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WIND SPEED-DAMAGE CORRELATION IN HURRICANE KATRINA

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1. INTRODUCTION

According to Knabb et al. (2006), Hurricane Katrina was the costliest hurricane disaster in the United States to date. The hurricane caused widespread devastation from Florida to Louisiana to Mississippi making a total of three landfalls before dissipating over the Ohio River Valley. The storm damaged or destroyed many properties, especially near the coasts.

Since the hurricane, various agencies have conducted building damage assessments to estimate the wind fields that occurred during the storm. The National Oceanic and Atmospheric Administration (NOAA, 2005a) conducted aerial and ground surveys and published a wind speed map. Likewise, the Federal Emergency Management Agency (FEMA, 2006) conducted a similar study and produced another wind speed map. Both studies used a combination of wind speed-damage correlation, actual wind measurements, as well as numerical model simulations.

This paper explores the relationship between building damage and wind speed through the use of the Enhanced Fujita (EF) scale developed by the Wind Science and Engineering Center (WSEC, 2006) and now utilized by the National Weather Service. Aerial and ground photographic imagery were obtained from NOAA (2005b) after Hurricane Katrina, and used with images from the author's damage survey of the region (see Marshall, 2006). The results of this study will be compared to the findings by NOAA and FEMA.

2. WIND SPEED-DAMAGE BACKGROUND

Fujita (1971) was among the first to utilize wind speed-damage correlation. He developed the "F-scale", rating building damage from 0 to 5 with increasing severity in damage. His scale has been utilized for rating tornado, hurricane, and straight-line wind damage. Fujita (1992) even plotted F-scale damage intensity maps for Hurricanes Andrew, Alicia, Camille, Diana, Frederic, and Hugo.

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Mehta et al. (1983) and Kareem (1984) utilized the concept of wind speed-damage correlation after Hurricanes Frederic and Alicia, respectively. In essence, each building acts like an anemometer that records the wind speed. A range of failure wind speeds can be determined by analyzing building damage whereas undamaged buildings can provide upper bounds to the wind speeds. In 2006, WSEC developed a wind speed-damage scale entitled the EF-scale, named after the late Dr. Ted Fujita. The author served on this committee.

Wind speed-damage correlation is useful especially when few ground-based wind speed measurements are available. Such was the case in Hurricane Katrina when most of the automated stations failed before the eye reached the coast. However, mobile towers were deployed by Texas Tech University (TTU) at Slidell, LA and Bay St. Louis, MS (Giammanco et al., 2005). Also, the Florida Coastal Monitoring Program (FCMP, 2005) deployed wind towers at Belle Chasse, LA as well as in Pascagoula, MS. Wind data obtained from each of these sites were compared to the derived wind speeds from the analysis of damage in this study.

3. STUDY PARAMETERS

This study centers on the area hardest hit by Hurricane Katrina, south and east of I-10 (Fig. 1).

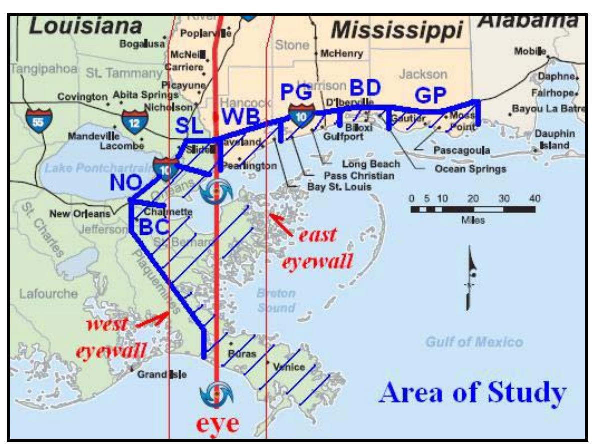

Figure 1. Study area (shaded in blue). The path of Hurricane Katrina's eye is shown by the red line. Abbreviations of towns (in blue) are listed below.

NOAA (2005b) took thousands of aerial images of the Louisiana and Mississippi coastline after Hurricane Katrina of which 350 images were taken within two days after the storm. NOAA's images reportedly were obtained from a camera mounted on an aircraft at an altitude of 2344 m (7500 feet). These images defined the domain of our study. About 150 images were selected for detailed analysis. The images were oriented correctly and magnified to their full resolution.

