(presented at the 9th Annual Windstorm Insurance Conference, Jacksonville, Florida, February 2008)

DIFFERENTIATING BETWEEN WIND AND FLOOD DAMAGE IN HURRICANE KATRINA

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Abstract – *The determination of whether wind or flood was responsible for building damage in Hurricane Katrina is not just a matter of academic curiosity or to develop lessons learned for improving building codes. The payment of an estimated $55 billion in Katrina-related insurance claims depends in part on "forensic investigations" by Architects, Engineers and other investigators called upon to analyze failure, determine cause of loss and make recommendations concerning scope and cost of repairs. This paper outlines a methodology used by the author in the investigation of more than 1,000 Katrina related insurance claims where the cause of damage was a matter of dispute between an Insured and Insurer.*

Key Words – Forensic Engineering, Hurricane Damage, Hurricane Katrina, Wind Damage, Flood Damage, Enhanced Fujita Scale, Engineering Methodology.

BACKGROUND

The genesis of this paper is a presentation to the American Institute of Architects (AIA) in San Antonio, Texas on May 2, 2007 at a symposium titled "The Architect's Role in Disaster Preparedness and Assistance". The format of this paper generally follows the outline developed by the author for Hurricane Katrina reports, each of which is titled "Building Damage Assessment". An *assessment* is a systemic collection and analysis of data, documentation, evaluation and recommendations regarding the various portions of an existing building which are the subject of the investigation. The term *assessment* is derived from ASCE-11 *Structural Condition Assessment for Existing Buildings* although the term *Building Damage Assessment* is used as opposed to *Structural Condition Assessment* for two reasons. First, use of the word "damage" as opposed to "condition" underscores the need to determine cause. Secondly, many forensic investigators ignore or trivialize hurricane damage unless it involves a load-bearing member. Finally, the word "building" is used to emphasize that the project scope includes an investigation of roof coverings, cladding systems, architectural finishes and interior piecework and not just load-bearing structure.

TYPES OF DAMAGE

When some part of a building other than the foundation (*i.e.* its superstructure) survived Hurricane Katrina, the remaining portions of the building can be physical inspected. Occasionally, and particularly with the passage of time, these buildings were repaired making site investigation difficult unless documentation of the loss condition was adequate. However many buildings were demolished before the loss condition could be documented or totally destroyed by hurricane loads (wind, flood or a combination of the two) before a site investigation could be performed. This last category damage has become known in the parlance of Katrina work as "slab claims", regardless of whether the foundation system was slab-on-grade, masonry pier, timber pile or concrete column (See Figure 1).

In order to understand the cause of slab claim damage, ideally it is important to understand each of the following:

1) The building's resistance to both wind and flood and its condition prior to the storm.

2) The grade and floor elevation of the building.

3) The direction, current velocity and wave activity of the storm surge and the timeline of these events as they relate to building response.

4) The direction, sustained wind speed and gustiness of wind and the timeline of these events as they relate to building response.

5) A general appreciation of other damage in the immediate area.

6) A specific appreciation of what structural damage could have been caused by wind in the absence of flood.

7) A specific appreciation of what structural damage could have been caused by flood in the absence of wind.

The author may be reached at [illegible].

8) A specific appreciation of other events including vandalism, levee breaches, overtopping and flood-borne debris such as barges, trailers and containers.

9) A conclusion as to what structural damage was caused by wind prior to the application of damaging storm surge.

10) A conclusion as to what ensuing damage was caused by wind prior to the application of damaging storm surge.

METHODOLOGY

The general provisions of Standards such as ASCE-11 are "not intended to be inclusive or prescriptive…other methods and procedures are not only permissible, but are encouraged, so long as they are deemed reliable and sufficient comparisons are available with other recognized methods". There is no guarantee that by following the methods used in this paper that two forensic investigators always will arrive at the same conclusion. That will seem disappointing to those looking for a deterministic solution to what is inherently a probabilistic problem. The interpretation of facts, creation of viable hypotheses and application of the scientific method is inevitably tied to the professional experience and judgment of forensic investigators each separately distinguished by their personal training, experience, and familiarity with theory, research literature and available data. To this one should add the availability of time and cost resources, the investigator's commitment to excellence and even one's philosophical approach to epistemology which weighs heavily in the debate between the realism of physical measurement and the idealism of computer modeling. The exploration of subjective probability and engineering judgment is well covered by Vick (2002).

MULTIDISCLINARY APPROACH

A complete investigation of Hurricane Katrina relevant to the analysis of building damage requires familiarity with scientific disciplines and practical knowledge (including terrain analysis, flood plain management, landscape design, meteorology, computer modeling and coastal hydrology) none of which are alien to the traditional practice of design but all of which require a forensic Architect or Engineer to expand his traditional knowledge base to include a working knowledge of these interfaces. A design professional tasked with writing a Katrina report should not plead ignorance of the natural phenomena which effect hurricane loads and limit states. The Civil Engineering community in particular has spoken out on this issue:

> *In the absence of [information on extreme wind speeds] the quality of design and construction of structures that perform inadequately in high winds cannot be properly assessed, and the development of design criteria allowing structures to be designed safely and economically is impeded. …Civil Engineers are prime users of this information and should speak strongly to policy makers in public and private sectors to assure its cost-effective acquisition and dissemination (ASCE, 2000).*

PEER REVIEW

Outside of academia what passes for "peer review" often is nothing more than a "supervisor's chop". The process of peer review in refereed journals itself may be flawed (Doswell, 2001). Where possible and time permitting, each slab claim analysis should be peer reviewed to assist the determination of facts and opinions leading to a firm conclusion as to the cause of damage. Because of the paucity of data, the final determination of cause can only be articulated as "the most likely scenario" based on all known facts subject to professional judgment and expert opinion.

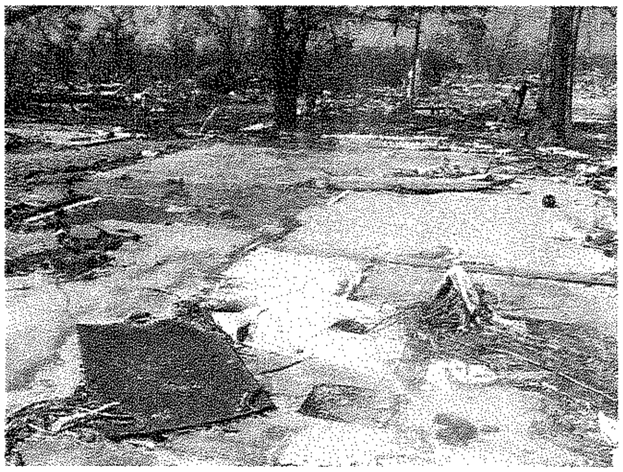

Figure 1. Post-Katrina remains of a residence on the Mississippi Coast.

