructures.* University of Florida. Presentation. MS Powerpoint. 2009.

Merrill, B. D., P.E. "SH 87 at Rollover Pass – Bridge Inspection Summary." Report sent to author. MS Word document. 15 January 2010.

Moqueda et al. "Damage to Engineered Buildings and Bridges in the Wake of Hurricane Katrina." ASCE conference Proceedings 250.4 (2007).

NIST, "Performance of Physical Structures in Hurricane Katrina and Hurricane Rita: A Reconnaissance Report " National Institute of Standards and Technology, US Department of Commerce, Gaithersburg, MD 1476, 2006.

Okada, S., Mitamura, H., and Ishikawa, H., "The collapse mechanism and the temporary restoration of Omori Bridge damaged by the storm surge of Typhoon No. 18 in 2004," *Technical Memorandum of Public Works Research Institute,* vol. 40, pp. 185-192, 2006.

Okeil, A. M. and Cai, C. S. "Survey of Short- and Meduim-Span Bridge Damaged Induced by Hurricane Katrina," Journal of Bridge Engineering 13.4 (2008): 377- 387.

Padgett, J. E., DesRoches, R., Nielson, B. G., Yashinsky, M., Kwon, O.-S., Burdette, N., Tavera, E. (2008) "Bridge Damage and Repairs from Hurricane Katrina," *ASCE Journal of Bridge Engineering,* ***Vol. 13 No. 1, pp. 6-14***, January, 2008.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Padgett, J. E., Spiller, A. E., and Arnold, C., "Statistical analysis of coastal bridge vulnerability using empirical evidence from Hurricane Katrina," *Structure and Infrastructure Engineering,* **DOI:10.1080/15732470902855343**, April, 2009.

Sawyer, A. "Determination of Hurricane Surge Wave Forces on Bridge Superstructures and Design/Retrofit Options to Mitigate or Sustain These Forces." Diss. Auburn University, 2008. Print.

State of Florida. Department of Environmental Protection. Division of Water Resource Management. Bureau of Beaches and Coastal Systems. *Hurricane Ivan: Beach and Dune Erosion and Structural Damage Assessment and Post-storm Recovery Plan for the Panhandle Coast of Florida.* Florida: State of Florida, 2004. Web. 8 May 2010.

State of Texas. Texas Department of Rural Affairs. Office of Rural Community Affairs. *Hurricane Ike Recovery Program: Assessment Data Sheet.* Field Visits. January, 2009.

Wang, C. andSalmon, C. G. *Reinforced Concrete Design.* 5th Ed. New York; Harper Collins, 1992. Print.

LIST OF FIGURES

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

LIST OF TABLES

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Table 1. Summary of damaged bridges in Houston/Galveston region, organized by damage state.

Bridge Name	Damage State	Failure Mode	Spans	Substructure Material	Superstructure Material	County	Function
Wayne Morris #1	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road
Wayne Morris #2	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Wayne Morris #3	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Wayne Morris #4	Destroyed	deck unseated	4	Timber	Timber	Chambers	Service Road
Leyroy Easer #1	Destroyed	deck unseated	4	Timber	Timber	Chambers	Service Road
Leyroy Easer #2	Destroyed	deck unseated	8	Timber	Timber	Chambers	Service Road
Cane Bayou #4	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road
Cane Bayou #3	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Cane Bayou #2	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Cane Bayou #1	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Fitzgerald #1	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road
Fitzgerald #2	Destroyed	deck unseated	4	Timber	Timber	Chambers	Service Road
Wanda Lagow #1	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road
Lake Anahuac #1	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Fitzgerald #4	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Fitzgerald #3	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Lake Anahuac #2	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Edwards #1E	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road
Edwards #1W	Destroyed	deck unseated	4	Timber	Timber	Chambers	Service Road
Spencer #1	Destroyed	deck unseated	2	Timber	Timber	Chambers	Service Road
Edwards #2W	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road
Edwards #4W	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road
Edwards #2E	Destroyed	deck unseated	3	Timber	Timber	Chambers	Service Road