Four types of buildings were selected in this study: gas station canopies, manufactured homes, residences, and metal building systems. These structures were selected for two different reasons. It was reasoned that canopies and manufactured homes would be more susceptible to wind gusts than residences and metal buildings. Also, residences and metal buildings were the most common building type within the study area. Structures in heavily forested areas were excluded from the sample as they were not visible on aerial imagery. Also, structures impacted by falling trees were excluded as the ultimate goal was to obtain wind velocities to the damaged structures. Destroyed structures in the storm surge zone also were excluded from this study.

The study region was divided into seven geographical areas to determine any variations in building damage or wind speed. The zones were identified by the following abbreviations which will be utilized on various graphs herein:

1. NO = New Orleans, LA – for locations east and south of the Lakefront Airport.
2. BC = Belle Chasse, LA – also includes Arabi, Chalmette, Meraux, and Violet.
3. SL = Slidell, LA east and south of I-10.
4. WB = Waveland-BaySt.Louis, MS
5. PG = Pass Christian, Long Beach, and Gulfport, MS.
6. BD = Biloxi, D'Iberville, Ocean Springs, MS
7. GP = Gautier-Pascagoula, MS

4. DETERMINING DEGREES OF DAMAGE

As shown by Marshall (2004), dismantling of a structure by wind usually develops first at roof level and progresses downward with stronger wind velocities. This is because wind velocity increases with height above the ground. Such characteristics of wind damage were incorporated into developing the degree of damage (DOD) numbers in the EF scale. Therefore, the DOD can be determined through the analysis of aerial imagery. Womble et al. (2006) had conducted a similar study by rating residential damage using aerial imagery.

4.1 Gas Station Canopies

Gas station canopies are quite susceptible to wind damage as they have large surface areas. Typically, metal fascia or cladding is attached to steel frames supported by steel columns. Wind damage usually begins with the loss of fascia (DOD 2) then progress to the loss of roof panels (DOD 3). Occasionally, canopies tip over due to bending of the columns (DOD 4) or canopies becomes detached from the columns (DOD 5). Examples of canopy failures in Hurricane Katrina are shown in Fig. 2.

The EF scale lists the expected value of wind velocities for DOD 2 canopies as 35 m s^{-1} (78 mph), DOD 3 as 41 m s^{-1} (92 mph), DOD 4 as 49 m s^{-1} (109 mph), and DOD 5 as 51 m s^{-1} (114 mph). It should be noted that the failure wind speeds can vary 20 percent or more depending on the type of construction and/or condition of the structure. Also, these values are three-second wind gusts at 10 m (33 ft.) in Exposure C (open terrain) per ASCE 7-05 (2006). Corrections of failure wind speeds would be needed at other heights and exposures. In addition, these three second gust speeds would be higher than one-minute "sustained" speeds.

Figure 2. Degrees of wind damage to gas station canopies in Hurricane Katrina: a) loss of fascia (DOD 2), b) metal panels stripped from canopy (DOD 3), c) rotation of columns (DOD 4), and d) collapse of canopy (DOD 5).

A total of 96 gas station canopies were selected on NOAA aerial imagery within the study area. There were 79 canopies (89 percent) with no visible damage (DOD $\leq$ 2), and 17 canopies (11 percent) with roof panels removed (DOD $\geq$ 3), including one collapsed canopy and two canopies that were transported across streets. Examples of various DODs to canopies on NOAA aerial imagery are shown in Fig. 3.

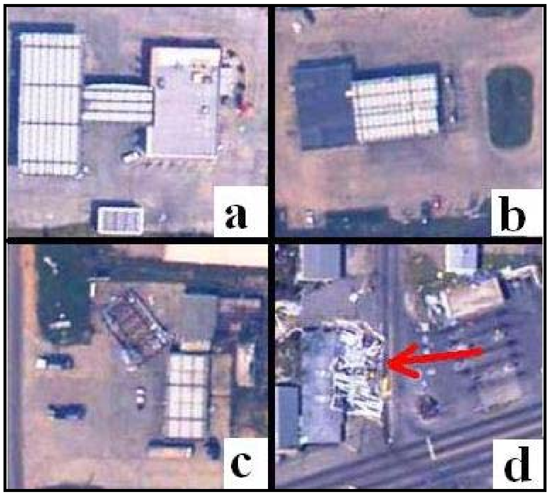

Figure 3. Various DODs to gas station canopies in the study area: a) no visible damage, b) removal of some roof panels (DOD 3), c) collapse of canopy (DOD 5), and transport of canopy across the street as shown by the red arrow (DOD 6).

