

Field Evaluation of Damage from Wind and Flooding

AUTHOR

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INTRODUCTION

Following Hurricane Katrina, engineers from around the country were called upon to evaluate commercial and residential structures along the Louisiana and Mississippi coasts to determine the extent of damage. Of paramount importance to many engineering clients was the separation of wind damage from flooding damage, and the engineer became a focal point for the resolution of many disputes between property owners and their insurance carriers. In these situations, it is essential for the engineering consultant to maintain their independence, objectivity, and adherence to good engineering principles. This requires an understanding of the forces produced by the storm, accurate evaluation of physical evidence available, and the proper interpretation of commonly available storm data. There has been a great deal of research performed regarding the effects of wind and water on structures, and an engineer should be able to rely upon industry-accepted tools like the Enhanced Fujita Scale to determine the relative force level between wind and water, even when the subject structure has been destroyed. Recent advances in computational weather analysis and weather radar can be helpful in some instances; however, the results of these tools should always be verified with real data, and they cannot replace detailed field inspection. When reporting the results of a wind/water analysis, it is important for the engineer to clearly communicate their conclusions and accurately represent the data that is quoted.

BASIC STORM PRINCIPLES

A hurricane produces a large disturbance in the ocean that is large enough to pile water in front of it as the storm system travels. As the ocean bottom slopes upward near shore, and as the storm approaches land, water pushed in front of the storm is squeezed into an increasingly small cross sectional area immediately in front of the storm path. The result is that water depth builds in front of the hurricane, and water is pushed ashore as flooding and wave wash commonly referred to as the storm surge. The surge is produced by the storm moving toward land, and it is a myth that the storm surge only occurs when/where wind is blowing onshore. As the surge depth increases in front of the hurricane, the force of the flowing water, erosion, and the effects of floating debris can be much more devastating than even the maximum winds of a hurricane. For comparison, consider that water is around 800 times more dense than air, and water moving at just 5 mph produces more pressure on a building than wind blowing at 140 MPH. Breaking waves and other effects can make the force of water in a storm surge enormous.

Hurricanes that threaten North America rotate counterclockwise, and the forward speed of the storm adds to rotational wind velocity in its northeast quadrant to create the maximum storm

winds (and storm surge). A typical hurricane is large enough to increase winds on land before the eye approaches shore, and as the hurricane moves toward land, wind velocities on land generally start small and increase to a maximum when the front eyewall reaches shore. Since the storm is the driving force behind the water surge, maximum flooding along the coast occurs almost simultaneously with the maximum wind in that the final surge height is pushed in with the hurricane eyewall. It should be noted, however, that hurricanes approaching shore can be influenced by environmental conditions and weather patterns over land, and they may weaken. Therefore, the storm intensity that drives the storm surge inland may not be completely representative of the corresponding wind intensity experienced on land. In the case of Hurricane Katrina, the storm weakened rapidly close to shore such that the storm surge was much more severe than the maximum winds recorded over land.

Category definitions comprising the Saffir-Simpson Hurricane Scale (discussed subsequently) include predictions of damage for hurricanes of various intensity, and definitions prepared for the National Oceanic and Atmospheric Administration (NOAA) indicate flooding that occurs hours in advance of landfall is typical of strong hurricanes (<http://www.nhc.noaa.gov/aboutsshs.shtml>). Tide gauges have shown repeatedly that flooding can reach destructive levels along the shoreline while the hurricane is still well offshore and the consequent wind forces on land are generally small. Certainly, wind forces that a hurricane imposes on a structure can be severe, but the relative strength of the surge forces and the build-up of floodwater in advance of landfall are important parameters for evaluating damage. Establishing the surge height as well as the timing of wind and water for a specific storm can become key supporting information from which an engineer determines the most likely cause of damage, especially when there is little structure left at a site for examination.

