Energy Infrastructure Damage Analysis for Hurricane Rita

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Energy Infrastructure Damage Analysis for Hurricane Rita

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Abstract: In 2005, Hurricane Rita caused significant damage to the energy infrastructure in the Gulf of Mexico region. In the context of this investigation, the "energy infrastructure" refers to the offshore oil platforms, refineries, and gasoline supply stations in the region, often referred to as the "petroleum infrastructure," the natural gas supply lines, and the delivery of electric power. In this paper, we examine the structural damage to the networks as defined by restoration, resilience, and fragility with a focus on the analysis of the electric power delivery disruptions. Our concern is not on the evaluation of risk, but rather to provide those who assess hurricane risk with relevant structural damage prediction models. We provide correlations of hurricane wind speed data with outages. We conclude that high winds alone can create significant damage to the energy infrastructure system.

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Background

On September 24, 2005, Hurricane Rita, a Saffir-Simpson (SS) Category 3 storm, with a maximum sustained wind speed of 161 kph (100 mph) made landfall near Port Arthur, Tex. (Knabb et al. 2006). Sections of Texas and Louisiana were heavily damaged by the storm (CNN 2005). Fig. 1 shows the path of Rita from September 18 to landfall several days later (www.noaa.gov/hurricanes). It can be seen that the storm category changed from 1 to 5 and then dropped to 3 over a period of several days. The storm surge in the region reached 4.6 m (15 ft) at landfall [National Weather Service (NWS) 2005] and many coastal towns in the region were flooded.

The energy supply infrastructure proved to be very vulnerable to damage by the hurricane. In the context of this investigation, the "energy infrastructure" refers to the offshore oil platforms, refineries, and gasoline supply stations in the region, often referred to as the "petroleum infrastructure" (EIA 2005), the natural gas supply lines, and the delivery of electric power. Fig. 2(a) (French et al. 2006) and Fig. 2(b) (EIA 2005) illustrate the path of Rita with respect to the locations of offshore oil platforms and three of the on-shore major refineries. According to French et al. (2006), 67 offshore oil platforms were destroyed by the hurricane. The storm has been described as a Category 3 in the region of the platforms with wind speeds in the range of 138–152 kph (86–94 mph) and a storm surge of 2.5–4.3 m (4–7 ft) (Knabb et al. 2006). According to EIA (2005), the three refineries shown in Fig. 2(b) were restarted almost immediately after Rita had passed through the region. A total of 16 refineries were closed prior to landfall and 13 remained shutdown as of September 26. Refineries in the Port Arthur region were delayed in restarting because the region took a more direct hit from the hurricane (EIA 2005). In addition, over a dozen natural gas processing plants were offline on the 26th not from direct damage but rather due to a combination of reasons such as flooding in the region or lack of supplies.

Even though Rita did not make landfall until it had entered the Gulf of Mexico, it produced storm surge in the Florida Keys on September 20. The storm also produced heavy rains in the Florida Keys and later on in portions of Mississippi, Louisiana, and eastern Texas (Knabb et al. 2006). Most of these areas recorded total amounts of rainfall in the range of 12.7–22.9 cm (5–9 in.) (Knabb et al. 2006).

The power delivery system proved to be very vulnerable to the combination of high winds, rainfall, and storm surge produced by Hurricane Rita. Over 500,000 customers were without power in Louisiana alone immediately after landfall (LPSC 2005a). In Texas, over 1.5 million customers were affected (PUCT 2006). It is noted that the electric power delivery system consists of three subsystems: generation, transmission, and distribution. Power is generated and transmitted through high voltage lines to substations where the voltage is dropped prior to distribution to customers. Rita caused significant damage to both transmission and distribution systems. The failure of steel lattice transmission system towers greatly hampered restoration as most towers were located in marshy areas that are difficult to access. Airborne debris was primarily responsible for the heavy damage sustained by over 87 substations in Texas (PUCT 2006), because in hurricane-prone regions, utilities commonly raise the essential equipment of the substation above the floodplain. In addition, distribution systems were difficult to repair because of numerous tree failures and related debris.