Fig. 4 shows the DODs for each of the seven geographic zones in this study area. Not surprisingly, canopies that lost metal panels occurred from Slidell, LA eastward, where the strongest winds occurred. A higher percentage of gas station canopies experienced a loss of metal panels in the Pass Christian-Gulfport, MS area with 35 percent of the canopies experiencing some damage. Overall, the frequency of gas station canopies losing panels in the study area was 1 in 10 and the frequency for collapse or displacement of canopies was 1 in 33.

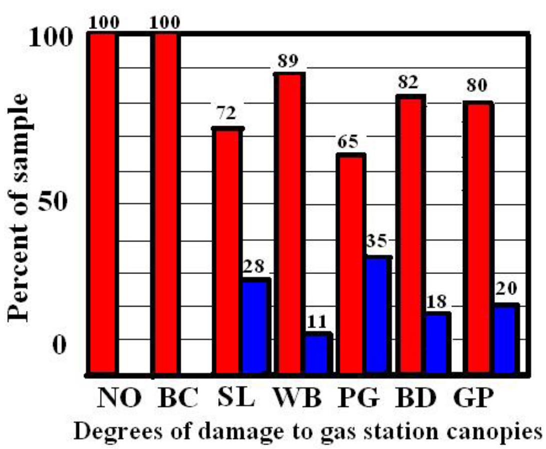

Figure 4. Normalized percentage of wind damage to gas station canopies in the seven geographic zones. Red bars are DOD 2 or less whereas blue bars are DOD 3 or more.

The EF scale lists failure wind speeds in Exposure C or open terrain. However, most structures in this study were in Exposure B, which were suburban or wooded environments. The increase in surface roughness would reduce the wind speed in Exposure B compared to Exposure C. Therefore, in this study, all failure wind speeds were increased 15 percent to adjust them to 10 m (33 ft.) in Exposure C using the power law in ASCE 7-05. This correction would allow us to compare the results in this study to the results in other studies including the building code. FEMA (2006) performed similar corrections from Exposure B to C in their analysis of Hurricane Katrina damage.

Thus, a 35 m s^{-1} (78 mph) wind that caused DOD 2 to a canopy in Exposure B was adjusted to a 40 m s^{-1} (90 mph) wind in Exposure C. Likewise, a 41 m s^{-1} (92 mph) wind that caused DOD 3 to a canopy in Exposure B was adjusted to a 47.5 m s^{-1} (106 mph) wind in Exposure C. In summary, wind speed-damage correlation to canopies indicated that the three-second wind gusts in the study area were primarily below 40 m s^{-1} (90 mph), but on occasion reached 47.5 m s^{-1} (106 mph) corrected to Exposure C at 10 m (33 ft.) above the ground.

However, an isolated increase in the DOD does not necessarily mean an isolated increase in wind speed. Note the collapsed canopy with loss of its metal panels in Fig. 3c adjacent to a relatively undamaged canopy. Flaws in the construction of the canopy or poor attachment/anchoring can better explain such sharp gradations in the damage rather than a rapid change in wind speed. Therefore, it is important to examine adjacent items when trying to determine a failure wind speed. Also, a site inspection may be required to better determine a failure wind speed.

4.2 Manufactured Housing

A total of 1678 single-wide, manufactured homes were selected within the study area on NOAA aerial imagery. Manufactured homes consisted of wood frames built on steel undercarriages, and were supported by stacked concrete masonry units (CMU) set on the ground. Typically, metal straps secured the steel frames to anchors driven into the ground. Roofs consisted of aluminum panels or were gable type covered with three-tab asphalt shingles.

Vann and McDonald (1978) described various failure modes of manufactured housing in other windstorms. Generally, the first sign of wind damage is the loss of skirting around the base of a manufactured home followed by displacement of portions of the roof covering (DOD 2). Unanchored homes are prone to being pushed off their supports especially if they are not anchored well to the ground and/or are broadsided by the wind (DOD 3). Sometimes, the entire roof covering is removed leaving the perimeter walls intact (DOD 4). Levitan et al. (1993) noted that high winds frequently removed the wood frame leaving the floor and underlying steel frame intact (DOD 6) in Hurricane Andrew. Various DODs to single-wide, manufactured homes are shown in Fig. 5.