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

7th St. Bridge	Destroyed	deck unseated	4	Timber	Timber	Galveston	Local
Rollover Pass Bridge	Destroyed	deck unseated	5	Concrete	Concrete	Galveston	Major Arterial
Jay Matthews	Heavy Damage	scour damage	3	Timber	Timber	Chambers	Service Road
Rodeo Bend	Heavy Damage	scour damage	1	Concrete	Concrete	Galveston	Local
Frenchtown Rd.	Heavy Damage	scour damage	1	Concrete	Concrete	Galveston	Local
Boondocks Bridge	Heavy Damage	scour damage	6	Steel	Steel	Jefferson	County Road
Humble Camp Bridge at Hildebrandt Bayou	Heavy Damage	deck displaced	24	Concrete, Steel, Timber	Steel, Concrete	Jefferson	County Road
Craigen Bridge	Heavy Damage	scour damage	5	Steel	Steel	Jefferson	County Road
River Road	Heavy Damage	scour damage	1	Timber	Timber	Liberty	Local
Nueces Road	Heavy Damage	scour damage	2	Concrete	Concrete	Liberty	Local
CR-4600 Pump Station Rd.	Heavy Damage	scour damage	5	Timber	Timber	Tyler	Local
CR-2150 Big Cypress Creek Bridge	Heavy Damage	scour damage	2	Timber	Steel	Tyler	Local
CR-2670 #2	Heavy Damage	scour damage	1	Timber	Steel	Tyler	Local
CR-3400	Heavy Damage	scour damage, impact damage	1	Timber	Steel	Tyler	Local
CR-3430 at Sugar Creek	Heavy Damage	scour damage	1	Timber	Timber	Tyler	Local
CR-3625 Ebenezer Church Rd.	Heavy Damage	scour damage	2	Timber	Timber	Tyler	Local
CR-3630 #1	Heavy Damage	scour damage	2	Timber	Timber	Tyler	Local
CR-3630 #2	Heavy Damage	scour damage	1	Timber	Timber	Tyler	Local
CR-3725 at Pamplin Creek	Heavy Damage	scour damage, impact damage	3	Timber	Timber	Tyler	Local
CR-4825 Hester Rd.	Heavy Damage	scour damage	4	Timber	Timber	Tyler	Local
CR-4875 Midway Rd.	Heavy Damage	scour damage, impact damage	4	Timber	Timber	Tyler	Local

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Rice Belt Road (CR105)	Medium Damage	scour damage, impact damage	2	Timber	Timber	Liberty	Collector
E. Roundbunch Rd.	Medium Damage	scour damage, electrical failure	6	Concrete	Concrete	Orange	Major Arterial
Freeman Rd. Bridge	Medium Damage	impact damage	3	Steel and Timber	Timber	Polk	Local
CR-3725	Medium Damage	scour damage	2	Timber	Timber	Tyler	Local
Clear Lake Dr.	Light Damage	scour damage, spalling damage	2	Concrete	Concrete	Galveston	Local
Tiki Drive	Light Damage	spalling damage	3	Concrete	Concrete	Galveston	Major Arterial
6th St. Bridge (East)	Light Damage	scour damage	2	Concrete	Concrete	Galveston	Local
Pelican Island Bridge	Light Damage	scour damage	92	Concrete	Concrete	Galveston	Major Arterial
Union Springs Rd.	Light Damage	impact damage	2	Timber	Steel	Polk	Collector

Table 2. Damage state definition and descriptions.

Damage State	**Description**
Light	Some reparable damages to the superstructure. No immediate danger.
Medium	Minor damage to the superstructure and possibly substructure of the bridge. Possible loss of structural integrity.
Heavy	Major damage to entire bridge structure. Severe loss of structural integrity, posing public danger.
Destroyed	Bridge structure unusable or missing.

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Table 3. Parameters used in wave load estimates for Rollover Pass Bridge and Humble Camp Bridge. Surge and wave parameters obtained from analysis of ADCIRC and SWAN simulations by Dawson and Proft (2010).