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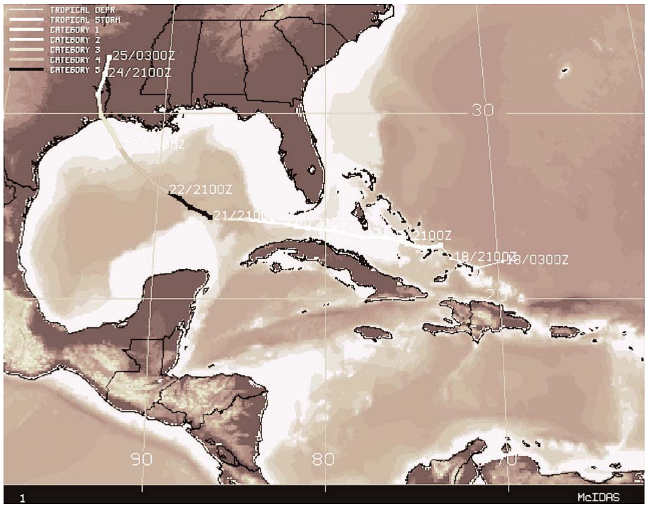

Fig. 1. Track of Rita from September 18–25, 2005; shades of gray correspond to the SS storm category with "5" being the highest (http://www.aoml.noaa.gov/hurricanes)

Structural Damage

Personal Observations

The first writer recorded structural damage in the weeks immediately after Rita's landfall. Records of damage to the power delivery systems and the gasoline distribution stations are shown in this section.

Electric Power Delivery: Transmission Systems

It is noted that the lines of transmission towers closely approximate a structural series or weakest link systems. Although power delivery may theoretically be delivered through other tower routes, in the instances shown, both the north-south and east-west tower lines failed making rerouting of power delivery extremely difficult. Fig. 3(a) shows a partial view of a line of failed transmission towers near Port Charles and Bridge City. The line crosses Highway 73. In this figure, a side view of a collapsed southern steel lattice tower in the foreground with three slightly damaged towers in the background is shown. The photo was taken at ground level on the shoulder of Highway 73 with coordinates of 30°00′29.98″N and 93°51′25.44″W. The three background towers had slight damage to the top portions. On the other side of the freeway, another collapsed tower along the same line can be seen in Fig. 3(b). The challenge in reaching these towers for repair is apparent. The closest recorded wind speed was 140 kph (86 mph) (Knabb et al. 2006). This value is significantly lower than the predicted sustained wind speed using ASCE 7-05. That is, the basic (3-s gust) wind speed of 242 kph (150 mph) for the coastline of Louisiana is equivalent to a 2-min sustained value of 186 kph (116 mph) using the Durst conversion plot [ASCE 7-05 (ASCE/SEI 2005)].

Wooden towers did not fare any better than the steel structures. Fig. 4(a) shows a group of towers in an open region near a major highway in which damage occurs along the line rather than normal to the line. The base failure of a wooden transmission tower off of Highway 73 near State Route 124 in Texas is shown in Fig. 4(b). Its location is (approximate) 29°32′N and 94°24′W.

Gasoline Supply

Surface damage also occurred to gasoline supply stations. These types of failures are widespread and disrupt the supply chain. Figs. 5(a–c) illustrate the type of common failures that occurred throughout sections of Louisiana and Texas affected by the hurricane. In Fig. 5(a), a canopy has become airborne and then come to rest on a convenience store. The pumping stations also suffered significant damage as the sidings have been ripped off possibly due to high winds. In Fig. 5(b), a canopy has been damaged although its attachment at the base is secure. The pumping stations have consequently been damaged in the process. Finally in Fig. 5(c), a canopy that broke at the support base evidently became airborne and came to rest across the street from the station. Their widespread failure creates disruptions in the supply of gasoline. It is also noted that the pumping stations require a power supply to operate.

Published Accounts

The data in this section are from the final report of the PUCT (2006) unless specified otherwise. The structural damage to the electric power delivery system in Texas was severe. The worst hit were Entergy Gulf States, Inc. (EGSI) and East Texas Electric Cooperatives (ETC). *EGSI lost all transmission connections between Louisiana and Texas*. In structural terms, 87 substations were damaged. For the transmission system, 286 poles, 321 H frame poles, 26 lattice towers, and one concrete pole had to be replaced. As for distribution, over 8,970 distribution poles were "broken in half." However, restoration occurred to all who could receive power by the end of 3 weeks. As for ETC, the restoration was also lengthy: the outage time for 105,905 customers ranged from 16 h to 36 days with an average of 11 days. Twelve and a half percent of its substations were damaged. Center Point Energy reported that 799 wood distribution poles were down. It is noted that the restoration of the distribution system after wind events may take much longer than for transmission lines due to the spatially dense network configuration, the large amount of debris, and the difficulty of access to damaged networks.