STORM DATA & REGIONAL SURVEYS

Hurricane strength is based solely on estimated windspeed. The strength is rated using the Saffir-Simpson scale of 1 to 5 for certain ranges of sustained windspeed. For example, a Category 1 storm is defined by sustained winds of one minute duration between 74 mph and 95 mph, and a Category 4 hurricane is defined by sustained windspeeds between 131 mph and 155 mph. While the strength ratings are very specific, the methods used to estimate the windspeeds of the actual storm are still approximate and generally large scale. Of particular note to an analyst of damage, hurricane winds are determined from dropsonde instruments released by aircraft as well as weather radar at thousands of feet above ground, and then this data is extrapolated to the reference height of 10 meters, making category strengths only estimates of ground-level winds, at best. Therefore, windspeed estimates from the National Hurricane Center may be greatly different than what is actually recorded on land. It should be remembered that the primary role of the NHC is forecasting and early warning, not establishing actual conditions at a specific site, and the engineer is cautioned against relying on television updates and contemporary news articles for data.

Within days of the storm, regional reports from the National Weather Service (NWS) often provide summaries of official weather recording stations and cooperative recording stations that are part of the Automated Surface Observation System (ASOS). These summaries can be found at the websites of the affected regional offices (<http://www.srh.noaa.gov/>), but early reports may not be completely annotated with unusual anemometer heights, documentation of incomplete

records, or reference to sustained or gust winds. Within weeks after the storm, the NWS is usually prompt in issuing a Post Storm Data Acquisition report, or PSDA, that may include preliminary measurements of the storm surge stillwater depth. These reports typically provide only the data immediately available to the NWS, but they are hard, factual data that focus on what happened near the ground. The National Hurricane Center uses the data collected by the NWS along with their account of the storm to prepare the Tropical Cyclone Report. From a damage assessment perspective, the two principal problems with the Tropical Cyclone Report are that it is usually not published for months after the storm, and the report can change or be updated even years later. The narrative may not agree completely with the appended data, so engineers should seek out storm data representative of the site. The PSDA report comes directly from the more field-oriented NWS, but it may include data from recording stations within the path of the storm that lost power or failed, resulting in incomplete records of wind near landfall.

Since the ASOS has often not captured the maximum winds at landfall, a number of independent researchers have made it their purpose to place anemometers in the path of major hurricanes threatening the United States coastline. Two very important sources of wind data outside the ASOS are the Florida Coastal Monitoring Program and the Texas Tech Wind Engineering Mobile Instrumented Tower Experiment. Both of these organizations place mobile instrumented towers in areas they hope will capture a complete record of storm winds, and the data collected by these two organizations have been invaluable to understanding the extent of structural damage sustained in an area. In the process of resolving disputes over damage, some have tried to dismiss the data from independent organizations as not being official, but the research towers are placed at standard reference height and with proper exposure in mind. There appears to be no credible reason to discount these data.

The storm surge can be established only by field measurements of the surge height determined from waterlines left on buildings and the debris line left by wave wash. The Federal Emergency Management Agency (FEMA) dispatches teams to survey the elevations of waterlines and debris, and they have published this data online as "flood recovery maps" since Hurricane Ivan in 2004. It is very important to note that the information provided in these maps is stillwater height. The effects of wave action and debris erosion will reach higher than the stillwater height, especially close to the shoreline. A theoretical wave moving inland may reach 0.78 times the depth of water, and it is common to assume wave heights of 0.50 times the depth of water. FEMA recovery maps therefore have carried a footnote stating the effects of flooding may extend as high as 50% of the depth of water over land.

The FEMA recovery maps are excellent sources of flood data, but it can be a long time before they are available (<http://www.fema.gov/hazard/flood/recoverydata/>). The final impact assessment report is usually issued months after the storm (e.g., FEMA 548 for Katrina in April 2005). As a result, various private and public researchers perform field evaluations and make storm data that they have collected available. In the aftermath of Hurricane Katrina, storm surveys and data compilations were generated by organizations like Haag Engineering Co., Texas Tech University, Mississippi State University, The American Plywood Association, National Institute for Standards and Technology, American Society of Civil Engineers, United States Geological Survey, U.S. Army Corps of Engineers, and others. Some of these studies were collaborative efforts funded by multiple organizations, but all of them included real data collected in the field. Once the FEMA maps are published, they generally become the standard reference, but these other sources may provide important information to supplement the FEMA data.