Figure 5. Various DODs to manufactured homes: a) loss of the roof covering (DOD 2), b) sliding of unit off its piers (DOD 3), c) rolling of home (DOD 5), and destruction of roof and walls leaving the floor in place (DOD 6).

In this study, manufactured homes usually were located in close proximity to each other in Exposure B environments. Some of the largest manufactured home parks were in Biloxi, MS. In many instances, metal canopies or sunrooms extended from the manufactured homes and the loss of these items led to additional damage to homes. Fig. 6 shows examples of DODs assigned to manufactured homes on NOAA imagery in this study. Overall, 1569 manufactured homes (94 percent) had less than 20 percent of the roof covering removed (DOD $\leq$ 2), and 109 homes (6 percent) had lost most of their roof coverings (DOD $\geq$ 4). The latter figure included 9 flipped homes (DOD 5), 18 homes with lost roof structures (DOD 6), and one vaulted home (DOD 7). Overall, the frequency of manufactured homes with greater than DOD 4 in the study area was one in 60.

Fig. 7 depicts the DODs within the seven geographic zones. Overall, there was not much difference in the degree of wind damage to manufactured homes across the study area. Only slightly more wind damage occurred to manufactured homes from Waveland to Gulfport, MS, where the strongest winds occurred.

Figure 6. Various DOD numbers to single-wide manufactured homes in Long Beach, MS after Hurricane Katrina. The red arrow indicates the direction of the flipped home. Manufactured homes not rated did not have significant roof damage.

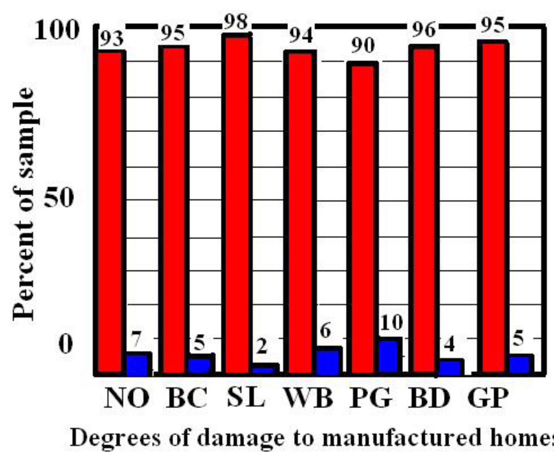

Figure 7. Normalized percentage of wind damage to manufactured homes in the seven geographic zones. Red bars indicate the percentage of DOD 2 or less whereas blue bars indicate the percentage of DOD 4 or more.

According to the EF scale, the three-second wind speed for DOD 2 manufactured homes is 33 m s^{-1} (74 mph) plus or minus about 20 percent in Exposure C. The same failure wind speed in Exposure B would equate to about a 38 m s^{-1} (85 mph) wind speed in Exposure C. Likewise, a 40 m s^{-1} (90 mph) wind speed that caused DOD 4 to a manufactured home in Exposure B would equate to a 46.5 m s^{-1} (104 mph) wind speed in Exposure C. Thus, wind speed-damage correlation to manufactured housing indicated that three-second wind gusts in the study area were primarily below 38 m s^{-1} (85 mph), but on occasion reached 46.5 m s^{-1} (104 mph) for Exposure C at 10 m (33 ft.) above the ground.

However, as pointed out earlier, an increase in DOD does not necessarily mean an increase in wind speed. Note the variation in damage to manufactured homes in Fig. 6. Some manufactured homes were destroyed adjacent to homes that had little damage. Such variations are better explained by flaws in the construction of the homes and poor attachment/anchoring rather than rapid increases/decreases in wind speed.

4.3 Residences

A total of 8119 residences were selected within the study area on NOAA aerial imagery. Residences were typically wood-framed structures located primarily in Exposure B (suburban) environments. Wind damage to residences usually begins with the removal of the roof covering especially on windward slopes, and at corners, eaves, and gable ends (DOD 2) where wind uplift forces are greatest. Exposure to higher wind velocities can lead to removal of most of the roof covering on the windward slopes (DOD 4). Other factors that affect the degree of damage are the type of roof covering, age, and attachment methods.