LPSC (2005a) reported that Center Point Energy Entex, a supplier of natural gas, had parish customer outages of 200 in Calcasieu, 1,200 in Cameron, and 50 in Vermillion on September 28. In the last report on October 17, these outages had not been restored. The details of the pipeline damage or other structural infrastructure were not provided. Similar reports of natural gas outages were not available for Texas.

Outage Analysis

Caveats regarding the Data Sets

Utility Data

In this section, we analyze outage data for affected parishes of the state of Louisiana provided by the Louisiana Public Service Commission (LPSC). The LPSC kept detailed spreadsheet records of hurricane data for both Katrina and Rita and identified which sections of the delivery system were damaged by one *or* the other. Certain sections of Entergy New Orleans damaged by Hurricane Katrina, for example, had not been restored by the time Rita made landfall so the outages did not "count" as Rita-based damage. The writers were not able to obtain geographical information system (GIS) data for the lines and feeders, which would have been beneficial in the evaluation of damage.

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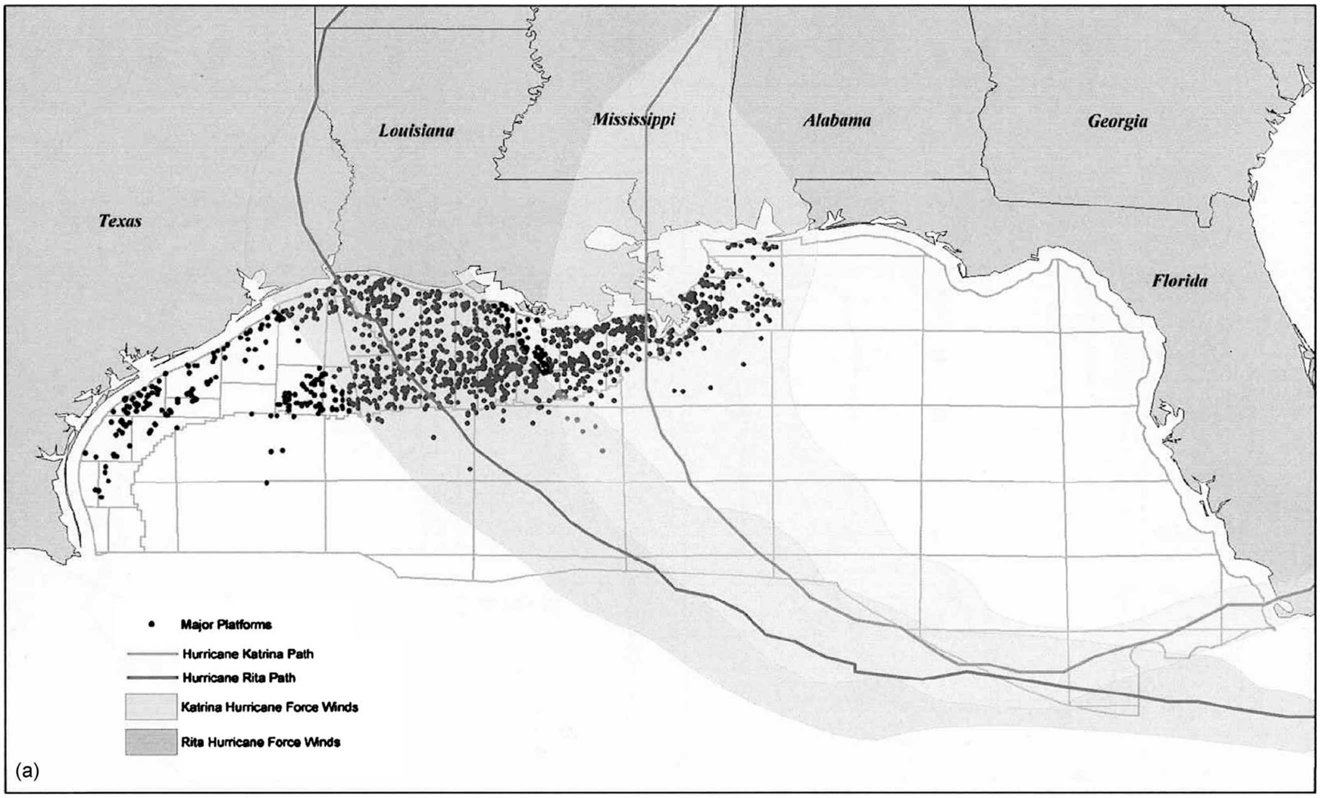