Surge heights determined in the coastal surveys establish only the maximum stillwater levels. To obtain information about how fast the water rose in advance of landfall, tide gauges must be consulted. NOAA tide gauge data can be accessed online (<http://tidesandcurrents.noaa.gov/>), and the sites are updated so frequently that one can almost obtain the data real-time as the storm moves inland. Like the ASOS wind data, however, these records are often incomplete in the area of greatest surge because the stations lose power or become inundated. In their attempts to assess damage, some have overlooked the tide gauge data because it was incomplete; however, it can be instructive to plot the wind and tide data up to the time the station loses power. The measured maximum stillwater measurements and the peak winds obtained from coastal surveys can then be used to extrapolate the plotted data. Gauges near the edges of the affected areas that are not inundated may also be used to establish the timing of the storm. In short, an engineer analyzing coastal damage should not ignore the information that partial records can provide in developing the timing of wind and water and establishing whether a storm has followed the pattern of flooding before strong winds.

Finally, weather radar and computer simulations are recent tools available to hurricane researchers, and these two sources of information were most often used after Hurricane Katrina when recorded data was unavailable or abandoned. In some instances, these sources were used to establish wind and flooding information without field verification of the assumptions used in their interpretation, and release of such information created unrealistic images of the storm in the minds of the users and the public. When used in conjunction with field inspection and correlated with real anemometer data, radar and computer simulations can be effective tools for establishing regional storm trends; however, they generally are not accurate enough to establish conditions at ground level for a specific site. Interpretation of weather radar and computer simulations require specialized training and experience, and they are not generally tools for the practicing field engineer, nor do they supplant the need for field surveys.

INTERPRETATION AND USE OF WIND DATA

The standards for collection of wind data and other recorded weather information are generally governed by the National Weather Service. The engineer should understand that official wind speeds are recorded at 10 meters (33 feet) above the ground in open, unobstructed terrain (Exposure C) or corrected to that elevation for comparison, unless otherwise noted. Further, official winds are typically reported as gusts, and unless a time duration is provided, they are probably peak gusts. It is essential for the engineer to note differences between the property being inspected and the conditions under which the reported windspeeds were recorded. Winds decrease closer to the ground surface and are slowed by sheltering ground features like urban terrain and trees. Comparisons made in SEAW/ATC-60, Commentary on Wind Code Provisions, suggest that the correction factor to account for Exposure B conditions (typical populated areas) and the reduction in height from 33 feet down to 15 feet is 0.57, a substantial reduction. Further, actual wind forces on a structure are a function of other parameters like orientation to the wind and architectural features. It is not acceptable for an engineer to simply conclude damage from a reported windspeed that is greater than typical design values. Site-specific inspection and evaluation is required to establish damage for specific properties.

It is also important for an engineer to accurately represent the wind data they reference. Hurricanes are rated with sustained winds, and weather records often provide peak gusts.

Engineering design was once based on the fastest mile wind, a computation, but is currently based on a 3-second gust. Narrative descriptions of storms like hurricanes may reference dropsonde data, radar, or another source that is not at standard reference height, and a damage analyst must be cognizant of the windspeeds they reference and report them accordingly. Many engineers mistakenly quoted extraordinary winds in their damage reports for Hurricane Katrina because they did not pay attention to the referenced height, exposure, gust vs. sustained wind, and windspeed location was recorded (e.g., a ship mast). Misunderstanding of their data led them, or others, to reach equally extraordinary opinions about wind damage.