The authors' firm inspected 310 residences within the study area that had asphalt shingle roofs and noticed that residences with laminated shingle roofs outperformed those with three-tab shingle roofs. Significant damage involving the removal of more than 20 percent of the roof shingles (DOD 4) was found in 42 percent of residential roofs with three-tab shingles compared to only 22 percent of laminated shingles. The Roofing Industry Committee on Weather Issues (RICOWI, 2007) found similar results in their study of roof damage after Hurricane Katrina. Currently, local building codes in high wind zones require that roof shingles should be secured with six nails per shingle placed in the proper locations.

The roof structure must be able to support dead loads from the weight of the roof, live loads like people walking on the roof, and code-specified values of wind uplift. Inherent deficiencies in roof structures can include inadequate bracing, poor joinery, a lack of deck clips, and deck fasteners that missed the rafters. These deficiencies sometimes are discovered after the storm and erroneously attributed to high winds, low barometric pressure, etc. Van de Lindt et al. (2007) described how winds from Hurricane Katrina exploited such weak points in the roof structure. He noticed that seemingly small details, such as the lack of nails in hurricane clips, resulted in the removal of large sections of the roof with most walls remaining (DOD 6). Fig. 8 shows examples of DODs to residences in Hurricane Katrina.

Figure 8. Various DODs to residences in Hurricane Katrina: a) loss of a small amount of the roof covering (DOD 2), b) loss of a significant amount of roof covering and some decking (DOD 4), c) removal of large sections of the roof structure (DOD 6), and removal of the roof on a residence elevated on timber pilings (also DOD 6).

In this study, 7304 residences (90 percent) lost less than 20 percent of their roof coverings (DOD $\leq$ 2), while 815 residences (10 percent) lost most of their roof coverings and/or had some removal of the roof decking (DOD $\geq$ 4). The latter included three residences that had lost large sections of their roof structure (DOD 6). However, in each of the three instances, we suspect that windows or doors had failed allowing internal wind pressure to add additional uplift to the roof. Also, these residences were adjacent to homes that had much less damage. Fig. 9 shows an example of the variation in residential damage as observed on NOAA imagery in Long Beach, MS. In summary, the frequency of roofs being removed in the study area was approximately one residence per 2700.

Fig. 10 depicts the DODs to residences within the seven geographic zones. Overall, there was not much difference in the degree of wind damage to residences across the study area. Slightly more wind damage did occur from Waveland to Gulfport, MS as expected since this area experienced the strongest winds. However, the DODs to residences were just as great in eastern New Orleans, LA as in the hardest hit areas in Mississippi. We suspect that the exposure of residences to northerly winds across Lake Pontchartrain accounted for higher degree of wind damage to roofs there.

Figure 9. Various DOD numbers to residences in Long Beach, MS after Hurricane Katrina. Residences not rated did not have significant roof damage.

There was a rapid increase in building damage at low elevations near shorelines; however, this damage was attributed to the storm surge, not wind. In contrast, buildings and structures elevated above the storm surge survived with wind damage limited mostly to cladding items. It was found that the DOD to elevated structures along the coast was no more severe than farther inland.

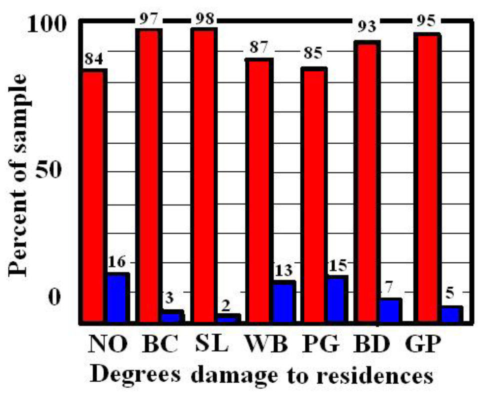

Figure 10. Normalized percentage of wind damage to residences for the seven geographic zones in the study area. Red bars are DOD 2 or less whereas blue bars are DOD 4 or more.

According to the EF scale, the three-second wind speed for DOD 2 residences is 35 m s^{-1} (79 mph) plus or minus about 20 percent in Exposure C. However, the same failure wind speed in Exposure B would equate to a 40.5 m s^{-1} (91 mph) wind in Exposure C. Likewise, the three-second wind speed for DOD 4 residences is 43 m s^{-1} (96 mph) plus or minus about 20 percent in Exposure C. The same wind speed in Exposure B would equate to about 49 m s^{-1} (110 mph) three-second gust in Exposure C. In summary, wind speed-damage correlation to residences indicated that the three-second wind gusts in the study area were primarily below 40.5 m s^{-1} (91 mph), and on occasion reached 49 m s^{-1} (110 mph) for Exposure C at 10 m (33 ft.) above the ground.