SYNOPSIS OF WEATHER CONDITIONS

It is important not only to confirm one's hypothesis but also to deconfirm opposing hypotheses. If after the initial investigation one's hypothesis is "wind destroyed the building", the most conclusive analysis will show not only how wind destroyed the building but why the effect of storm surge and flood water was less consequential. This not always is the case because often the conclusion reached is not only that "wind destroyed the building before the arrival of storm surge" but "storm surge would have destroyed the building in the absence of damaging wind". When such a conclusion is reached, the timing of wind and flood is crucial. Absent sufficient groundtruth and/or reliable eyewitness accounts, the most important tool available to the Investigator is a timeline of wind and flood showing wind speed and surge height applicable to the specific location. Often a timeline analysis includes other important information such the direction of wind.

the direction and current velocity of storm surge and the height of waves.

WIND AND FLOOD TIMELINES

One of the earliest timelines made available after Katrina was produced by WorldWinds, Inc. (operating at Stennis Space Center, Mississippi) using ADCIRC (ADvance CIRCulation), a finite element hydrodynamic model with applicability for floodplains. The Stennis hindcast used operational Hwinds data from the Atlantic Oceanography and Meteorology Lab (AOML) to model Katrina storm surge height at eight landfall locations on the Mississippi coast between Waveland and Ocean Springs. Figure 2 shows the Stennis hindcast for Waveland City Hall.

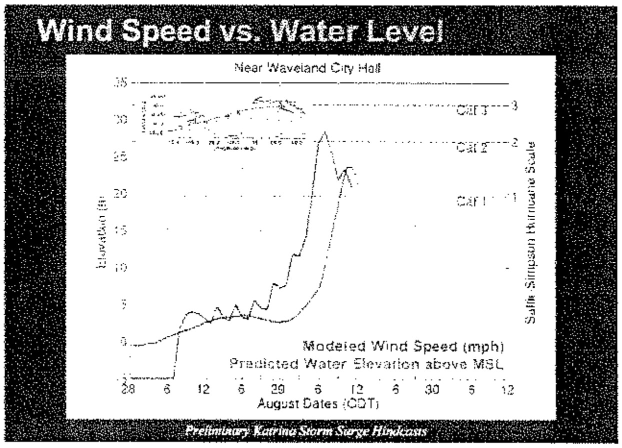

Figure 2. Stennis Hindcast for Waveland, MS.

The timely release of the Stennis hindcasts into public domain shortly after Katrina created a popular "buzz" concerning the timing of wind and flood. However, the Stennis hindcasts were problematic for several reasons. The operational Hwind data which had served to drive the hindcast model was later modified, lowering one-minute sustained wind speed at most locations. The preliminary model did not consider inland flooding; consequentially modeled surge height along the coast was inflated. The timeline displayed sustained wind speed while ignoring three-second wind gust activity.

Despite these problems, even a crude understanding that peak wind speed crossed a particular location before maximum storm surge allowed investigators to entertain damage scenarios other than total destruction by storm surge. The next generation of timelines by WorldWinds and other consulting firms produced more accurate flood models based on revised wind data and consideration for floodplain inundation. These products often included a comparison of storm surge height and wind gust speed. Figure 3 shows a hindcast model for Pass Christian, MS produced by Accuweather.

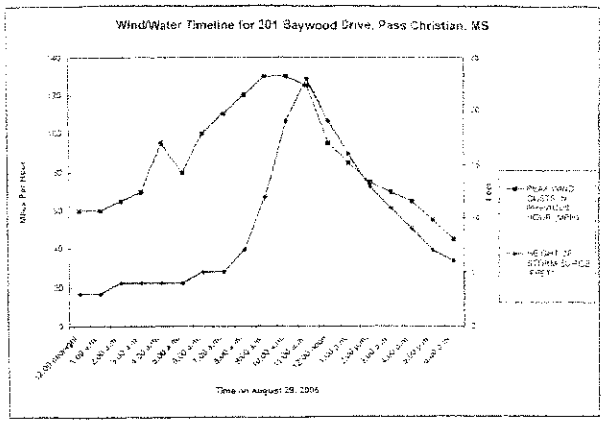

Figure 3. Accuweather Hindcast for Pass Christian, MS.

PROBLEMS WITH DATA COLLECTION

The Investigator must be familiar with data collection techniques in order to establish a level of confidence for the data to be used in the analysis. An Investigator may cite the NWS Tropical Cyclone Report in order to establish that the maximum wind gust speed measured at the New Orleans Lakefront Airport was 86.25 mph at 0653 CDT. But the citation is incomplete unless the Investigator is aware that the airport anemometer failed before maximum wind crossed the area.

Many Katrina investigators point to the lack of NWS reported tornados in coastal Mississippi as proof complete that no tornados were spawned by Katrina wind bands. This allegation ignores established NWS rules for reporting a tornado which includes confirmation by a ground survey team. After Katrina, the New Orleans NWS Office was too busy relocating to Baton Rouge, LA to dispatch survey teams to Mississippi. Figure 4 shows mesocyclone signatures detected by Slidell, LA Doppler radar between 0330 CDT and 0900 CDT. This algorithm does not detect mesocyclones with a low cloud base, so more mesocyclones are likely. NWS Slidell, LA lost valuable information due to the electronic overwriting of collected data after 0900 CDT. NWS Mobile, AL continued to operate after the Slidell instrumentation failure, but information collected by NWS Mobile was hampered by the earth's curvature.

SUSTAINED AND 3-SECOND GUST WIND

Design wind speeds given by ASCE 7 (and used in model building codes) are 3-second gust speeds, not the sustained wind speeds associated with the Saffir-Simpson Hurricane Scale. "Sustained wind" is wind speed determined by averaging observed values over a given period of time. The National Hurricane Center (NHC) uses a 1 min averaging time for reporting sustained wind observed or estimated to have occurred at a standard meteorological height of 33 feet in open exposure. (The

Automated Surface Observation System [ASOS] used to collect airport data uses a slightly lower 2 min averaging time [HRD, 2006]. The difference is generally ignored.) Trees, buildings and other obstacles can cause large differences in the wind experienced at observation stations (Powell et al., 1996). For example, the peak 3-second wind gust speed of 105.4 mph measured by a Texas Tech (TTU) wind tower at Stennis International Airport is often sited as the highest measured wind gust for coastal Mississippi although it does not represent an open exposure. Critics pointed out that a dropsonde falling near Stennis Airport reported 83 mph wind at 45.9 feet at 0600 CDT which when converted to 33 feet produced a peak standardized wind speed of 79 mph compared to TTU data showing 40-50 mph at 33 feet, suggesting flow obstruction upwind of the TTU tower (Fitzpatrick, 2007). In fact, the raw wind speed of 105.4 mph when modified for the calculated roughness length of the wind fetch produced a peak standardized wind speed value of 112.8 mph (Giammanco, et. al., 2007).