Windspeed data can guide engineering analysis of damage, but it should not supplant site-specific observations nor be the defining factor that governs one's conclusions. Hurricane Katrina, for example, generally destroyed structures located within a few blocks of the shoreline where the surge was deep, and therefore, site specific information for damage determination was limited. In the absence of complete information, affected property owners often consulted atmospheric scientists who were unfamiliar with the engineering process and the development of forces on structures. Some of them used regional methods like weather radar and computer simulations to establish windspeeds for specific structures and then infer damage. In other instances, engineers accepted such windspeeds at face value without adequate consideration of the conditions in the field and then used them to infer damage. Whether the opinion was advanced by an engineer or someone else, field evaluation and aerial photography often demonstrated the inaccuracy of first starting with a windspeed and then using it to govern damage assessment. In some instances, opinions were so inaccurate that sustained winds in excess of 150 mph were stated for areas where structures had not even lost asphalt shingles from their roofs. Assumptions about windspeed should be verified at a site before making a damage determination by considering physical evidence of the actual forces generated on structures. When other forces are at play, like the storm surge, forces generated on structures from wind should be determined by inspection of structures still standing.

In the previous section, it was mentioned that computer simulation and weather radar were not substitutes for a storm surge survey or recorded wind and tide data. Unverified computer simulations were released after Hurricane Katrina that were quoted to be recorded NWS weather data or represented to be a substitute for missing data. In truth, no computer simulation can ever be regarded as data, and an engineer can avoid the pitfalls created by simulations if they simply field verify what the computer generated. Weather radar, on the other hand, is real data, but it is not commonly data that an engineer can interpret. Weather radar may be used after a hurricane to examine whether a localized wind event like a tornado might have affected a site. It is important for the civil engineer to know that radar data can show areas within the storm where circulating wind developed at some elevation above ground. A radar signature, however, does not confirm the presence of a tornado at ground level. Equally important, a radar signature does not confirm winds of sufficient strength to damage or destroy structures. Weather radar should not take precedence over field observations to the contrary.

A final note about tornadoes is in order. The issuance of a tornado warning by the NWS does not suggest that a tornado might have destroyed a structure before the hurricane or storm surge made landfall. The National Weather Service published a service assessment in June 2006 entitled, *Service Assessment, Hurricane Katrina, August 23-31, 2005*, that discussed tornado warnings. The assessment explains that the tornado warning system was used by the National Weather Service to alert the public to take shelter for the hurricane, and they are not

confirmations of tornadic activity. Once again, the engineer should establish what happened at a site through field inspection and not rely upon what weather warnings were issued.

INSPECTION & CONSIDERATION OF DAMAGE

Inspection and evaluation of damage begins with an understanding of how wind and flooding affect a building and then establishing a basic inspection criteria. In so doing, it becomes clear that understanding the type of damage, distribution, and typical patterns of damage is more important than knowing windspeeds, storm surge depth, surge timing, or water velocity. In effect, the condition of the structure, and/or nearby structures, will demonstrate the predominant cause of damage, and specific data is used to refine/interpret the information gathered from inspection. When considering damage, the engineer should recognize that both wind and water are fluids. They both swirl and create turbulent eddies. Therefore, one cannot state that twisted debris or twisted structural components are signatures of wind damage. Likewise, the soil anchoring trees may become soft due to flooding, and different trees may fall at different times during passage of the storm due to either wind or water forces. Several trees falling in different directions is not proof of a tornado.

Damage caused by surge, wave wash, and floating debris is readily apparent; it typically begins low on the structure and progressively worsens as the surge height increases. When wind piles water against a shoreline, or swells a bay, the force of the flowing water, wave action, and floating debris can become substantial as the water moves inland creating both water pressure and impact forces on surfaces at the water level. Foundation erosion and extreme structural damage at the wave level may occur and may result in collapse of the building. When severe damage occurs due to battering of the lower structure, the upper structure may remain intact, and wind susceptible features like the roof may be found largely undamaged. If the structure is not sufficiently anchored, the structure may become buoyant and then float inland with the surge where it is either deposited intact or broken apart. Structures that are sufficiently anchored may be broken apart onsite. Regardless, a distinguishing characteristic for structures that have primarily sustained flood damage is concentrated damage low on the structure in conjunction with the relatively intact condition of the upper structure.