4.4 Metal Buildings

A total of 1212 metal buildings were selected within the study area on NOAA aerial imagery. These buildings were primarily warehouse type structures with low-pitched gable type roofs clad with metal panels. The metal buildings were located mostly in Exposure B (suburban) environments.

Ellifritt (1984) and Dean (1993) described various failures of metal building systems during Hurricanes Alicia and Andrew, respectively. Both studies indicated that failures of overhead doors were common (DOD 2). This allowed the increase in internal pressure which sometimes led to the loss of nearby roof and siding panels (DOD 3). They also noted that end bays were susceptible to wind damage due to lighter framing and lack of cross bracing. End bays pushed inward on the windward sides of buildings bent columns (DOD 4) and buckled purlins and girts (DOD 5). Fig. 11 shows various DODs to metal buildings in Hurricane Katrina.

Figure 11. Various DODs to metal buildings in Hurricane Katrina: a) the threshold of visible damage (DOD 1), b) failure of overhead doors (DOD 2), c) loss of metal roof and wall panels (DOD 3), and d) failure of the windward end bay leading to rotation of the columns (DOD 4) and buckling of roof purlins (DOD 5).

In this study, 1074 metal buildings (89 percent) had little (DOD 1) to no wind damage and 138 buildings (11percent) had lost some roof panels (DOD $\geq$ 3). Thus, the frequency of roofing being removed on metal buildings was about one building in nine. Six metal buildings exhibited structural failures from wind where column anchorage failed (DOD 4). However, in each instance, these buildings were adjacent to other metal buildings or canopies exhibiting little to no damage indicating that factors other than wind (i.e. poor column anchorage) probably contributed to the damage. Fig. 12 shows examples of metal building damage as observed on NOAA imagery taken within days after Hurricane Katrina in Gulfport, MS.

Figure 12. Various DOD numbers to metal buildings in Gulfport, MS after Hurricane Katrina. Buildings not rated did not have significant roof damage. Note the lack of damage to the adjacent gas station canopy.

Fig. 13 depicts the DODs to metal buildings within the seven geographic zones. Interestingly, more wind damage occurred to the older metal buildings at the Ingalls shipyard in Pascagoula, MS than in other areas. However, the greatest numbers of damaged metal buildings were in Gulfport, MS but due to the heavy concentration of undamaged buildings, the overall percentages of building damage averaged out.

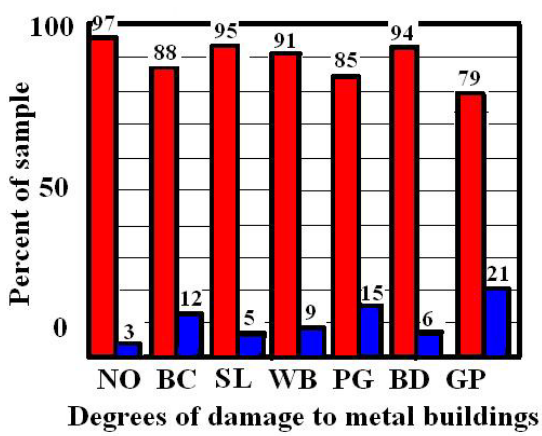

Figure 13. Normalized percentage of wind damage to metal buildings for the seven geographic zones in the study area. Red bars are DOD 2 or less whereas blue bars are DOD 3 or more.

According to the EF scale, the three-second wind speed for DOD 2 metal buildings is 40 m s^{-1} (89 mph) plus or minus about 20 percent in Exposure C. However, the same failure wind speed in Exposure B would equate to 46 m s^{-1} (102 mph) wind in Exposure C. Likewise, the three-second wind speed for DOD 3 metal buildings is 42.5 m s^{-1} (95 mph) plus or minus about 20 percent in Exposure C. The same wind speed in Exposure B would equate to about a 49 m s^{-1} (110 mph) three-second gust in Exposure C. In summary, wind speed-damage correlation to metal buildings would indicate that the three-second wind gusts in the study area were primarily below 46 m s^{-1} (102 mph), and on occasion reached 49 m s^{-1} (110 mph) for Exposure C at 10 m (33 ft.) above the ground.