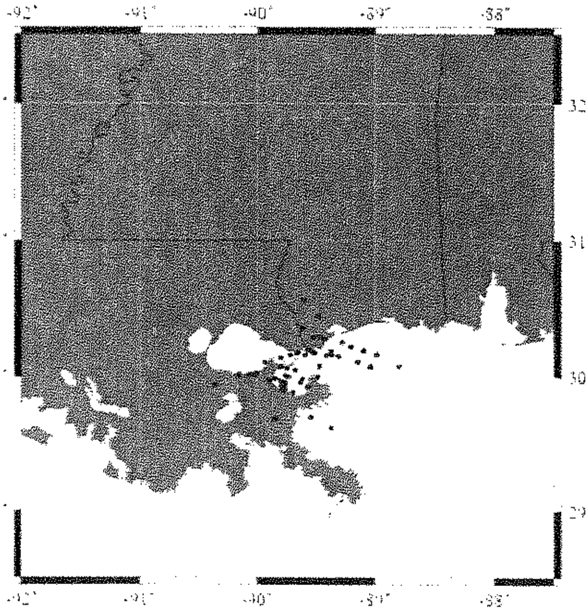

Figure 4. Possible tornados based on mesocyclone markers detected by NWS Slidell, LA radar.

Many Katrina reports ignore 3-second gusts. The lack of reported wind gust data is no reason for forensic engineers to ignore their effect. Generally peak wind gusts are estimated 30% higher than sustained wind speeds (HRD, 2006). Comparing measured gust factors at various airports during ten hurricanes and one tropical storm, Hsu (2003a) found wind gusts 42% higher than sustained wind speeds. Krayer and Marshall (1992) propose a 65% factor. Vickery and Skerlj (2005) add that anomalous gusts caused by "small-scale convective gust transferring higher wind speeds from aloft to the surface" can account for surface winds 100% higher than sustained wind speeds, adding "these large gusts can and do occasionally occur, and may be responsible for small regions of higher than average damage within a storm".

WIND GUST MAPS

Shortly after the release of the Stennis hindcasts, NOAA published a wind gust map (Figure 5) on its Katrina website (www.ncddc.noaa.gov/Katrina/WindSpeedMap/). The map depicted peak wind gust speeds compiled by FEMA and mapped by Forest One, a private mapping company. NOAA commentary accompanying the map stated:

> *The wind speed values depicted on this map represent FEMA's best estimation immediately following Katrina and were derived from the Atlantic Oceanography and Meteorology Lab Hwinds models and in situ observations. These models are preliminary and experimental. Later analysis found model wind values were lower than the actual values recorded from official wind stations.*

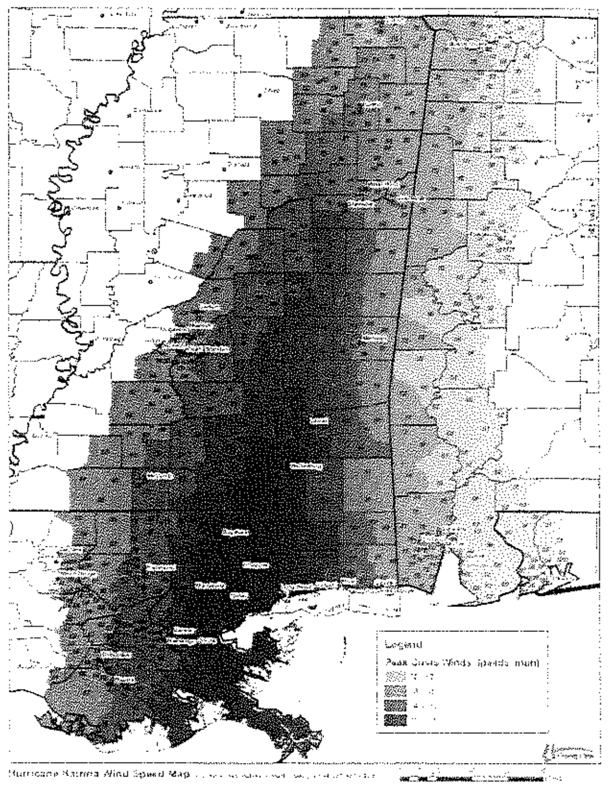

Figure 5: The Hurricane Katrina Wind Speed Map aka as the "Forest One" map.

Although wind speeds displayed on the map are not site specific, the data is useful to estimate peak gust wind speed which crossed a small scale area. The Hwind data provided to Forest One was based on the early operational run which eventually was modified by further analysis. The revised Hwind data along with "measured gusts, ground surveys and estimates from aerial imagery" were incorporated by NOAA into a revised wind gust analysis (www.ncddc.noaa.gov/Katrina-2005/WindSpeedMap/).

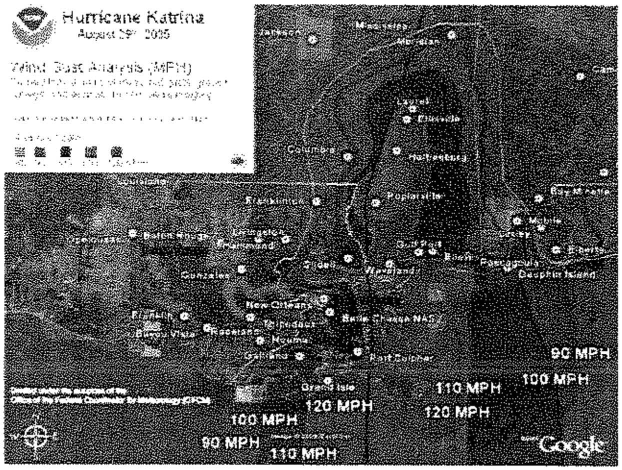

Figure 6: NOAA Wind Gust Analysis map.

The NOAA commentary which accompanies the revised wind gust map states:

NOAA conducted ground and aerial damage surveys in parts of southeast Louisiana, Mississippi and Alabama. A blend of these surveys along with recorded gust values, and the over-water portion of NOAA's Hurricane Research Division wind analysis, was utilized to produce this wind gust analysis product. The analysis depicts 3 to 5 second wind gust values with the caveat that local effects can easily result in a +/- 15% variability in gust values at any one location.

ELEMENTS OF THE FLOOD INVESTIGATION

Many Katrina reports assert flood as the cause of damage but provide no information other than data showing that storm surge reached a particular height. This assertion ignores the possibility of wind damage occurring before the building was attacked by storm surge, usually because the Investigator does not consider the timing of wind and flood as separate events. In order to determine the actual damage caused by flood, it is necessary to determine (1) the actual damage caused by wind prior to flood and (2) the effect of flood load on the already damaged structure. In the course of analysis, it is also helpful to understand the effect of flood load on the building assuming it was not damaged by wind prior to flood. With due consideration for eyewitness accounts of the flood event and flood damage to buildings, the investigation should consider flood not only as a single event but analytically by its components: hydrostatic load, hydrodynamic load, debris impact and wave action.