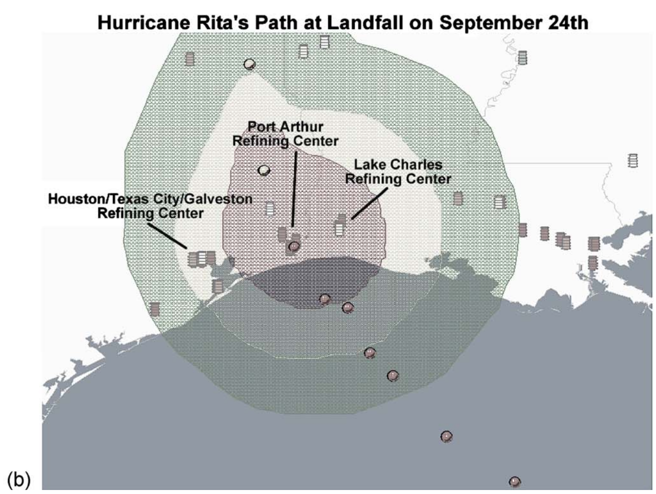


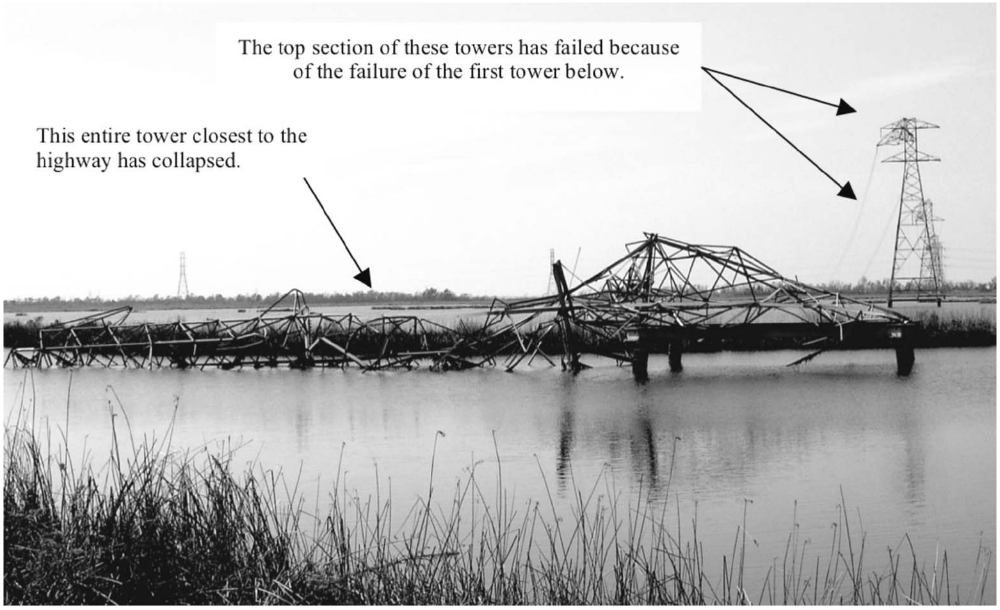
Fig. 2. (a) Path of Hurricanes Katrina and Rita in the Gulf region overlain with the location of major offshore platforms (French et al. 2006); (b) the landfall of Hurricane Rita relative to refineries (from EIA.gov Web site)

Our objective in this investigation is to develop models to predict structural network damage due to hurricanes (e.g., Powell et al. 1995) to not only identify possible means of hurricane hardening, but also to provide those who assess risk such as Liu et al. (2005) accurate tools for making predictions. Characterizing the hurricane risk to the region is beyond the scope of our investigation.