5. COMPARISON TO OTHER STUDIES AND ACTUAL DATA

As mentioned earlier, NOAA (2005a), and FEMA (2006) had conducted damage assessments to estimate the wind fields during Hurricane Katrina. These studies utilized the concept of wind speed-damage correlation, actual wind measurements, as well as numerical model simulations and their results are presented in Table 1 by geographic location. In addition, actual wind recordings are also presented from Giammanco et al. (2006) and FCMP (2005).

TABLE 1
SUMMARY OF ESTIMATED AND ACTUAL WIND SPEEDS BY OTHERS IN HURRICANE KATRINA*

Location	NOAA	FEMA	Actual**
NO	40 (90)	47 (105)	-
BC	45 (100)	49 (110)	46 (102)
SL	47 (105)	51.5 (115)	44 (99)
WB	54 (120)	56 (125)	51 (113)
PG	54 (120)	58 (130)	-
BD	47 (105)	54 (120)	-
GP	45 (100)	49 (110)	42 (93)

*three second-gusts in m s^{-1} and mph at 10 m (33 ft.) in Exposure C
**TTU and FCMP measured speeds corrected for terrain roughness

Table 2 summarizes the results in this study for each building type. On average, wind speeds in the study area were found to be at or below about 41 m s^{-1} (92 mph) for the vast majority of structures, but on occasion reached 48 m s^{-1} (108 mph). The standard deviation for these wind speeds are approximately plus or minus 20 percent.

TABLE 2
ESTIMATED WIND SPEEDS
FOR FOUR BUILDING TYPES
IN THIS STUDY

Structure Type	Sample number	Lower wind speed*	Upper wind speed*
Canopies	96	40 (90)	47.5 (106)
M. Homes	1678	38 (85)	46.5 (104)
Residences	8119	40.5 (91)	49 (110)
Metal Bldgs	1212	46 (102)	49 (110)
Total/Avg.	11105	41 (92)	48 (108)

*three second-gusts in m s^{-1} and mph at 10 m (33 ft.) in Exposure C plus or minus 20 percent.

Overall, the wind values in this study agreed quite well with the maximum wind speeds estimated by NOAA and FEMA (Figs. 14 and 15). However, since most buildings were in Exposure B not C, and were well below 10 m (33 ft.), the vast majority of structures in hardest hit areas did not experience the strongest winds.

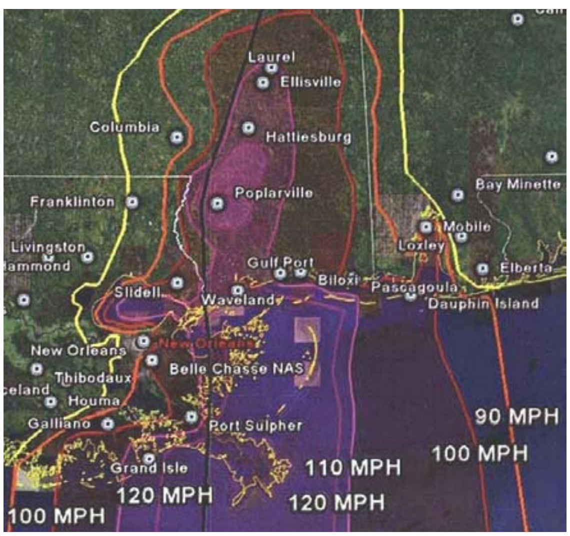

Figure 14. Estimated maximum wind gusts (in miles per hour) for Louisiana, Mississippi, and Alabama during Hurricane Katrina by NOAA (2005a).

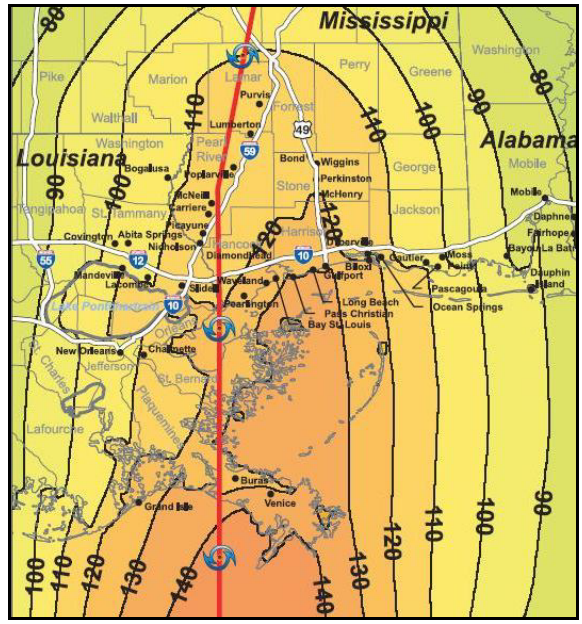

Figure 15. Estimated maximum three-second wind gusts (in miles per hour) for Louisiana, Mississippi, and Alabama for Hurricane Katrina at 10 m (33 ft.) above the ground in Exposure C by FEMA (2006).