Parameter	Rollover Pass	Humble Camp
Surge Height (ft)	15.1	13.0
Period (s)	9.4	2.1
Wave Height (ft)	5.3	3.3
Clearance (ft)	5.0	4.5

APPENDIX A: AASHTO Equations and definitions for estimating peak uplift forces

The interaction of waves with the bridge deck involves a quasi-static component as well as a slamming component caused by the trapping of air between the wave and the bridge deck. This section summarizes the approach for estimating maximum vertical wave loads, as presented in AASHTO (2008), which was adopted for the case study force estimates presented in the paper. These forces are the maximum force imparted by the maximum wave and surge elevation, taken as the sum of the maximum quasi-static vertical force and the slamming force. The maximum vertical quasi-static force is given by:

$$F_{V-MAX} = \gamma_W \bar{W} \beta \left(-1.3 \frac{H_{MAX}}{d_s} + 1.8\right) [1.35 + 0.35 \tanh(1.2T_P - 8.5)] \left(b_0 + b_1 x + \frac{b_2}{y} + b_3 x^2 + \frac{b_4}{y^2} + \frac{b_5 x}{y} + b_6 x^3\right)(TAF)$$

In which all variables are defined at the end of the Appendix, and:

$$\bar{W} = \left[\lambda - \left(\frac{\lambda}{H_{MAX}}\right)(Z_c + \frac{H_{MAX}}{2}\right]$$

$$if\ \frac{\bar{W}}{W} < 0.15\ Then\ \bar{W} = 0.15W$$

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

$$If\ (\eta_{max} - Z_c) \le 0, then\ \beta = 0$$

$$If\ 0 < (\eta_{max} - Z_c) \le d_b, then\ \beta = \frac{(\eta_{max} - Z_c)}{d_b}$$

$$If\ (\eta_{max} - Z_c) > d_b, then\ \beta = 1$$

$$x = \frac{H_{MAX}}{\lambda}$$

$$y = \frac{\bar{W}}{\lambda}$$

The bridges that were considered in this paper do not possess I or T girders, so the following coefficients are used in the above equations to reflect the flat deck:

$$\begin{gathered} b_0 = 0.0498d_b - 0.336 \\ b_1 = 5.29d_b + 20.3 \\ b_2 = -0.0074d_b + 0.0678 \\ b_3 = -30.43d_b + 22.0 \\ b_4 = 0.00009d_b - 0.001 \\ b_5 = -0.0147d_b{}^2 - 0.352d_b + 2.16 \\ b_6 = 5.6d_b + 10.2 \\ TAF = 1.0 \end{gathered}$$

The maximum slamming force on the bridge deck is given by:

$$F_S = \gamma_w H_{MAX}{}^2 A \left(\frac{H_{MAX}}{\lambda}\right)^B$$

$$A = 0.0149\left(\frac{Z_c}{\eta_{max}}\right) + 0.0316\ for\ 1.0 \ge \frac{Z_c}{\eta_{max}} \ge 0$$

$$A = \frac{1}{-1563 + 1595exp\left(\frac{Z_c}{\eta_{max}}\right)}\ for\ 0.0 \ge \frac{Z_c}{\eta_{max}}$$

$$B = 0.659\left(\frac{Z_c}{\eta_{max}}\right)^2 + 0.537\left(\frac{Z_c}{\eta_{max}}\right) - 1.193$$

The variables used in the above equations are defined as follows:

F_{V-MAX}= Maximum vertical quasi-static load (kips)

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

F_S=Maximum vertical slamming force (kips)

γ_w = Unit weight of water taken as 0.064 kips/cubic foot

η_{max}= Distance from the storm water level to the wave crest (ft)

Z_c=Vertical distance from the bottom of the cross-section to the storm water level, positive if the storm water level is below the bottom of the cross-section (ft)

d_b=Slab thickness plus deck thickness (ft)

d_s= Water depth at or near the bridge (ft)

H_{MAX}= Maximum possible wave height (ft)

λ=Wave length (ft)