Weather Data

The Atlantic Oceanographic and Meteorological Laboratory Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA) provided through its website near real-time analyses of the maximum sustained surface wind speeds (HRD 2005). Poststorm analyses were also made available online; to ensure greater accuracy, the poststorm data were used for this study. The data were formatted as GIS shape files that we imported into the ARCGIS-9 program. ARC-GIS9 is a program developed by ESRI (2008). Information is available at http://www.esri.com/software/arcgis.

The sustained wind speed is defined as "the highest 1 min[ute] surface winds occurring within the circulation of the system . . . estimated to occur at the standard meteorological height of 10 m in an unobstructed exposure." (NWS 2006). The National Weather Service (NWS) Automated Surface Observation System (ASOS) has adopted a 2-min average standard for its sustained wind definition. Gusts are the peak wind speed averaged over a few seconds; ASCE 7-05 uses the 3-s gust speed for its calculations. According to Powell et al. (1996b, 1998b) and Powell and



(a)

(b)

Fig. 3. (a) Side view of the failed lattice-type transmission towers taken at ground level on the shoulder of Highway 73. Partial failure of the distant towers can be seen. (b) Tower in the same line located on the opposite side of Highway 73.

Houston (1998a, 1996a), the hurricane peak speed is usually 1.3 times higher than the 1-min sustained speed. Even though the boundary layer profile equations do not apply to hurricane wind speeds, it is noted that the Durst conversion plot of ASCE 7-05 provides a ratio of 1.3 to a conversion of a peak to a 2-min sustained wind speed (see ASCE 7-05, p. 308, Fig. C6-4). For this reason, we used a 1.3 conversion factor for the ASCE 7-05 basic wind speed to convert it to the sustained value in order to scale the wind speed data. That is, instead of using the "raw data," we employed a ratio of the HRD data available from the shape file to the ASCE 7-05 2-min sustained value of 183 kph (114 mph). In equation form, the wind speed ratio is

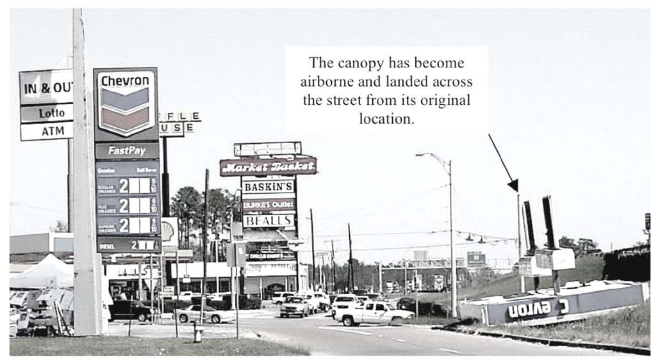
(a)

(b)

Fig. 4. (a) Row of tower failures along the line; (b) wooden tower failure at the base

(a)

(b)



(c)

Fig. 5. (a) Damage to a gasoline station. Ripped from the base of its column attachments, the canopy has been destroyed and the pumping stations have suffered significant damage. (b) Damage to a canopy and pumping station. (c) An airborne canopy traveled across the street before landing.

wind speed ratio

$$= \frac{\text{maximum sustained wind speed from the HRD data for the parish}}{\text{ASCE-7 basic 2-min wind speed for Louisiana}} \quad (1)$$

Another route would have been to use the wind speeds associated with each SS category such as 119 kph (74 mph) as the onset of a hurricane. However, Powell and Reinhold (2007) have found that the SS scale provides a poor assessment of the wind destructive potential. Given that the storm itself at landfall was considered a SS Category 3, we felt that the conversion of wind speeds to categories would be confusing.

In addition, we used the maximum surface sustained wind speed per parish as opposed to an area-averaging method over that parish. Networked systems connected by lines do not fail structurally all at once; in other words, a failure is initiated structurally at a section and then the rest of the line is affected. So averaging winds over an area would not portray an accurate loading picture. It is noted that other structural forms susceptible to hurricane damage such as low-rise buildings are not easily characterized by wind speed alone since pressure coefficients are the determining factor for structural performance. With the networked towers and substations considered here, the same restrictions do not apply. Pressure coefficients were not considered.

