MythBusters for Wind versus Water Damage

J. Arn Womble\(^1\), Douglas A. Smith\(^2\)

\(^1\)President, WindForce Associates, Inc.; LNSS & Associates; Instructor, Texas Tech University Wind Science & Engineering, ArnWomble@aol.com
\(^2\)Professor of Civil Engineering, Texas Tech University Wind Science & Engineering; Principal, LNSS & Associates, doug.smith@ttu.edu

ABSTRACT

Recent tropical storms such as Hurricanes Ivan (2004), Katrina (2005), and Ike (2008) have resulted in elevated levels of wind and storm surge. With the potential for both wind and storm surge to cause damage to coastal structures, questions have continually arisen as to what damage was caused by wind and what damage was caused by storm surge. Such questions are further complicated when a structure is destroyed, leaving little-to-no direct evidence of the exact damage sequence. In reviewing numerous reports addressing wind versus water damage causation in Hurricane Katrina in Mississippi, we have observed a host of implausible failure theories that can be potentially misleading. This paper examines common misconceptions encountered in the wind versus water debate and provides guidance for application of the appropriate physical principles.

INTRODUCTION

Wind and storm-surge actions and the ensuing structural responses will not violate the laws of physics, but they will readily violate our mistaken perceptions of these laws.

Because of a separation in insurance coverage in the U.S. for damages caused by wind and water, questions have continually arisen as to what damage was caused by wind and what damage was caused by storm surge. The determination of whether hurricane damages are the result of wind or of storm surge becomes a crucial issue in the settlement of insurance claims. Such is the case for recent investigations for damage caused by Hurricane Katrina (2005) along the Mississippi coast. Disagreements as to the cause of such damages have led to an unprecedented series of legal challenges between homeowners and insurers, involving engineering and meteorological reports directed at the performance of residential buildings subjected to wind and storm surge.

Employed in many of these reports are failure theories that can be potentially misleading. Such theories appear to stem from a misunderstanding of the basic physical principles of fluid action and structural response; the selective and incomplete application of such physical principles; the use of non-standard or inapplicable data; and/or incomplete analysis of clues provided by a damaged structure and its surroundings. The supposition that tornado damage is responsible for the selective destruction of structures has also been mistakenly used in place of considering variations in structural resistance. Improper extensions of the EF Scale to predict hurricane damage have also been commonly observed.

We are therefore compelled to examine and highlight some of these theories in an effort to educate the engineering community on possible pitfalls in the determination of wind versus water damage in hurricanes. Our experience following Hurricane Katrina has prompted the following recounting of physical principles, anecdotes, observations, and recommendations.
BASIC ACTIONS

Basic differences in wind and storm-surge actions on residential structures have been summarized by many researchers, building officials, and practitioners [1, 2, 3, 4]. Wind damage tends to be most severe at the roof and upper walls and particularly near leading edges where wind pressures are largest. Storm-surge damage is most severe near the base of a structure due to the actions of rising water and waves.

Womble, Smith, and Adams [5] have also examined the damage signatures of residential structures with various types of foundations. Unbalanced depths of water inside and outside lead to a net buoyant force on a structure. Pier-and-beam residences, mobile homes, and other elevated residences not adequately attached to their foundations are prone to flotation and transport by the storm surge. Rapidly rising water makes these residences vulnerable to floating off their foundations before interior and water levels can equalize. The structures may then be transported relatively intact or may be torn apart. Slab-on-grade and other well-founded elevated structures may not break loose from their foundations and, rather than moving as an entire unit, can experience severe damage to their walls, resulting in either partial loss of walls or collapse of the entire structure. Once the supporting walls have collapsed, intact roof assemblies can become buoyant and may be transported separately from the original structure, as was commonly encountered in Hurricane Katina [5].

REMEMBERING BERNOULLI

In the study of basic fluid mechanics, engineers learn that Bernoulli’s equation describes the exchange of pressure, velocity, and gravitational potential in an ideal fluid. Bernoulli’s equation also provides a general and qualitative basis for the exchange of pressure and velocity in turbulent, non-ideal flows of interest to wind engineers, telling us that pressures (and subsequently forces) due to moving fluids are proportional to the density of the fluid and to the square of the velocity. As water is approximately 800 times as dense as air, very little water velocity is required to exceed the pressures exerted by even a strong wind.