FIGURE 1. Classic flood damage showing washthrough (left) and collapse with no shingle damage (right).

In contrast to water, wind affects the upper parts of the structure and claddings first. Redirection of the air flow results in varying magnitudes of negative and positive wind pressure over building surfaces. Since the flow of air cannot negotiate sharp discontinuities in building surfaces such as wall corners, eaves, roof ridges, and roof corners, the flow will separate from building surfaces resulting in outward-acting pressures. Failure or removal of cladding in these areas typically will occur first followed by greater cladding damage and then damage to weak or loosely fastened structural components. Substantial damage to the exterior cladding, and damage from debris impact, typically will precede damage to interior finishes from structural distortion. If structurally significant deformations have occurred in the structural frame, then displacement will be evident in the attached wallboard and finish materials. Wind damage is not hidden.

The effects of wind on buildings are well researched and well documented, and it has been the standard practice in wind engineering research for many years to confirm wind estimates through field verification. Following a wind event, the condition of structures are commonly compared to windspeed/damage correlations to evaluate wind conditions and check the accuracy of regional estimates for broad areas (e.g., weather radar, estimates from computer simulations, and sometimes even recorded weather data). One of the most recent windspeed/damage correlations comes from the Enhanced Fujita Scale published by the Wind Science and Engineering Center at Texas Tech University and available online. This study has been adopted by the National Weather Service for their post-storm inspections following tornadoes and other wind events and is an update of the original windspeed/damage correlation published by T. Theodore Fujita in 1971. Field verification of wind estimates is still the industry standard.

The Enhanced Fujita Scale was developed as a tool for estimating windspeeds, but the supporting documentation and degree of damage indicators included with the study provide a very good starting point for any field evaluation of wind damage. For the field engineer, the progression of damage represented by the degree of damage indicators offers an approximate guide to cause of damage and force levels created by the wind. For example, the progression of damage given for a house begins with loss of roof coverings/claddings and progresses sequentially through broken windows, loss of roof deck and weaker structural features, possible shifting of unanchored houses on their foundations, removal of large sections of roof structure (with most walls still standing), collapse of top floor exterior walls, collapse of most interior walls of the top story, wall collapse on the bottom floor, and finally total destruction. Engineers might argue about the wind force required to cause certain types of damage, but the sequence of damage has been demonstrated repeatedly in countless tests and storm studies.



FIGURE 2. Roof shingle and decking damage (left) and severe damage including walls (right).

Sequences of damage like those described for different types of buildings in the Texas Tech document may be especially important when there is little left of the building being inspected. Documentation of surrounding structures still standing (e.g., a structure elevated above the storm surge or beyond the debris line) can offer insight into the strength of wind forces that has affected an area and/or the limit of damage that the structure might have sustained from wind prior to it being destroyed by water. Recently, there have been suggestions that an engineer's conclusions about damage should be disregarded when they stem from estimating a windspeed because determining windspeed is the science of meteorology. However, the study of forces and the distribution of forces on a building is central to the field of structural engineering, and the civil engineer should be allowed to offer opinions about the probable wind forces at a site. The engineer may or may not be accepted as an expert on windspeed, but wind velocity is not necessary to draw comparative conclusions from site inspection and area structures.

The engineer might find several free documents listed in the references helpful in applying the concept of windspeed-damage correlation. While the discussions are often aimed at establishing a windspeed, they illustrate how various observations are weighed. In review of these sources, it should be noted that the original Fujita Scale was developed for both hurricanes and tornadoes, and the precepts are applicable to virtually any wind. With respect to wind-resistant construction, one might argue that coastal structures with wind resistant detailing are stronger than structures typically studied. However, the basic progression of damage is still germane regardless of the force level at which each step occurs. Structural details like rafter ties do not enhance the shingles, cladding, or windows. Structures in an area are usually built similarly, and empirical comparisons remain helpful no matter where the damage analysis is being performed.