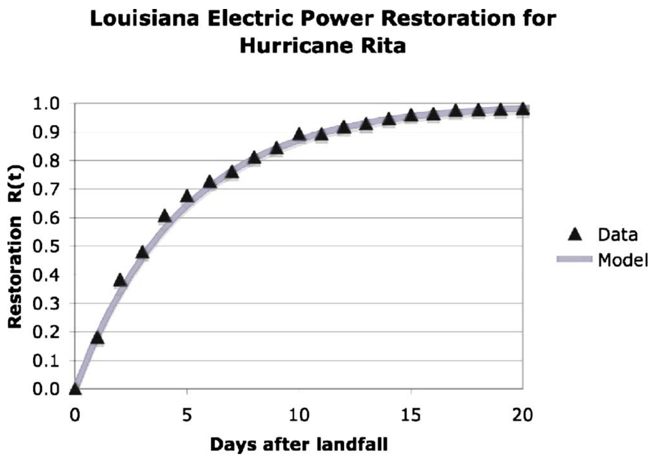


Fig. 6. Restoration function for the affected parishes of Louisiana for Hurricane Rita

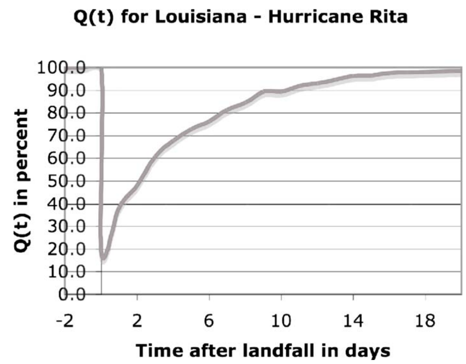


Fig. 7. Quality function $Q(t)$ for Hurricane Rita for the affected parishes of the state of Louisiana

Indeed, as described in the PUCT (2006) report, damage to many substations was initiated by airborne debris or missiles rather than the application of wind loadings directly. Despite the limitations on the data sets, certain salient features of the network performance may be determined.

Restoration and Quality

One well-known form of restoration denoted as $R(t)$ is defined by, e.g., Chang (1998)

$$R(t) = 1 - e^{-bt} \tag{2}$$

where t=time in days; and b=an empirically derived constant that provides information on the rapidity with which the restoration occurs. The restoration is complete when $R(t)=100\%$. This function is used primarily by emergency managers who try to predict the recovery and restoration resources needed in the aftermath of natural disasters such as hurricanes and earthquakes. Fig. 6 shows the results of the actual and predicted restoration curve for Rita for the affected parishes of the state of Louisiana. The value of the exponent b is 0.21 with a goodness of fit parameter R^2 value of 98.8% and a duration of 22 days. For the Loma Prieta earthquake, Chang (1998) found a value of 2.75 for b and Park et al. (2006) found a b value of *10.1* for the restoration of Nisqually earthquake based damage to Seattle City Light. Even though the data set is small, an initial comparison of the two hazards indicates that the power infrastructure damage due to hurricanes takes much longer to repair.

Another function developed by the Multidisciplinary Center for Extreme Event Research (MCEER) and used by civil engineers to identify the *resilience* of a structure, or system of connected structures, is $Q(t)$ or *quality* (Bruneau et al. 2003). A quality value of 100% means that the network is functioning or operating properly. A zero-based value of $Q(t)$ indicates that the network is not functional or inoperable. We derived the $Q(t)$ function using the Louisiana state data for Hurricane Rita where the total number of customers in the affected parishes was used as the fully functional value (approximately 505,000) as opposed to the total number of customers in the entire state. The result is shown in Fig. 7. The *resilience R* based upon the properties of the quality function may be estimated using

$$R = \frac{\int_{t_1}^{t_2} Q(t)dt}{(t_2 - t_1)} \tag{3}$$

where t_1 and t_2=endpoints over which the resilience is being determined. The *resilience* is said to have other properties including *robustness*, *rapidity*, and *resourcefulness* (e.g., Bruneau et al. 2003; O'Rourke 2007). The robustness, vulnerability, and recovery aspects of the quality curve are identified in Fig. 7 for Hurricane Rita. For these data, the resilience is 81%. *Resourcefulness* usually refers to the capability of the community to respond to the hurricane and it implicitly includes the amount of available resources. In this context, we believe that the Institute of Electrical and Electronics Engineers (IEEE) performance index *SAIFI* may be a good indicator for electric power delivery as it is dependent upon the number of crews and equipment available for repairs.