HYDROSTATIC FLOOD LOAD

Hydrostatic loads occur when standing or slowly moving water comes into contact with a building or structure. It is assumed that "lateral hydrostatic forces are generally not sufficient to cause deflection or displacement of a building or building component unless there is a substantial difference in water elevation on opposite sides of the building or component" (FEMA 2005, p. 11-11). During Katrina, the slow rise of storm surge allowed water to rise inside most buildings almost as quickly as it rose outside. As a result of this pressure equalization, few walls were damaged by hydrostatic load. A dramatic illustration of this effect is St. Bernard Parish, Louisiana where – except for areas near levee breaches or subject to wind-induced waves – hydrostatic load was the only flood load component. Although most properties in St. Bernard were inundated with 8-9 feet of water, few if any homes collapsed due to flood load.

Since hydrostatic load can be applied vertically underneath homes which are not constructed on concrete slab foundations, it is important to consider the building's resistance to vertical hydrostatic flood load (buoyancy). However, if a building lacks strapping or other features designed to resist buoyancy, then likewise the building is poorly constructed to resist lateral, overturning and uplift effects of wind. Whatever resistance factor is considered for flood must be considered for wind along with a determination as to proper sequence of load application.

HYDRODYNAMIC FLOOD LOAD

Water flowing around a building or structure imposes additional loads including frontal impact load, drag effect on the building sides and suction on the downstream side. Hydrodynamic load is a factor of current velocity, building geometry and angle of attack. ASCE 7 considers water moving at velocities less than 5 ft/sec as hydrostatic load. Where water velocities do not exceed 10 ft/s, ASCE 7 allows the dynamic effects of moving water to be converted into equivalent hydrostatic loads. Greater than 10 ft/s, a detailed analysis utilizing concepts of fluid mechanics is employed.

Although virtually every Katrina report asserting flood as the cause of damage invoked the term "hydrodynamic load", rarely did these reports estimate the velocity of storm surge crossing the property lot. Even if the USGS river gauges had survived Katrina, they were not designed to record current velocity. The depth and shape of scour holes at coastal structures offers some assistance in determining recent current velocity (Sumer & Fredsoe, 2002). Little empirical data is available concerning the survivability of buildings due to hurricane storm surge. A Japanese tsunami study suggests survivability of wood-framed structures to a current velocity of 13.78 f/s and masonry building to 33.47 f/s (Matsutomi and Shuto, 1994).

Throughout 2006 only a handful of ADCIRC studies provided current velocity data, including an LSU Hurricane Center model showing 2.0 f/s current velocity in Lake Borgne near St. Bernard Parish (Mashriqui, 2006) and the IPET report concentrating on Lake Pontchartrain (Corps of Engineers, 2006). Hindcast data for the Mississippi coast including current velocity and direction has been compiled by at least one academic researcher but to date the entire data set has not been released for public scrutiny. Portions which have been released indicate a maximum current velocity about 10 ft/s in the Back Bay of Biloxi and 12 ft/s in St. Louis Bay near Diamondhead, MS. Lacking measured or modeled data, surface current can be approximated using the "3% rule", i.e. the surface current is approximately 3% of the wind speed (Hsu, 2003b).

Figure 7: Breick-veneered house in Chalmette, LA after recession of 8-9 feet of flood water.

WAVE ACTION

Wave loads are a peculiar type of hydrodynamic loads. There are a variety of wave forces including non-breaking waves (usually computed as hydrostatic forces against walls and hydrodynamic forces against piles), breaking waves, broken waves (similar to hydrodynamic forces) and uplift (caused by run-up, deflection or peaking under horizontal surfaces). Wave height and wave period are important considerations in determining wave load. It is always prudent to design for the breaking wave because it produces the most severe load. But whether or not a building encountered breaking waves depends on environmental factors (including wind direction, shoaling, refraction, fetch distance, bottom roughness, rigid vegetation and height-limited waves) which cannot be ignored in a forensic analysis.

Figures 8 and 9 illustrate the need to carefully consider anecdotal evidence particularly when the information is found on the Internet. Figure 8 purportedly shows waves attacking the Mississippi coast at Bay St. Louis, MS. Figure 9 shows the original image as depicting water from Lake Borgne overtopping the levee on the north shore of St. Bernard Parish.

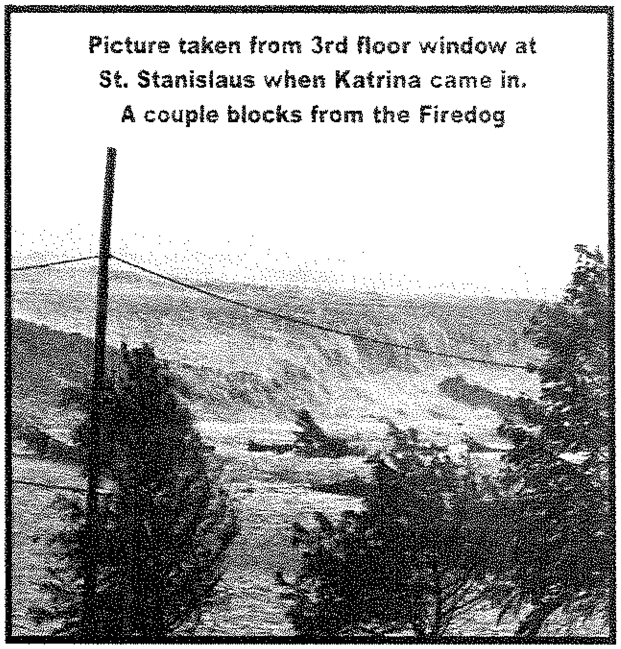

Figure 8: Blog photo purporting to show coast of Bay St. Louis during Hurricane Katrina.

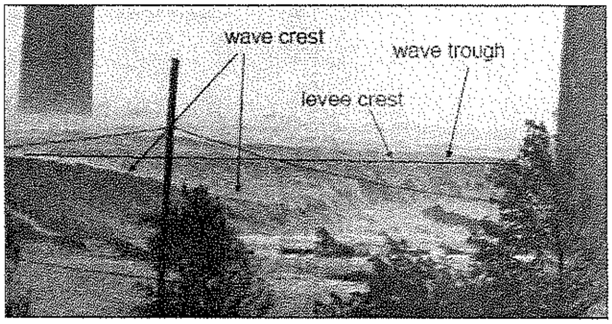

Figure 9: Original photo later reproduced in the Army Corps of Engineers IPET Report.