6. TIME OF FAILURE WIND SPEED

As Bunting and Smith (1993) noted, the direction of failure of a building component, tree, or other object usually indicates direction of the wind at failure. For example, the canopy in Fig. 3d failed during an east wind (080 degrees) whereas damage to manufactured homes in Fig. 6 occurred during an east-southeast wind (110 degrees). Since wind directions change counterclockwise around hurricanes in the northern hemisphere, the approximate time of failure can be inferred by analyzing nearby wind data.

Table 3 lists wind data obtained from Keesler Air Force Base in Biloxi, MS as Hurricane Katrina approached the coast. These data ceased about one hour prior to the eye making landfall to the west, at the mouth of the Pearl River. From these data, it was deduced that the canopy in Fig. 3d failed around 6 a.m. local time whereas the mobile home damage occurred around 9 a.m. local time.

TABLE 3
WIND SPEED AND DIRECTION ON AUGUST 29, 2005 FOR KEESLER AIR FORCE BASE

Time (LDT)	Wind Speed ($m\ s^{-1}$)	(mph)	Direction (deg)
155	16 g 22	36 g 50	060
255	13 g 18	29 g 40	060
355	11 g 17	25 g 38	060
455	15 g 22	34 g 50	070
555	18 g 27	40 g 60	080
655	15 g 28	34 g 63	100
755	22 g 32	50 g 71	100
855	24 g 40	54 g 89	110

7. SUMMARY

This paper explored the concept of wind speed-damage correlation in Hurricane Katrina. Selected aerial images taken by NOAA within days of the storm were obtained for the Mississippi and Louisiana coast. Degrees of damage were determined by analyzing 11,105 structures on the aerial images utilizing damage descriptions in the EF-scale. Four building types were selected for analysis: gas station canopies, manufactured homes, residences, and metal buildings.

Failure wind speeds were determined using the EF-scale for each of the four structure types and corrected for exposure differences. On average, three-second gust wind speeds in the study area at 10 m (33 ft.) in Exposure C were found to be less than about 41 $m\ s^{-1}$ (92 mph) for the vast majority of structures, but on occasion reached 48 $m\ s^{-1}$ (108 mph). The standard deviation for these estimates was approximately plus or minus 20 percent. Such estimated wind velocities were below the 58 $m\ s^{-1}$ (130 mph) to 63 $m\ s^{-1}$ (140 mph) basic design wind design criteria as specified for this area in ASCE 7-05. The wind values derived in this study agreed quite well with the maximum wind speeds estimated by NOAA and FEMA.

Seven geographic areas were selected for detailed analysis from New Orleans, LA to Pascagoula, MS in order to determine if any regional variations existed in the degrees of damage to the four structure types. For the most part, wind damage was relatively uniform across the study area with only a slight increase in intensity noted east of the eye. The vast majority of the direct wind damage to structures was limited to cladding items such as the roof coverings. Only in rare instances did wind remove roof decking or portions of the roof structure. Such isolated spikes in the degrees of damage typically were surrounded by structures with far less damage. It was reasoned that spots of high DODs likely resulted from inherent deficiencies in the construction, anchoring, or attachments of the building rather than rapid increases/decreases in wind speed. No tornado damage tracks were found within the study area.

The EF scale remains an important tool to evaluate the degree of damage to a structure and to indirectly obtain a range of failure wind speeds. However, it does not take the place of an onsite survey by experienced personnel. Furthermore, the EF scale is a work in progress and will likely be updated as new information becomes available. There remain a number of issues with regard to the EF scale (see Doswell et al., 2006). One issue is the duration of the wind speed with regard to structure type. Lower wind speeds for longer durations can cause more damage to certain types of structures. However, such a correction would yield more conservative estimates of failure wind speeds than reached in this study.

Finally, it was shown that an approximate time when the structure cladding or component failed could be determined by analyzing wind direction records.

8. ACKNOWLEDGEMENTS

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