IEEE Performance Index

One of the industry standards for characterizing utility outages is the system average interruption frequency index (SAIFI) as defined by IEEE (2001) as

$$\text{SAIFI} = \frac{\sum \text{customer interruptions}}{\text{total number of customers}} \tag{4}$$

For Louisiana, the SAIFI is approximately 2.0 interruptions per year for 2005 (LPSC 2005b). The SAIFI does not include "major" events when more than 10% of all customers lose power. For major events, we use *STAIFI* as defined by Brown et al. (1997) where the SAIFI value is evaluated for the duration of the storm. That is, the amount of outages for a storm is characterized in terms of the normal number of nonstorm outages for the same location. For the Louisiana Rita data, the average *STAIFI* was 51 interruptions per year. In other words, if the interruption behavior during the storm was "distributed" across the year, it would result in 51 significant outages over that year as opposed to two interruptions per year, which is the normal nonstorm value. In previous analyses of winter storms (Reed 2008), it was found that a normalized STAIFI designated as STAIFI_n, as defined by

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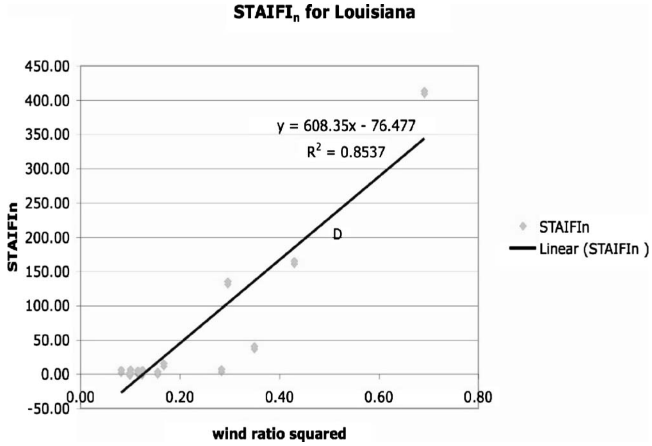

Fig. 8. STAIFI$_n$ analysis for Louisiana parish data

$$\mathrm{STAIFI}_n = \frac{\text{STAIFI for the storm data in interruptions per year}}{\text{SAIFI for the year the storm occurred in interruptions per year}} \tag{5}$$

was linearly related to a gust ratio; that is, the peak 5-s gust during the storm divided by the peak gust for the year the storm occurred.

In our analysis, we used the STAIFI values *per parish* rather than for each *company*. The company delivery system boundaries did not correspond to the same spatial scale as the wind speed data or storm pathway. Therefore, we used the data collected for the first week after landfall to calculate the STAIFI using Eq. (4). We also used the wind speed ratio of Eq. (1) for our analysis.

Fig. 8 illustrates the relationship between the STAIFI$_n$ values and the wind speed ratio squared. The squared ratio is used because it is assumed to correspond to a pressure variable. A linear relationship exists although the goodness of fit R^2 variable is only 85%. The relationship is

$$\mathrm{STAIFI}n = 608.35(\text{wind ratio squared}) - 76.48 \tag{6}$$

The results suggest that for Hurricane Rita, the wind speed was the dominating weather parameter for line damage. They may also illustrate that the *rate* of repair or *resourcefulness* was constant.