A special case of Bernoulli’s equation describes the flow through a constriction (such as in a pipe constriction) in which the fluid accelerates to maintain a constant flow rate. In exchange for the increased velocity, the fluid also experiences a lowering of static pressure (that is, the pressure is lower where the velocity is increased). Incomplete understanding of this relationship leads to a misconception that the acceleration of wind flow through the vented crawlspace beneath a pier-on-beam residence can “blow a house off its foundation.” In reality, quite the opposite is true: the accelerated flow would exert a suction pressure, resulting in a downward-acting force on the floor above, which could nominally assist in holding the residence on its foundation. In actuality, the near-surface flow and resulting downlift forces are likely to be negligible. The ability for the wind to pass beneath the residence is also soon impeded as the storm surge fills the crawlspace and provides buoyant uplift on the residence.

Another potential misconception is that wind flow channeled along a tree-lined driveway serves to create a “wind tunnel” that accelerates the wind toward a stately residence accentuated by the tree rows and thereby exerts additional wind pressure on the residence. Such occurrence is highly dependent on the exact geometry of the tree-lined driveway and residence as well as the height and density of surrounding trees and structures. In the above analogy of a pipe flow, the fluid mass in question has no alternative but to accelerate through the constriction, thereby maintaining the mass flow rate. Given the choice of entering a conduit in which it must navigate a subsequent constriction or else flowing more easily outside the exterior of the conduit, the bulk
of the flow will choose the latter. Since the wind is likely to see the tree-lined driveway blocked by the stately residence at the far end as a constriction, much of the wind flow will avoid this constriction if the surrounding geometry provides an easier alternative. Flow entering the alleged “wind tunnel” will tend to stagnate, causing much of the remaining flow to select alternative paths. For heavily suburban and/or forested terrain such as found along the Mississippi coastline, the overall lifting of the boundary-layer flow by a “displacement height” also suggests that wind is generally unlikely to accelerate appreciably down the tree-lined driveway and to thereby bombard the residence. Because the exact flow regime is so highly dependent on surrounding geometry, a boundary-layer wind-tunnel test employing a scaled geometric area model is suggested for determining the extent of any acceleration.

**IMPORTANCE OF WATER VELOCITY**

The effects of Hurricane Katrina’s storm surge along the Mississippi coast are occasionally compared with the effects of levee breaches in New Orleans. The comparison seeks to cast doubt on the notion that storm surge was responsible for destroying residences along the Mississippi coast by posing the question: “If storm surge destroyed houses along the Mississippi coast (where hurricane winds were strongest), why were flooded houses left standing in New Orleans (on the weaker side of hurricane)?” Inspection of aerial photographs of the levee-breach areas shows that fast-moving waters near the levee breaches did move or destroy nearby residences, reminiscent of conditions along the Mississippi coast. Residences located several blocks from the breaches were subjected to lower velocity waters and mostly remained in place. Such residences suffered in-place flooding from relatively slowly rising waters. Slowly rising water enables water levels inside a residence to equalize with those outside – reducing the net buoyant effects. Even historical accounts from the 1900 Galveston hurricane remind us of occupants chopping holes in the elevated floors of their houses, allowing the entry of water and thereby reducing buoyancy of the structure [6].

**IMPORTANCE OF VALID DATA**

It is fundamental to wind engineering applications that wind velocity data must be standardized for height, exposure, and averaging time. We have observed the use of suspect and non-standardized data in many instances. For example, we observed the use of dropsonde velocity data from an elevation of 1000 ft applied as if they were surface-level wind data at 33 ft (10 m). Obviously, such data must be adjusted for height before they can be used to compute wind pressures acting on buildings. Compared with credible and standardized storm-maximum velocity data compiled in the H*WIND product [7, 8], the instantaneous data from 1000 ft elevation produced overestimates of 45% in windspeed and more than 100% in the resulting pressure. Use of such non-standardized data can lead to erroneous conclusions as to whether or not wind pressures were sufficient to destroy a structure.