TAF= A factor to adjust the vertical quasi-static force for variable amounts of entrapped air

T_P= Period of the waves with the greatest energy exhibited in a spectrum (sec)

b_0 to b_6= Coefficients (ft)

W= Bridge width (ft)

Figure1a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

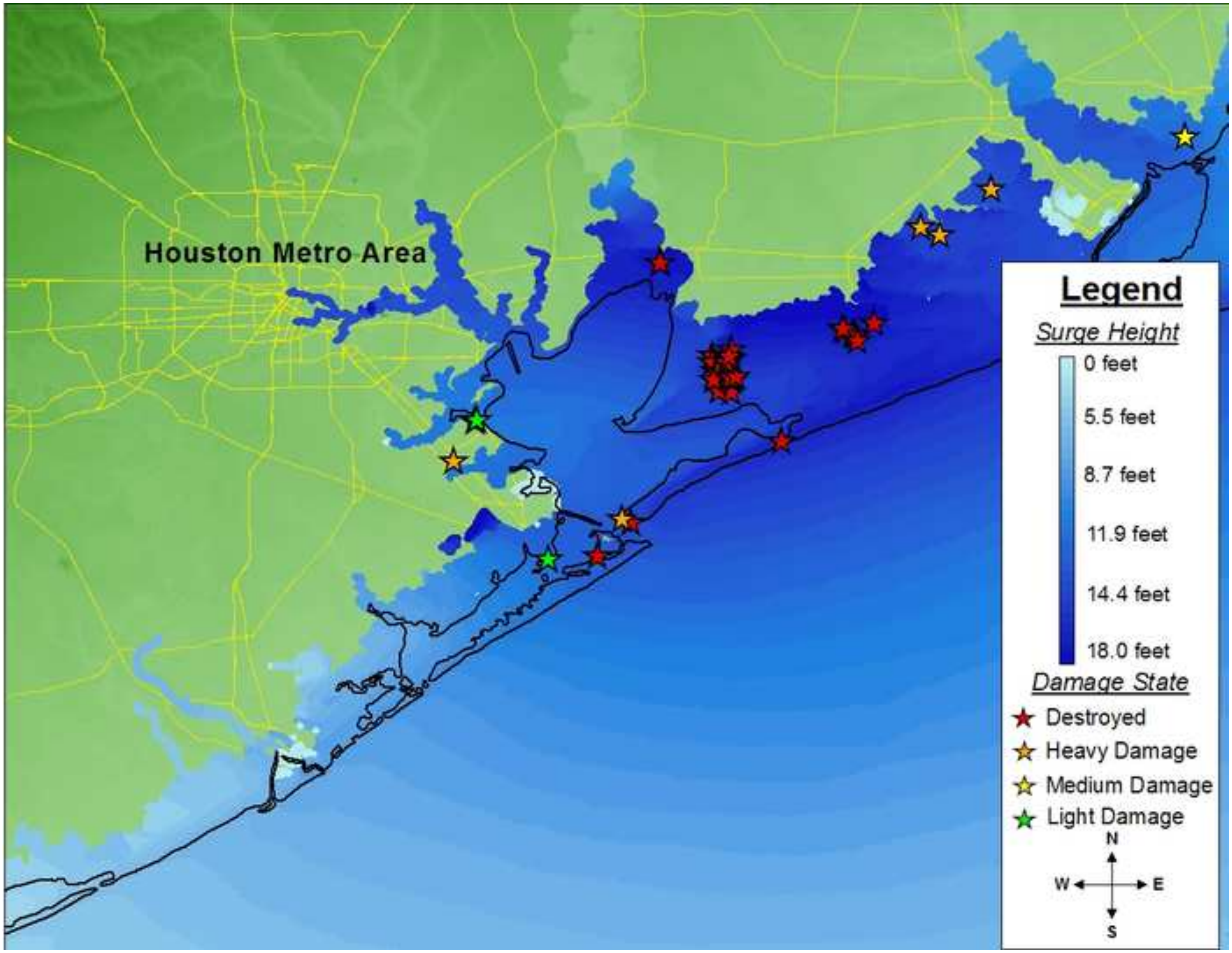

Figure1b

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

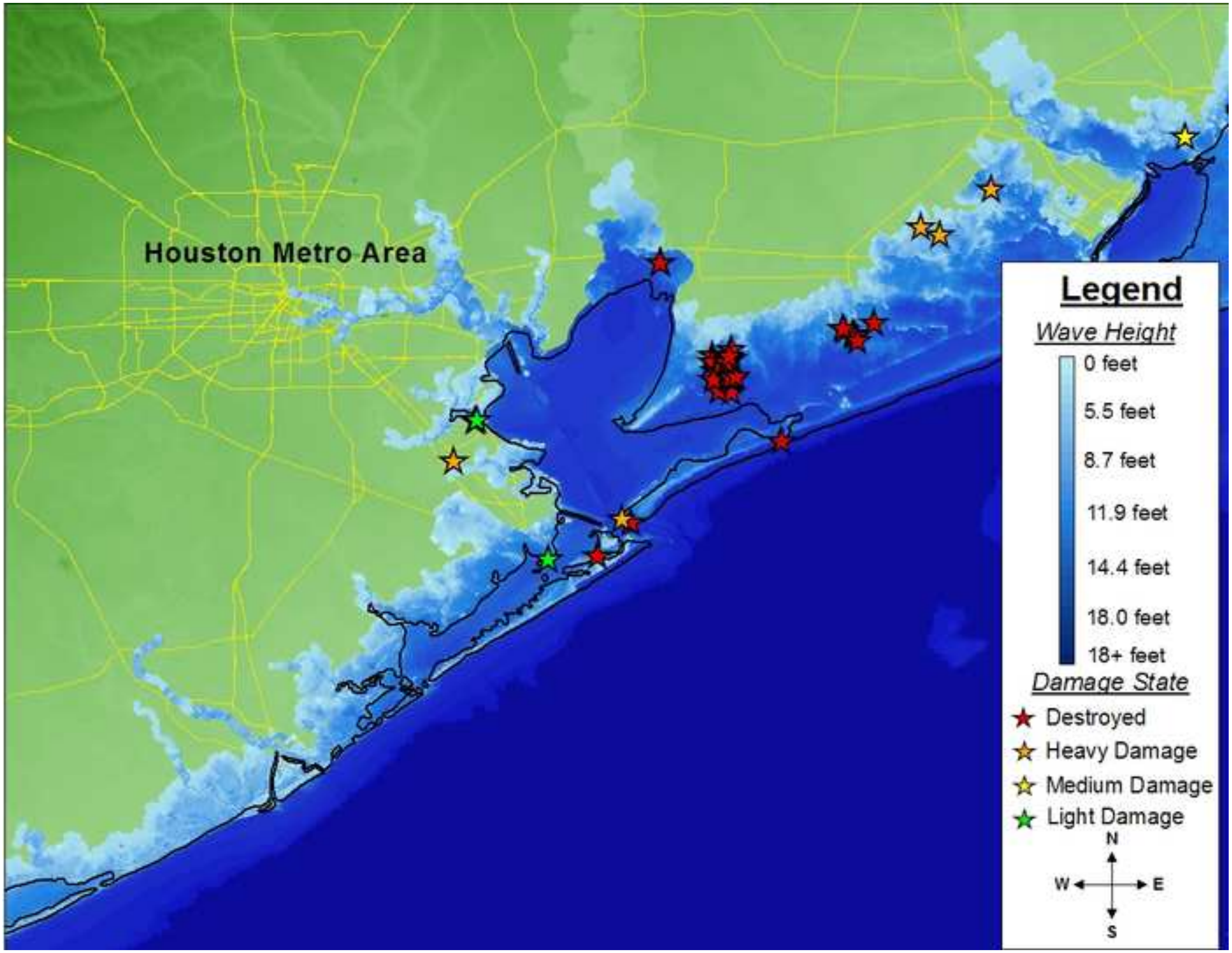

Figure2

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

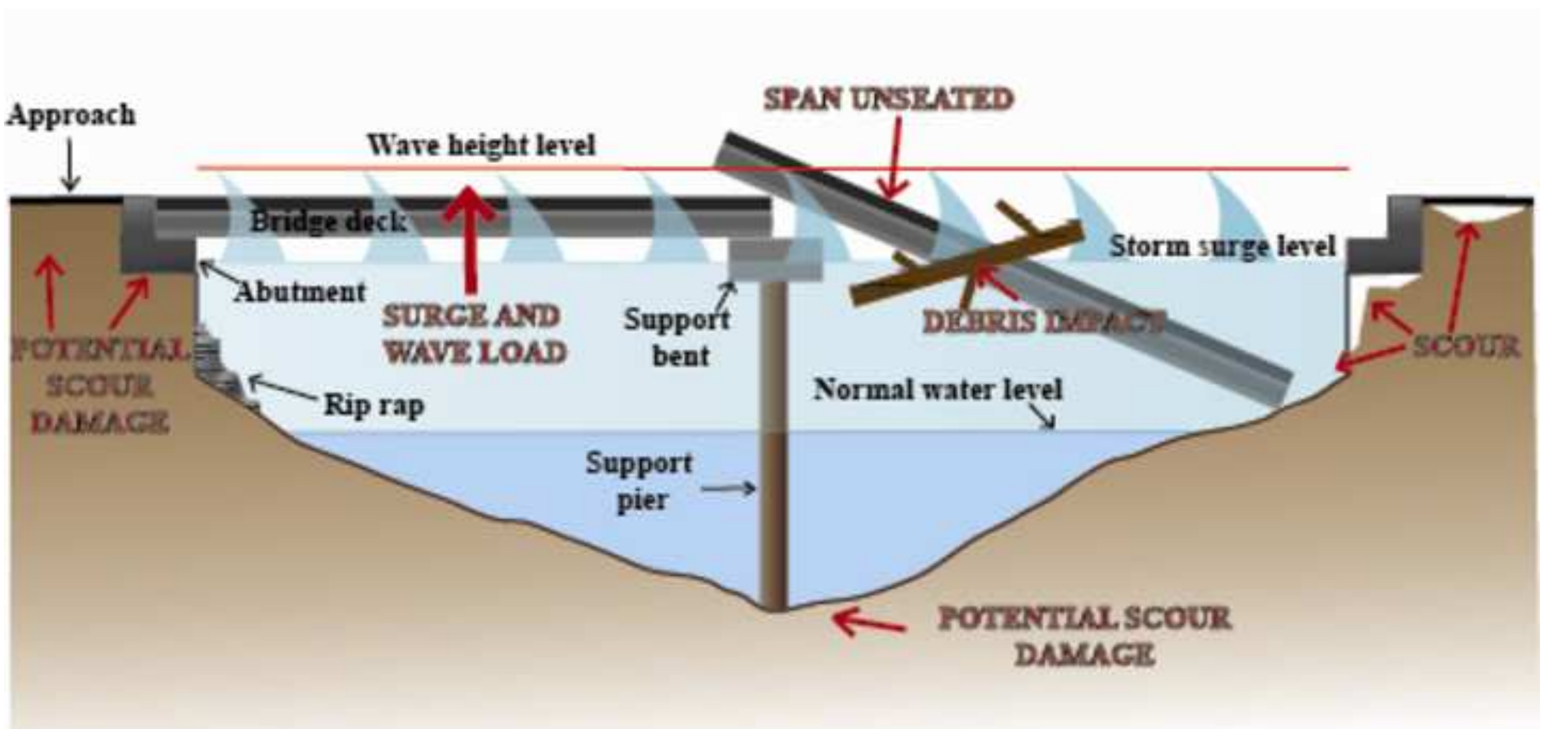