Wave height is an important consideration not only to determine load factors but also to understand the height of surge against buildings and structures. The height of "significant waves" equal to the average of the highest one-third of all waves is important. Researchers have found from the analysis of wave records that significant height is nearly equal to the height reported from visual observations (Bretschneider, 1965; Holthuijsen, 2007).

Nearshore and onshore significant wave heights modeled by programs such as SWAN and STWAVE tended to be higher than observations reported by eyewitnesses, possibly because wave propagation and generation significantly altered by surge in shallow wetlands and rougher vegetation cover onshore were not accounted for in the models.

FLOOD DEBRIS IMPACT

Impact load from flood debris must be considered as well as impact load from wind debris. An understanding of flood debris impact load must include the type and weight of debris, surface current velocity, required draft for large objects such as containers and paper rolls, and time of flood versus wind. Figure 10 shows a trailer hitch which travelled from the Gulfport Port Facility.

Figure 10: Flood debris in Gulfport, MS

DESKTOP ANALYSIS

A desktop comparison of the building condition before and after Katrina is conducted before the site investigation occurs. Ideally the following list of documents is reviewed. In reality not all of these documents can be assembled:

1) Phone interview with homeowner.

2) Satellite photos before and after Katrina.

3) High and low oblique aerial photography.

4) Street maps, topographic maps, flood inundation maps, Flood Insurance Rate Maps (FIRM) and Flood Insurance Studies (FIS).

5) Appraisals, Tax Assessor records and photographs.

6) Engineering reports, construction plans, Certificates of Elevation, Letters of Determination and applicable building codes.

Figures 11 and 12 compare pre- and post-Katrina views of an elevated wood-framed residence in Diamondhead, MS. The construction type, building geometry and use of materials are clearly defined. Vertical dimensions can be estimated by counting the stair treads. Figures 13 and 14 compare pre- and post-Katrina views of Henderson Point in Pass Christian, MS.

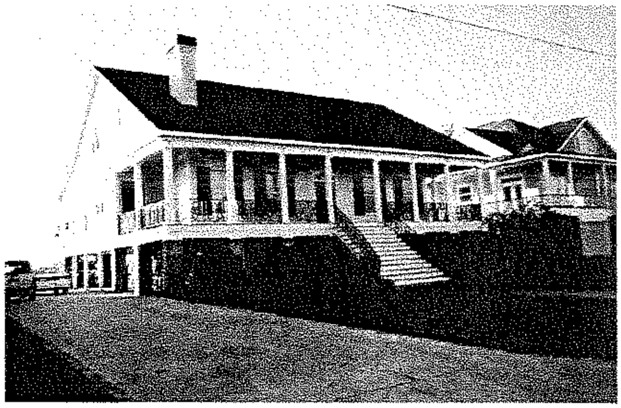

Figure 11: Diamondhead residence before Katrina.

Figure 12: Diamondhead residence after Katrina.

FIELD INVESTIGATION

Field investigation is essential except for the rare case where the site is inaccessible, such as due to resale and lack of cooperation by the new owner. The investigation should take into account "not only the structural damage to the facilities but also…proper consideration to the surroundings, including the character of the debris fields and the response of the vegetation and trees to the wind and/or storm surge forces" (Kilkari, 2007). Ground indicators which assist the investigation include high water marks, wind debris fields, flotsam lines, and building damage such as bent anchor bolts and plumbing pipes.

Figure 13: Henderson Point, MS before Katrina.

Figure 14: Henderson Point, MS after Katrina

HIGH WATER MARKS

The highest quality water marks are stillwater marks (mudlines and debris marks) which do not show evidence of wave run-up or climb. In areas near the coastline it is difficult to find surviving structures let alone stillwater marks inside or outside of structures. Field data published by FEMA is available. For a complete methodology see http://www.fema.gov/hazard/flood/recoverydata/katrina/katrina_ms_methods.shtm#methodology01

ANCHOR BOLTS AND PLUMBING PIPES

Often the only building components remaining at a slab-on-grade foundation are anchor bolts embedded in the concrete slab, nails protruding from the bottom plates of exterior walls and plumbing pipes made of PVC or copper. Analysis must proceed with caution particularly if debris has been removed by wildcats or bulldozers. Figure 15 shows a fractured PVC pipe pointing northwest. Generally the configuration of bent metal and fractured plastic building parts indicate the direction of applied lateral force from which it can be determined whether the walls collapsed due to wind or storm surge. However variations in the direction of wind attack and strength of foundation anchorage can cause exterior walls to collapse accordingly. Marshall (1993) reminds us that "objects twist according to their own properties". A bent nail protruding from a bottom plate may not show the true direction of externally applied force because cause may be overdetermined: wind or flood can produce similar effects depending on the angle of attack and anchor point of the wall system around which the structure rotates.

WIND DEBRIS FIELDS

The mapping of wind debris fallout helps an investigator determine where building components and contents from inside the building traveled due to wind. Snow et. al. (1995) established a methodology for mapping fallout after tornadic windstorms in Oklahoma and Texas. Since the lofting dynamics of tornados embedded in Gulf Coast hurricanes has not been studied, Snow's study is useful only to reach a general understanding that extreme wind can carry objects varying in weight and size a considerable distance. If building components and contents items from inside the building are found at considerable distance from the property lot, mapping their location can help determine if the items were transported by wind or flood.

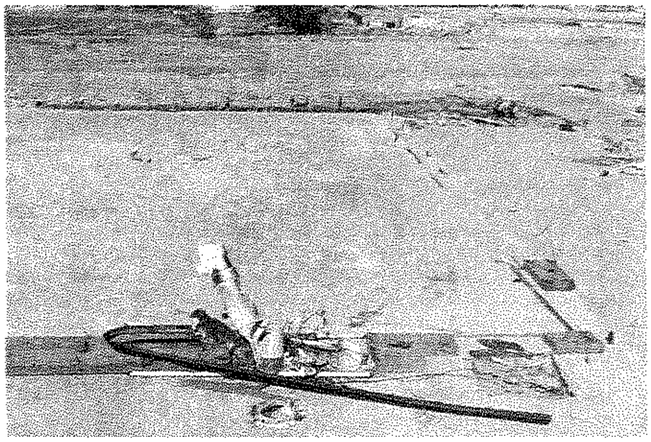

Figure 15: Plumbing pipe bent in direction of removed wall.

The search for wind debris after Hurricane Katrina was complicated by the removal and relocation of items by property owners, clean-up crews and unauthorized individuals. Items transported by wind may have been relocated by storm surge. Building components and contents items from a particular building have been found 100-800 feet downwind of building locations (Figure 16). Property owners have successfully identified items such as custom roof tiles, baseball trophies, anniversary plates, initialed luggage and dental patient X-rays.