We have also observed the use of suspect windspeed records from anemometers positioned in separated or shear-flow regions atop buildings and near roof corners, where velocities can be significantly higher than ambient conditions. Marshall [3] demonstrates that windspeeds from an anemometer positioned 1.5 m above the corner of a warehouse roof at Ingalls Shipyard in Pascagoula, MS during Hurricane Katrina recorded maximum windspeeds more than twice as large as windspeeds recorded nearby (standardized to 10 m height). Use of such windspeeds can lead to estimates of wind pressures more than four times as large as those actually acting on a structure, again potentially leading to incorrect conclusions of wind/water damage causation.
High-water marks collected at nearby locations [9] are also helpful for analyses seeking to differentiate wind and water damage causation. Many high-water indicators remain visible and can be measured with precision after the storm. Surge and wave depths may also be measured in-situ during the hurricane using submerged pressure transducers.

**IMPORTANCE OF LOAD SEQUENCES**

With the potential for both wind and storm surge to cause damage, the time history of wind and water levels is extremely important. Another popular misconception centers on the timing of *peaks* of wind and storm surge, with the hypothesis being that wind must be responsible for destruction if the peak windspeed precedes the peak storm-surge level. In truth, however, the timing of the peaks is moot if the structure is destroyed before either peak occurs.

Smith, Womble, and Lombardo [10] discuss the use of windspeed and surge-level timelines to compare lateral wind and surge loads acting on the base of a typical exterior wall for a residential structure. For Hurricane Katrina in coastal Mississippi, timelines show that wind and storm surge generally rose together, with the maximum windspeed occurring up to about 1.5 hours before the maximum storm surge, depending on location. While wind and water actions are governed by the same physical laws, the wind forces are dominated by velocity, whereas the surge forces are dominated by the relatively large density of water and depth of inundation. As surge levels rose, resulting loads rapidly overcame wind loads and escalated quickly to likely failure levels. Wind loads were generally well below likely failure levels when surmounted by surge loads, and surge loads typically reached probable failure levels several hours before the wind or surge reached their maxima. Since the storm surge was capable of collapsing buildings several hours before the wind reached its peak, it was of little consequence that windspeeds reached their maximum prior to surge levels reaching their maximum.

**REVIEW OF THE AREA (PLACING DAMAGE IN CONTEXT)**

The exact wind resistance of structures is difficult to discern. It is complicated further when the structure is completely removed and critical evidence is destroyed. Review of a lone structure may not sufficiently tell the entire story of what has happened. Review of surviving structures and trees in the area is critical to a proper evaluation of the events leading to failure. The performance of nearby similar buildings and trees that remain gives an indication of the loading (and damage) experienced by a demolished structure [5].

Along the Mississippi coast, windspeeds decrease slowly relative to surge levels with distance inland. Unless specific channeling or shielding effects exist, structures only a few hundred feet apart in the same exposure can experience a similar windspeed but can experience differences of several feet in surge levels. A review of structures along the infamous “debris line” along the Mississippi coast in Hurricane Katrina readily confirms the above. The debris line was pushed inland by the storm surge approximately ¼ to ½ mile, depending on the steepness of the terrain slope and the density of vegetation and/or built environment. Most structures seaward of the debris line were completely demolished or heavily damaged. A few structures with adequate foundations and frames survived seaward of the surge line with little wind damage to their roofs. Structures situated directly along the surge line were often damaged by waterborne debris impacting the walls on the seaward side. Landward of the debris line, most structures survived with little-to-no wind damage to their roofs, though many were inundated by the storm surge. Use of factors prescribed in the ASCE 7-05 commentary for inland decay of winds shows differences of only about 1% in windspeeds between surviving structures landward of the debris line (with little wind damage) and demolished structures seaward of the debris line.
It is not reasonable to conclude that windspeeds were sufficient to demolish residences just across the debris line from residences that sustained little-to-no damage to roof coverings.

**DIRECTION OF COLLAPSE**

Buildings with a high aspect ratio (large length compared to width) can have relatively stiff and weak axes. If the base floor or foundation of such a structure is lost, the direction of the subsequent collapse can be aligned with the weaker building axis and may not be fully aligned with the direction of prevailing wind or water currents.

**DIRECTION OF TRAVEL**

Once becoming buoyant, objects such as houses, roof assemblies, automobiles, mobile homes, and even railroad cars/shipping containers can travel in a resultant direction influenced by both the wind and water currents – analogous to the travel of a sailboat [11]. Thus, while the surge can cause an object to achieve buoyancy and to float off its foundation, the wind can thereafter assist in steering the object once it has set sail. Transport of debris and even entire structural assemblies in a direction somewhat different than the storm surge is not proof that wind destroyed or substantially damaged a structure.