SUMMARY

Armed with the tools previously described, an engineer can make a site inspection that establishes the condition of the structure and the distribution of damage to upper and lower parts of the building. Stillwater marks can be used to establish surge height, but the engineer is cautioned to distinguish between eroded drywall (height of wave action) from dirty lines on surfaces (stillwater height). Recording a surveying backsight on the ocean with the time of measurement may help approximate an actual elevation for the surge. If this information is not available or has been cleaned, storm surge surveys like that prepared by FEMA can be used. The force of moving water is very powerful, and structures can be severely damaged, floated out of position, or destroyed by only a few feet of water. Solid trends in debris patterns like the consistent bend of foundation anchors might be helpful in reconstructing a catastrophic damage sequence, but the engineer should realize the pattern of debris observed during inspection is the sum total of all storm influences. These influences start at the time waves first begin lapping at the foundation and include the surge in, wave wash and floodwater circulation as the storm passes, and then receding of the storm surge. Water eddies, swirls, and flows just like wind, and an engineer should be careful about reading too much into the final condition of the debris.

The comparative force of wind in an area can be established by considering the known progression of wind damage. The condition of roofing, decking, and roof structure at the site and/or at nearby properties can be used to establish whether winds were sufficient to cause the

severity of damage observed. Aerial photographs taken by NOAA after hurricanes and posted online (e.g., <http://ngs.woc.noaa.gov/katrina/>) can be particularly helpful in comparing area damage. Weather data, if available, can be used to guide the engineer's judgment about wind if exposure and height are adequately considered, but it should not be the governing information. One should note that strong winds may not fully bear on a structure, and conversely, weak structures may be more severely affected by comparatively weak winds. Consideration of how wind and water forces affect a building, the progression of damage for wind and flooding, and the actual distribution of damage at a specific site is the best way to ascertain wind and water damage. Whether weak or strong, the structure displays the evidence of what forces were most influential.

If the building still stands, damage below the stillwater and wave height is usually attributed to water while damage higher on the structure is attributed to wind. However, it should be stressed that flood damage results in a loss of support, and therefore, it can be the cause of damage above the waterline due to collapse. Wind, on the other hand, rarely causes damage low on a structure. If the water depth is deep or the building is destroyed, it may be necessary to rely more heavily on general parameters like the timing of the surge before wind and the comparative strength of wind and water forces. Greater forces are typically generated by water, and once a site floods, the structure is subjected to hours of repeated wave wash and battering until the wind passes. Since water moves inland ahead of the storm eye, the surge is a more likely cause of total building destruction. In Hurricane Katrina, for example, it was evident that structures were often completely destroyed within the surge zone, but structures elevated above the surge or just inland from the debris line displayed comparatively minor wind damage. Even in such fairly clear circumstances, however, it is prudent for the engineer to consider the amount of wind damage that might have occurred before water destroyed the building. Consideration of buildings still standing is the best method for exercising such judgment. An engineer can potentially lose credibility if they fail to consider all credible possibilities.

With the rise of internet sources for the repository and access of information, a wealth of information becomes available after a hurricane, some accurate and some not. The engineer must use caution to weigh the merits of this information. In the future, the engineer may be aided by two additional tools that saw some proprietary use after Hurricane Katrina. LIDAR, light detecting and ranging, coupled with mapping programs offers the prospect of easily determining elevations at a site very accurately for comparison with watermarks. A number of governmental agencies need such data, and reliable, up-to-date, information may soon be readily available to the public at the click of a mouse. Likewise, new image processing methods for aerial pictometry provide more information than just aerial photographs. Aerial pictometry produces oblique views of buildings from aerial photographs that show the front, rear, and sides of the building viewed. Such technology will allow an engineer to more accurately consider structures over a broad area when making comparative analyses of storm forces. Engineering analysis of the information, however, will still use the same procedures as described herein.

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