FLOTSAM LINES

During Katrina, the advance of storm surge left a line of flood debris which is clearly seen in most aerial and satellite photographs published by private firms and government agencies. Uncritical analysis of large-scale panoramas conveys the impression that a tsunami-like wall of water "bulldozed" everything including entire building structures inland. Close physical inspection of flood debris lines reveals a tangled mass of flotsam consisting of dimensional lumber, roof sheathing, building siding and buoyant items such as refrigerators, and ice chests. It is unclear from the physical evidence whether the buildings were undamaged by wind before storm surge transported the construction debris inland. It also is unclear how much of the building debris resulted from wind before the arrival of storm surge.

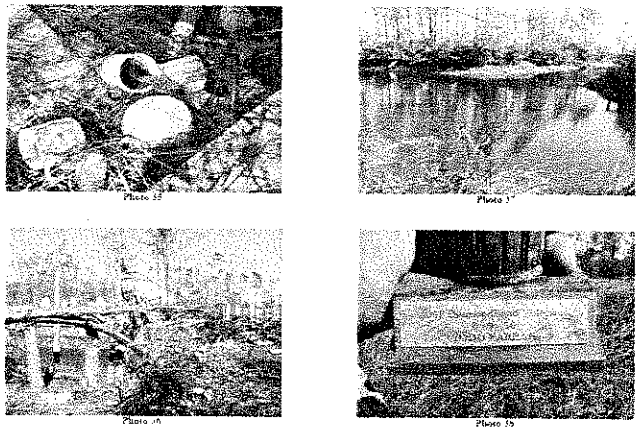

Figure 16: Items found 100-800 feet from a residence in Diamondhead, MS.

TREES AND OTHER VEGETATION

Knowledge of trees and other vegetation is useful to determine the direction and speed of wind and flood. Damage patterns to large groups of trees (Figure 17) strongly suggest tornado or microburst activity. For factors influencing treefall risk in windstorms see Francis (2000) and Peterson (2006).

A simple rule is to look for a fallen tree (preferably one which remains rooted to the ground to exclude the possibility it was transported by storm surge) across a concrete slab. In such case, obviously the building structure was removed by some hurricane force before the tree fell. The direction of treefall indicates the direction of wind at the time of failure which can be established from meteorological records. If the treefall occurred before the arrival of damaging storm surge, a conclusion can be reached that wind removed the building structure.

The rule-of-thumb that removed bark indicates damage caused by flood debris should be used with caution. Wind stress also can remove bark. Figure 18 shows bark removed from a tree 500 feet north of the further advance of storm surge in Gulfport, MS.

Figure 17: Tornado or downburst activity in Pass Christian, MS.

Figure 18: Bark removed from tree 500 feet north of flotsam line in Gulfport, MS.

THE ENHANCED FUJITA SCALE

The Enhanced Fujita (EF) Scale was developed by the Wind Science and Engineering Center at Texas Tech University (TTU) under a cooperative agreement award with the National Institute of Standards and Technology (E-F Scale, 2006). Starting February 2007 the National Weather Service (NWS) initiated EF-Scale training for all personnel involved in ground surveys of tornado damage. Recognizing its importance as an analytical tool, the author has employed the EF-Scale in about 1,000 Katrina slab investigations since 2005. Other investigators using or endorsing the EF-Scale for hurricane analysis include Norman (2007) and Rogers (forthcoming).

USING THE EF-SCALE FOR TORNADOS

The EF-Scale uses 18 damage indicators easily identified by ground survey teams including buildings (*e.g.* one or two-story residences, elementary schools and metal building systems), structures (*e.g.* transmission line towers and free-standing light poles) and vegetative features (*e.g.* hardwoods and softwood trees,. Each damage indicator is assigned a series of descriptive failure modes called "DODs" for "degree of damage". Figure 19 shows the DODs associated with one and two-story residences. Generally the DODs are listed sequentially in terms of progressive failure. DOD5 in Figure 19 ("entire house shifts off foundation") is contingent on the strength of foundation connections. The EF-Scale is not meant as a stand-alone tool divorced from professional judgment, which must be employed not only to determine the degree of damage but also the determination of pre-storm building resistance in terms of "expected", "upper bound" and "lower bound" conditions:

The range of wind speed defined by the upper and lower bound wind speeds accounts for circumstances that cause the actual wind speed associated with the damage to deviate from the expected value. The expected value of wind speed to cause a given DOD is based on a set of "normal" conditions: No glaring weak links, traditional construction quality, appropriate building materials, compliance with local building code and continuous maintenance. A weak link is a discontinuity in the load path, which runs from the building surface through the structural system to the foundation. Inadequate nailing of wood roof decking, marginal anchoring of roof structure to top of wall, discontinuity in the connection between first and second floor, use of cut nails instead of anchor bolts to attach sill plate to foundation are examples of load path discontinuities. Traditional construction quality means construction practices are considered acceptable in a majority of similar [one and two-story residences] in an area. Appropriate building materials are suitable for their specific use and for the environmental of the area. Normal maintenance implies that the facility has not run down or deteriorated over time. (E-F Scale, 2006).

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

Figure 19: One- and Two-Story Residential Dwelling DOD from the E-F Scale, Revision 2.

Figure 20 shows the condition of a residential structure classified by the EF-Scale as DOD 4 ("uplift of roof deck and loss of significant roof covering"), which for a normally constructed building most likely would occur as the result of a 3-second gust at 97 mph. Figure 21 shows the condition of a residence classified as DOD 7 ("top floor exterior walls collapsed") which most likely would occur as the result of a 3-second gust at 132 mph.

USING THE EF-SCALE FOR HURRICANES

Generally there is no need to consider the EF-Scale when enough of a building survived Hurricane Katrina for more traditional analysis. However, in slab claims the lack of superstructure frustrates the determination of cause. In order to use the EF-Scale for slab claim analysis, the following information minimally is required:

1) The condition of the building prior to Katrina.

2) The elevation of the building's floor levels.

3) A timeline of wind and flood including current velocity and height and period of wave activity.