**ROOFS AHoy!**

In hundreds of instances throughout the Mississippi coast, intact roof assemblies were detached from their supporting walls and transported by the storm surge [5]. Some roof assemblies showed signs of minor wind action since areas of shingles were uplifted along the leading edges, though many roof assemblies had all shingles intact. Rarely was any decking removed from these roof assemblies. Virtually all roof assemblies were found in the upright position, suggesting transport by storm-surge action from beneath, rather than wind action from above which would tend to flip many of the roof assemblies.

In many cases, maximum surge levels were higher than the roof elevations. Scrape marks observed at lower elevations on nearby trees, however, suggest that objects such as roof assemblies and other debris were often transported prior to surge levels reaching roof height. In other cases, maximum surge heights did not reach roof levels, yet detached roof assemblies were still found throughout the area. A popular misconception therefore arose: “The roofs must have been removed and transported by wind action, for how can roofs be removed and transported by storm surge that did not reach roof height?” This argument overlooks the ability of the storm surge to produce failure loads on supporting walls when surge levels are yet below the roof level, as demonstrated by Smith, Womble, and Lombardo [10]. When the walls collapse, the liberated roof assembly simply drops and is transported atop the surge (with the direction of travel possibly aided by the wind, as noted above).

**MODELING PROPER FAILURE MECHANISMS**

Engineering calculations based on credible wind velocity and surge-level data can be used to demonstrate the relative magnitude and timing of wind and storm-surge forces on a structure, e.g. [2, 10]. We caution, however, that load calculations are actually simplified models of reality and as such should seek to model actual failure mode(s) observed in the field (e.g., bending, tensile, or connection failures).

Review of debris found throughout the Mississippi coast following Hurricane Katrina shows that most structural elements (e.g., studs, rafters, trusses, and roof decking) remained
intact, indicating that failures commonly resulted from exceeding the capacity of connections and not from exceeding the capacities of individual structural members. It follows that calculations related to these failures should address the exceedence of connection capacities rather than member capacities. For many of these failures, we observed instances of bending-stress calculations applied to individual members while connection capacities were not evaluated. Use of unduly large windspeeds (as discussed above) indicated that members could fail in bending, whereas use of realistic windspeeds showed that bending failures were not anticipated. In several cases, remnants of the damaged buildings remained nearby and were available for closer inspection, revealing that incorrect failure modes were modeled by calculations seeking to prove damage causation.

**Overestimation of Loads**

Forensic analysis is inherently different than structural design, requiring that factors of safety be stripped away to determine the most likely wind and surge loads experienced by the structure. Load standards such as ASCE 7 [12] necessarily give conservative wind loads for most circumstances. Direct use of such design wind loads without accounting for safety factors and other conservative assumptions inherent in the load standards can overestimate the actual wind loads experienced.

In a significant instance involving damage from Hurricane Katrina in Mississippi, an engineering report estimated the wind uplift pressure on a sloped roof (for main-wind-force resisting system or MWFRS) to be more than an order of magnitude too large. This miscalculation of uplift pressures resulted from the compounded overestimation of several applicable parameters, including the windspeed and roof slope. The gust speed was estimated at 200 mph rather than 111 mph as shown by H*WIND analysis, resulting in a windspeed 1.8 times too large and a basic velocity pressure 3.2 times too large (= 1.82). Furthermore, the analysis applied the pressure coefficient for a flat roof to a roof with a 30-deg slope. ASCE 7-05 shows that MWFRS uplift pressure coefficient for a 30-deg roof is only about 25% that of a flat roof’s edge. This overestimation resulted in a pressure coefficient 4 times too large. Combining the overestimated gust speed with the overestimated pressure coefficient resulted in an overestimation of likely uplift pressures of at least 12.8 times, not counting conservatism inherent in the ASCE 7 pressure coefficient. (More precise values of pressure coefficients for particular geometries and exposures can be obtained from wind-tunnel testing, if necessary; however, the simple check shown above using tabulated pressure coefficients for various roof slopes readily indicated the gross overestimation involved in this computation.)

The building in question was destroyed, as it was set on a pier-on-beam foundation and subject to floatation in the more than 6 ft of base surge level crossing the site, accompanied by waves reaching 10 ft above ground. For comparison, an adjacent 2-story steel-frame building lost first-floor cladding and contents to the storm surge that passed through the first floor, yet the flat roof and second-floor building envelope sustained almost no damage. Nearby trees remained standing with little damage. Such remaining physical evidence at the site also cast doubts upon the calculations used to determine wind versus water damage causation.