Fragility Analysis

In an effort to assess the influence of the wind speed on the outages, we used the HRD values described earlier and outage data for the State of Louisiana. Our choice essentially corresponds to a line failure initiated by the maximum sustained wind speed rather than an averaged value that would be loading a longer section of the line. Even with these restrictions, we obtained a useful relationship. We found that a fragility relationship based on the wind speed ratio squared could be described by a lognormal relationship as shown in Fig. 9. *Fragility* in this analysis is *the ratio of the outages in a parish divided by the total number of customers in that parish for the date of landfall*, which corresponded to the time frame of the wind data. Previous analyses by Park et al. (2006) found fragilities as based upon *the damage in a line per length of the total line* in a contour of peak acceleration values for the Nisqually earthquake. As noted earlier, we did not have the GIS data required for such an extensive fragility analysis, so we used the outages per parish divided by the total number of customers in that parish as our substitute for fragility. We used a probability paper to fit the data set consisting of 17 observations. The lognormal distribution was selected based upon previous investigations for lifeline networks for both extreme winds (e.g., Reed 2008) and seismic fragilities (e.g., Nojima and Sugito 2002). Despite the spread in values shown, a trend is apparent. A 20% wind speed ratio squared results in a fragility of 60%. That is, when the wind speed was 45% of the Louisiana basic 2-min wind speed, then 50% of the line "failed;" i.e., 50% of the customers in affected parishes experienced outages. Of course, this performance may be affected by other storm variables but it provides some information on the relationship between the structural capacity of the connected lines and the extreme winds.

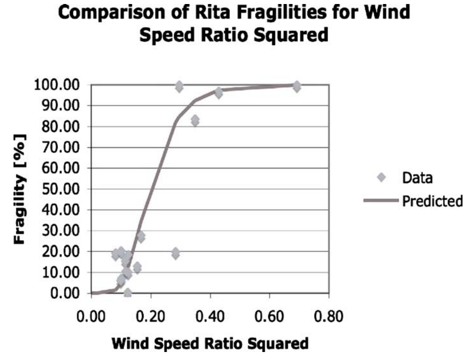

Fig. 9. Fragility curve for Hurricane Rita using data from the affected parishes of Louisiana based upon wind speed

Implications for Hurricane Hardening

Structural engineers achieve improved performance in buildings through enhancing redundancy and robustness. If we apply this concept to the power delivery system, enhanced structural redundancy and resilience at the network level seem to be appropriate. Clearly the repair and reconstruction of transmission lines and towers would be quicker in regions that are more conducive for crew access than the existing marshes. The structural form of tower failure is another topic for examination. Steel lattice towers did not appear to sustain high winds in exposed areas. The collapsed forms suggest buckling of critical members. Newer tower forms such as cross-arm steel or concrete may exhibit greater flexibility to deform under loading which would be useful under these conditions. In addition, the ability of individual towers to "drop" lines may be useful at certain wind speeds in order to avoid a series-type line failure. Wooden towers and poles appeared to fail at or near the base in exposed regions. In these instances, geotechnical examination and tower base redesign should be considered. That is, the use of geofibers to strengthen the base support for selected poles may be appropriate. PUCT (2006) recommended that substation sitings be reexamined in consideration of the flooding that occurred in the 2005 hurricanes. However, the large number of substations that sustained damage due to airborne debris and high winds suggests that more rugged designs for housing the electrical equipment be investigated.

Summary and Conclusions

We have examined the structural damage to the energy infrastructure for Hurricane Rita with an emphasis on electric power

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delivery. The traditional IEEE performance index SAIFI has been estimated; restoration and quality have been investigated; and fragilities based upon parish outages have been estimated. Despite the limited data available we have the following preliminary conclusions:

- The results of our investigation indicate that the high wind speeds of this hurricane were responsible for most infrastructure damage as opposed to the prolonged heavy flooding created by other hurricanes such as Katrina.
- Dramatic failures of transmission lines occurred in exposed marshy areas. A redesign of these systems (lines) may be appropriate.
- Fragilities based on outage data at the parish or county level seem appropriate. The results for Louisiana suggest that line failures occur at wind speeds less than half the ASCE 7-05 basic wind speed for Louisiana. This situation should be investigated further.
- The IEEE performance index STAIFI may not be as useful for structural engineers in predicting damage as for utility companies to assess performance for electrical engineering considerations. Resilience measures are more descriptive for structural engineers as they may be used to characterize robustness and the rapidity of restoration. However, the IEEE performance index does implicitly indicate the level of resources employed in restoration and may ultimately be related to the resilience parameter of "resourcefulness" as employed in the MCEER model described by Bruneau et al. (2003).
- Although the HRD provides an invaluable support base of spatial and temporal wind speed data, the actual application of these wind speeds to structural engineering problems is a complex process. More research is required to accurately characterize the actual wind speeds near the ground level during hurricane landfall.

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