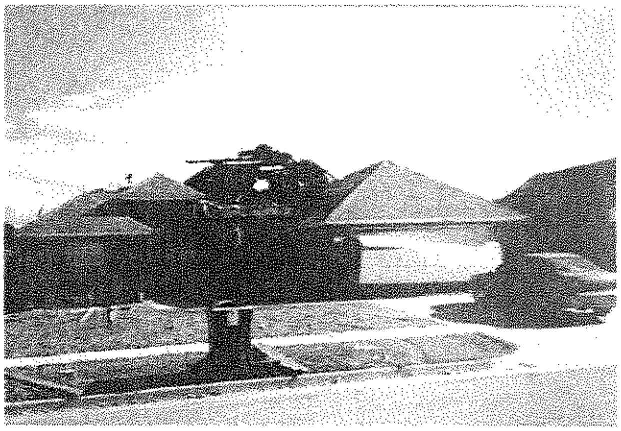

Figure 20: E-F Scale DOD 4 for Residential Dwelling

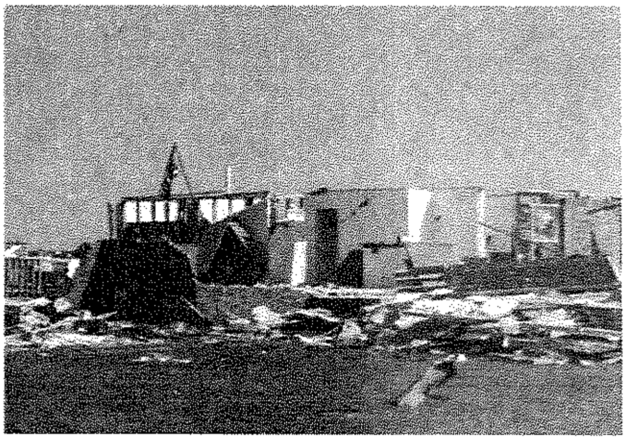

Figure 21: E-F Scale DOD 7 for Residential Dwelling

Knowledge of the building's condition is needed to determine the appropriate use of expected, lower bound or upper bound wind speeds. The timeline is necessary to compare wind and flood loads on an hourly basis, taking into consideration the response of building structure to various wind gust speeds versus flood load including current velocity and wave activity. The elevation of floor levels is necessary to determine the time when storm surge first damaged the building – assuming it remained intact until that point in time.

The practice of assigning the wind speed rating of a residence which survived Katrina to a neighboring slab claim should be used with extreme caution. The EF-Scale is intended for application to an individual building, structure or other damage indicator (DI) and specifically warns that "members of the [EF] Forum were very specific in their opinion that a single building, structure or other DI should not be used to rate a tornado event. Several DIs should be considered in assigning an EF-Scale rating to a tornado event" (EF-Scale, 2006). The warning is even more applicable to coastal hurricanes where the only neighboring DIs are buildings that survived both wind and flood loads. It is presumptuous to assume that buildings that did not survive were undamaged by wind and wholly damaged by flood. It is reasonable to assume that buildings closer to the coast were damaged by wind to a greater extent than buildings further from the coast.

Not only may the degree of damage of buildings in the same neighborhood vary due to differences in resistance factors based on design, code application, construction techniques and maintenance but the degree of damage may vary due to temporal and spatial differences in the wind stream. As well put by Dr. Robert Simpson in a 1991 interview, "...if you've ever survived damage after a hurricane you know that one block of houses may be almost totally destroyed, and two blocks to either side there will be little damage at all. ...it's the difference in the hurricane, not the difference in the engineering that caused the difference in the amount of damage received" (Simpson, 1999).

CRITICISMS AGAINST USING THE EF-SCALE FOR HURRICANE ANALYSIS

Use of the EF-Scale for hurricane analysis is subject to two major criticisms. First, the EF-Scale "is (at best) an exercise in educated guessing" (Edwards, 2007). But to paraphrase one respected meteorologist's comment concerning the original Fujita scale, while the EF-Scale may not be perfect, neither is it chopped liver. TTU used an expert elicitation process relying on the subjective judgment of a hand-picked panel of architects, engineers and meteorologists. The second argument against using the EF-Scale for hurricane analysis is that it was designed for tornado damage but not hurricane damage. However, as Marshall (1993) informs us, "Damage surveys by McDonald and Marshall [1983] after tornados and Savage [1984] after hurricanes have revealed the same types of building response regardless of the phenomenon creating the wind."

Arguably one important difference between tornados and hurricanes exists. The translational velocity of a Plains tornado is 30-60 mph; a typical Plains tornado crosses a suburban property lot in 2-5 seconds. Phan and Simiu (1998) found that the 1997 Jarrell, TX tornado which wiped residences from their foundation slabs traveled slowly at 5-10 mph and concluded that the tornado was not an F5 event with tornadic winds between 261-318 mph as originally calculated but rather an F3 event with tornadic winds between 158-206 mph. From this it is concluded that wind events of longer duration result in greater damage to building structures than the same wind events of shorter duration (Marshall, 2002). Since Hurricane Katrina wind attacked most coastal residences for hours before the arrival of storm surge during which time hundreds if not thousands of debilitating wind gusts impacted the building structure, it follows that the wind speeds used in the EF-Scale (which are based on empirical observations of tornado damage) represent 3-second wind gust speeds higher than those necessary to cause equivalent building damage during a hurricane with repetitive gusts.

ONGOING RESEARCH AGENDA

The main thrust of this paper has been to demonstrate a methodology for the investigation of Katrina "slab claims" defined as buildings totally destroyed by hurricane loads (wind, flood or a combination of the two) before a site investigation could be performed. In the course of developing the method, a review of theoretical literature left unanswered many questions brought to mind by empirical investigation. Three areas in particular require will be the focus of continued research by the author:

WIND EFFECTS AT THE COASTAL BOUNDARY

Exposure D is defined in ASCE-7 as "flat, unobstructed areas exposed to wind flowing over open water" extending inland from the shoreline a distance of 1,500 feet. Since ASCE 7-98, shorelines in hurricane prone regions are excluded from Exposure D based on research indicating that the aerodynamic roughness of ocean waves in a hurricane approaches Exposure C (Vickery and Skerlj, 2000). More contemporary research suggests that a foam layer at the wind/wave interface causes a reduced drag coefficient in hurricanes (Powell, Vickery & Reinhold, 2003). Should Exposure D be restored for shorelines in hurricane prone regions? In the case of Hurricane Katrina, does the relative smoothness of flood inundated land approximate Exposure D? Would coastal buildings designed for Exposure C have fared better if they were designed for Exposure D, and does this in part explain the damage pattern along the coastline?

FACTORS INFLUENCING TREEFALL DURING HURRICANE EVENTS

The EF-Scale includes Damage Indicators for hardwood and softwood trees. Rigid vegetation is perhaps the most ubiquitous structure on the coastal landscape to survive the effects of wind and flood. A better understanding of how factors such as tree species, age, diameter, height, leaf/stem type and root placement relate to tree damage and treefall in hurricane events would greatly benefit the analysis of wind and flood.

LOCAL CONSTRUCTION AND BUILDING CODES

A key aspect of failure analysis is an understanding of the interrelationship of load factors and resistance factors. A frustrating assignment for all investigators was the attempt to determine the nature of connections in order to best understand the resistance factors of a particular building structure. Most probabilistic models currently in use assume that building stock generally complies with current building code requirements, yet absent a set of as-built construction drawings, no better than legacy building codes and contemporary practice can be assumed.