Improper application of the Simplified Procedure (Method 1) of ASCE 7-05 [12] for determining MWFRS wind loads has also caused overestimation of wind loads. As clearly detailed in Figure 6-2 of ASCE 7-05, windward (positive) and leeward (negative) wall pressures have been pre-combined into the tabulated Simplified Design Wind Pressures. As these pressures have already been combined, it is incorrect to further combine positive and negative pressures (such as in other sections of ASCE 7). We have observed instances where an
engineering analysis further combined the maximum positive and negative pressures tabulated in ASCE 7-05 Figure 6-2, resulting in a gross overestimation of wind loads that would have acted on the structure.

Improper assumptions as to span length can readily lead to overestimated wind loads, as well. The simple use of 9-ft wall studs for theoretical calculation of bending stresses, rather than 8-ft wall studs employed in the actual construction of a destroyed building, amounts to a 27% overestimation in bending stresses. Combined with overestimated wind loads, such calculations can readily produce stress levels suggesting likely bending failures – failures which, as demonstrated above, may not be accurate representations of failure evidence noted in the field.

**Cautions on Claims of Tornado Activity**

In instances where one residence was destroyed and yet all nearby residences remained in place with visible surge damage but little wind damage, we have encountered claims that a tornado (often the responsibility of the wind-insurance carrier) impacted the lone destroyed residence. While it is not uncommon for some hurricanes to spawn relatively weak tornadoes (typically F0-F1 levels) [13], the windspeeds for such tornadoes (< 117 mph) produce loads far less than the ultimate loads specified by common wind-load standards such as ASCE 7.

Strong tornadoes also typically leave a distinctive long, narrow path through urban areas, bare fields, and forests – typically several hundred yards wide and several miles long. For tornadoes of the severity needed to destroy a residence, we expect to observe these distinctive paths on the ground and/or in aerial and satellite photos. In conducting field studies and examining high-resolution aerial photographs covering the entire Mississippi coast following Hurricane Katrina, we have found no such evidence of tornado paths.

In cases where the “precision-strike tornado” was postulated, it was commonly observed that the foundation anchorage of the destroyed house was inferior to that of the surviving neighbors. Post-hurricane inspections reveal that numerous pier-and-beam residences along the Mississippi coast relied only on gravity and friction to keep them on their foundations. Many elevated residences were founded on non-imbedded piles attached to a concrete slab with relatively weak steel reinforcement. In both cases, the residences were prone to sliding and buoyant failures, resulting in localized pockets of destruction within the surge zone. We have no reason to believe that these weakly-founded residences became targets of tornadoes.

Not all long, narrow, clear paths are the result of tornadoes. One meteorological report claimed to have detected a long, narrow, clear path among beachfront residences in Pascagoula. Upon examination, we, too, observed a long, narrow, cleared path but found it to actually be a row of slabs cleared by storm-surge action. Where this row of cleared slabs was interrupted by a surviving residence (with, incidentally a superior foundation better suited for withstanding storm surge), the alleged tornado track conveniently made an abrupt 90-degree turn – creating yet another long, narrow clear path which was otherwise known as an “avenue” [yes, the roadway itself]. This “path” had been there for decades prior to the hurricane.

The presence of multiple bare slabs positioned in a straight line within a surge zone is also not proof of a tornado track. Due to zoning and setback regulations in many municipalities, it is common for many residences to be arranged in a line. We note that storm surge is fully capable of moving these residences off their foundations, leaving a line of bare slabs. Inevitably, in areas such as southwest Pascagoula, the row of bare slabs was interrupted by a few lone surviving residences – more a testament to adequate foundation anchorage than to a tornado hop-scotching along the row.

Twisting of structures or even loose debris is also not unique to tornadic activity. The
fact that tornadoes rotate or are commonly referred to as “twisters” has apparently persuaded the public at large that twisting of objects must indicate tornadoes. While tornadic winds can cause such objects to twist, so too can other forms of fluid transport – including hurricane winds, straight-line winds, and (yes) even storm-surge transport. Marshall [14] reminds us that objects twist according to their own properties and that objects which are small relative to the size of a rotating storm (tornado or hurricane) experience essentially a straight-line wind that changes direction with time.