Figure3

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

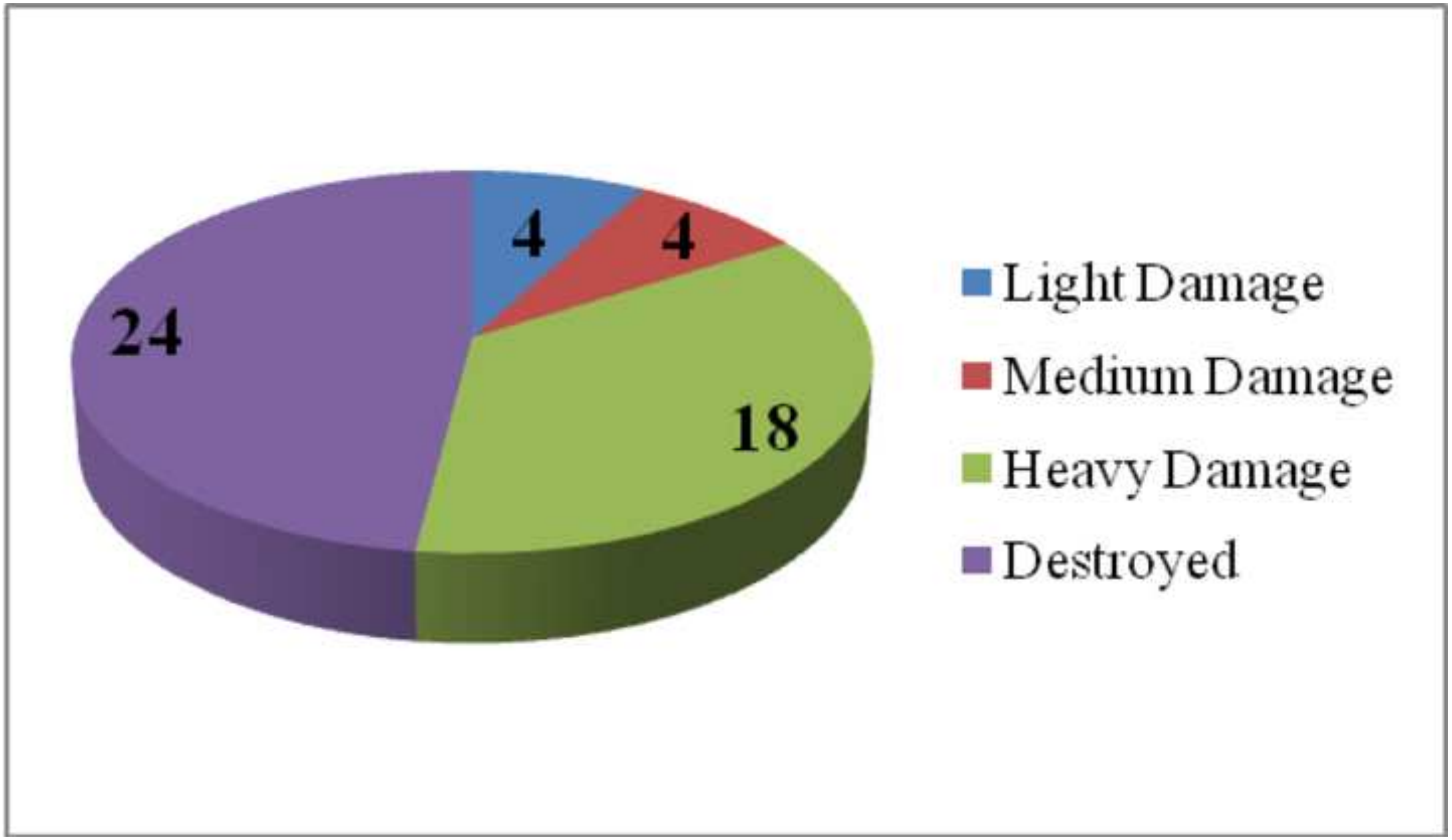

Figure4

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011; posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure5a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure5b

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure6a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure6b

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure7a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure7b