SUMMARY

While not every aspect of this paper is applicable to every slab claim investigation, the methodology offers a broad spectrum of analytical tools and satisfactorily employs both inductive and deductive reasoning in the course of the investigation. Structural analysis and probabilistic models are ideally suited for the purpose but most often are hindered by a lack of construction knowledge peculiar to the investigation. Key to the methodology offered in this paper is a robust acceptance of the E-F Scale as an analytical tool useful in the analysis of wind damage caused by landfalling hurricanes along the Gulf Coast.

REFERENCES

ASCE (2000). Measurement of High Wind Speeds Near the Ground: ASCE Policy Statement 476.

Bretschneider, C.L. (1965). Generation of Waves by Wind - State of the Art. Office of Naval Research, 96 pp.

Corps of Engineers (2006). Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System. Draft Final Report of the Interagency Performance Evaluation Task Force. 1 June 2006.

Doswell, C. (2001). Thoughts on Refereed Journal Publication. www.cimms.ou.edu/~doswell/pubreviews.html

Edwards, Roger (2007). On-line Tornado FAQs. NOAA Storm Prediction Center. http://www.spc.noaa.gov/faq/tornado/

E-F Scale (2006). A Recommendation for an Enhanced Fujita Scale (EF-Scale) Submitted to the National Weather Service and Other Interested Users. Wind Science and Engineering Center, Texas Tech University, Lubbock, Texas 79409.

FEMA 55 (2005). Coastal Construction Manual. Principles and practices of planning, siting, designing, constructing and maintaining building in coastal areas. 3 vols.

Fitzpatrick, Pat (2007). New research on Hurricane Katrina wind issues. PowerPoint provided by author.

Frances, J.K. (2000). Comparison of Hurricane Damage to Several Species of Urban Trees in San Juan, Puerto Rico. Journal of Arboriculture 26(4): July 2000.

Giammanco, I. M., et. al. (2007). Hurricane Katrina Deployment Summary, Texas Tech University Hurricane Research Team 27-30 August 2005. Updated 3 Jan 2007 to include additional reference.

Hall, N.B. (2007). Post-Disaster Building Damage Evaluation. 2007 AIA Convention, San Antonio, Texas, May 2, 2007.

Holthuijen, L.H. (2007). Waves in Oceanic and Coastal Waters. Cambridge: 2007.

HRD, (2006). FAQ: Hurricanes, Typhoons and Tropical Cyclones. http://www.aoml.noaa.gov/hrd/tcfaq/D4.html. Atlantic Oceanographic and Meteorological Laboratory.

Hsu, S.A., (2003a). Nowcasting the variation of wind speed with height using gust factor measurement. National Weather Digest, December 2003.

Hsu, S.A., (2003b). Estimating Overwater Friction Velocity and Exponent of Power-Law Wind Profile from Gust Factor during Storms. Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, July/August 2003.

Kilkari, S., (2007). Can a structural engineer truly determine whether wind or storm surge caused the damage to property during Hurricane Katrina? The Louisiana Civil Engineer, 15, 3, 8-9 and 27-30.

Krayer, W.R. and Marshall, R. D. (1992). Gust factors applied to hurricane winds. Bulletin of the American Meteorological Society, 73(5), 613-617.

Mashriqui, H.S., et. al. (2006). Experimental Storm Surge Simulations for Hurricane Katrina. Coastal Environmental and Water Quality (ed. by Y.J. Xu & V.P. Singh) 481-490. Water Resources Publications, LLC, Highland Ranch CO.

Marshall, T. P., (1993). Lessons learned from analyzing tornado damage. The Tornado: Its Structure, Dynamics, Prediction and Hazards. Geophysical Monograph 79, 1993 by the American Geophysical Union.

Marshall, T. P. (2002). Tornado damage survey at Moore, Oklahoma. Weather and Forecasting, Vol. 17, Issue 3, June 2002, pp. 582-598.

Matsutomi, J. & N. Shuto (1994). Tsunami Engineering Technical Report No. 11, DCRC, Tohoku University, 29-32.

McDonald, J.R. and T.P. Marshall (1983). Damage survey of the tornados near Alyus, Oklahoma, on May 11, 1982, Pul. 68D, Tex. Tech Univ., Lubbock, Texas.

Minor, J.E. (2005). Lessons learned from failures of the building envelope in windstorms. Journal of Architectural Engineering, 11(1), March 1, 2005.

Norman, C. R. (2007). Damage assessment of homes and buildings – Distinguishing between storm surge and wind.. 2007 Structure Congress: New Horizons and Better Practices, ASCE 2007.

Peterson, C. J. (2006). Factors Influencing Treefall Risk in Tornados in Natural Forests.

Phan, L.T. and E. Simiu (1998). The Fujita Tornado Intensity Scale: A Critique based on Observations of the Jarrell Tornado of May 27, 1997. NIST Technical Note 1426.

Powell, M.D. and T. Reinhold, (1996). Hurricane Andrew's landfall in South Florida. Part I: Standardization measurements for documentation of surface wind fields. Weather Forecasting, 11, 304-328.

Powell, M. D., Vickery, P.J. & Reinhold, T.A. (2003). Reduced drag coefficient for high wind speeds in tropical cyclones. Nature, Vol 422, 20 March 2003.

Rogers, C. (forthcoming). Forensic Methodology for Determining Site Specific Wind Speeds and Resulting Damages to Residential and Commercial Buildings. Abstract for presentation at SEI Structures 2008 Conference in British Columbia.

Savage, R.P. (1984). Hurricane Alicia: Galveston and Houston, Texas, August 17 and 18, 1983, Committee on Natural Disasters, National Academy Press, Washington, D.C., 158 pp.

Simpson, R. (1999). The Saffir/Simpson Hurricane Scale: An Interview with Dr. Robert Simpson. Mariners Weather Log Vol 43, No. 1, April 1999. NOAA Publication.

Snow, J.T., A. L. Wyatt, A.K McCarthy and E.K. Bishop (1995). Fallout of debris from tornadic thunderstorms: An historical perspective and two examples from VORTEX. Bulletin of the American Meteorological Society, 76(10), 1777-1790.

Sumer, B. M. & J. Fredsøe (2002). The Mechanics of Scour in the Marine Environment. World Scientific: 2002.

Vick, Steven (2002). Degrees of Belief: Subjective Probability and Engineering Judgment. ASCE Press.

Vickery, P.J. and P.F. Skerlj (2000). Elimination of Exposure D along Hurricane Coastline in ASCE 7. Journal of Structural Engineering, April 2000.

Vickery, P.J. and P. F. Skerlj (2005). Hurricane gust factors revisited. Journal of Structural Engineering, 131(5), 825-832.

ACKNOWLEDGMENTS

Thanks to Dr. Patrick Fitzpatrick at Mississippi State University for his unselfish time discussing the meteorological aspects of Hurricane Katrina.