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure8

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure9

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

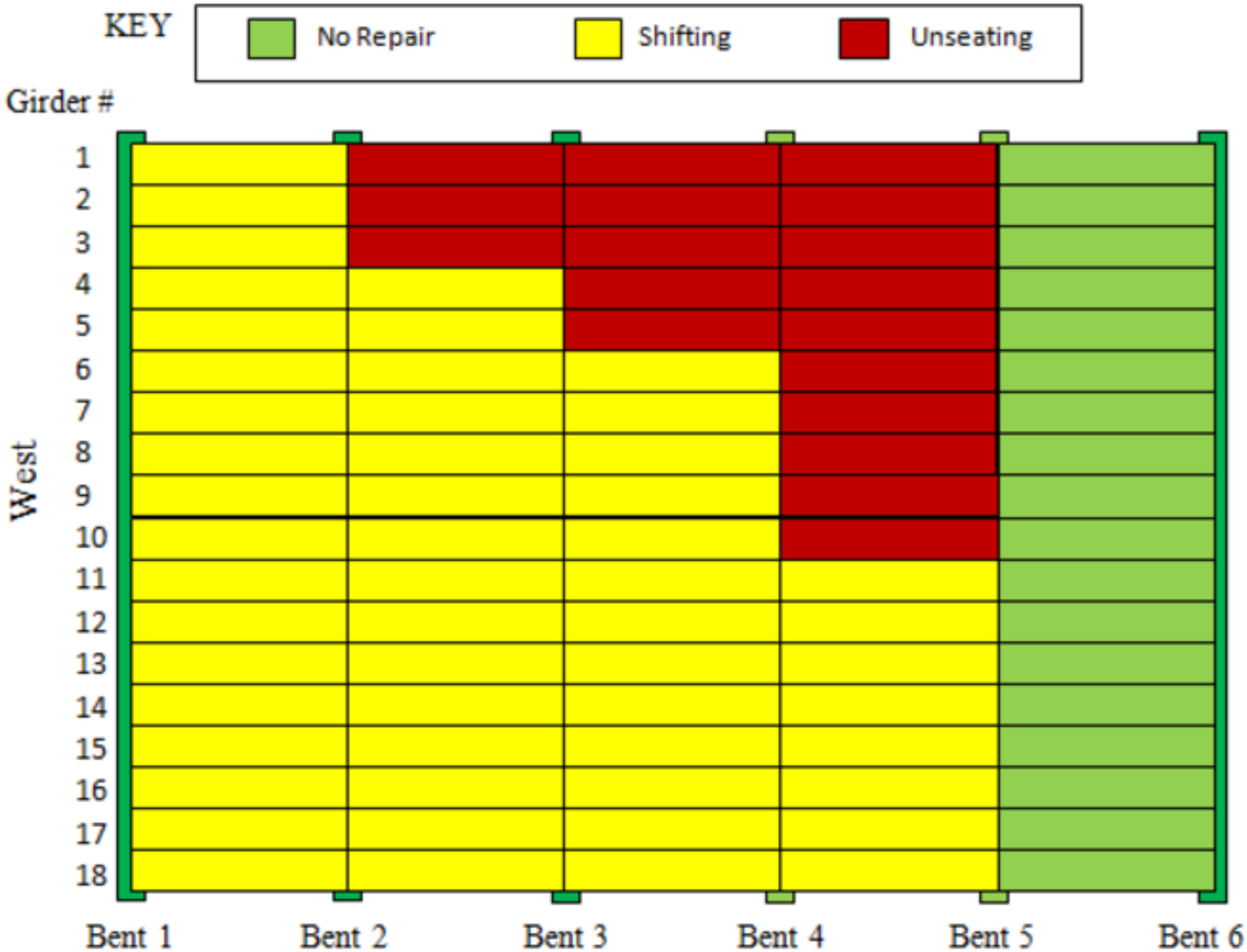

Figure10a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure10b

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure10c

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure11a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure11b

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure12a

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213

Figure12b

Journal of Performance of Constructed Facilities. Submitted September 27, 2010; accepted February 9, 2011;
posted ahead of print February 11, 2011. doi:10.1061/(ASCE)CF.1943-5509.0000213