It has also been claimed that dozens (possibly hundreds) of tornadoes did occur seaward of the debris line along the Mississippi coast in Hurricane Katrina but that the path evidence was subsequently removed by the storm surge. This claim is dubious, as none of these tornado paths have been observed on the landward side of the debris line.

In Hurricane Katrina, radar data and the issuance of tornado warnings were offered as proof of tornadoes that destroyed residences along the Mississippi coast prior to the storm surge. Radar data alone are insufficient to detect tornadic activity, much less to give the precise location of a tornado relative to individual structures [3, 15]. Radar characteristics such as hook echoes and rotational mesocyclone signatures only show an elevated chance for tornadic activity; they offer no proof that a tornado has actually formed and touched ground. For real-time detection of a tornado, it remains necessary for a ground observer to confirm that a tornado actually forms and reaches the ground. Neither should the issuance of a tornado warning by the National Weather Service be considered proof that a tornado even formed, much less destroyed a structure prior to the arrival of the storm surge [1].

THE CASE OF TREES

The condition of trees in hurricane-affected areas is often cited on both sides of the wind vs. water issue. While helpful clues can be gleaned from the post-hurricane condition of trees, a few cautions are warranted [1]. Our observations and experience with hurricane-damaged areas suggest the following advice.

Trees can fall and break in windspeeds far less than those needed to severely damage or destroy a reasonably constructed residence, particularly when the surrounding ground is severely saturated by rains well in advance of hurricane winds. On the other hand, the destruction of houses amid trees that are only slightly damaged can be a good indication that damage to a residence is due to storm-surge action and not to wind action.

The falling of trees in multiple directions is frequently offered as proof of tornado occurrence. In actuality, trees have a very small diameter relative to any tornado. During the course of the hurricane, trees experience a straight-line wind that changes direction in time. We thus anticipate that trees can fall in multiple directions as the hurricane winds inevitably shift direction and the soil surrounding the root ball becomes saturated to a greater depth. This is not necessarily indicative of tornado action – especially where there is no larger-scale path of downed trees (i.e., the tornado path characterized by converging treefall damage oriented along a long, narrow path).

Twisted and broken tree trunks are frequently offered as proof that a tornado crossed a site; however, trees can be twisted by a straight-line wind, and twisting of a tree is not necessarily due to tornado action. Twisting of trees occurs as a result of asymmetric loading, arising from non-uniformity in the wind pressures loading different portions of the tree and also from the non-symmetric tree canopy.
**Windborne Debris**

It is well known that windborne debris (or “missiles”) are a significant cause of damage in hurricanes and tornadoes [16] – but we must consider two fundamentals.

First, windborne debris requires a nearby, upwind source. Inspection of high-resolution aerial images along the Mississippi coast shows no such upwind debris sources (e.g., damaged roofs) for residences located directly along the beach. Windborne debris impacts are typically more prevalent in the second row (inland) of structures and beyond, yet as demonstrated in Hurricane Katrina the majority of failures occurred along the front row of residences – which logically experienced the most severe storm surge, yet had little-to-no upwind source for windborne debris.

Secondly, where is the evidence? If windspeeds are sufficiently high to produce windborne debris, we expect to observe windborne missile strikes to surviving residences. Examination of structures in other windstorms where flying debris was present shows numerous instances of windborne missile strikes to surrounding areas of damaged structures and nearby surviving structures. An oft-repeated failure pattern for well-founded houses on the Mississippi coast was for the bottom floor to be washed through by the storm surge, while the second floor and roof remained with no evidence of windborne debris breaking windows or striking walls (damage indicators we would expect to observe had windborne debris destroyed the bottom floor).

**Wind or Water Transport? Either Way, It’s Fluid Transport**

Another frequent claim regarding windborne debris and destruction of residences by wind action is postulated thusly: “Shingles from a residence were found several hundred feet to the northwest. The shingles cannot float [in water] and can only be transported to this location by wind.” First, we consider the notion of these objects floating. While shingles can be denser than water and will therefore not float in water, it follows that they will most certainly not float in air that is some 800 times less dense! Therefore, floating is not the issue, but rather momentum transport by moving fluids – air or water. Note that objects dropped into moving water do not simply sink directly to the bottom, but rather are carried along some distance by the current. The “heavier-than-water” shingles could be transported some distance away by moving water – just as these same “much heavier-than-air” shingles could be transported by wind action. The above observation is not proof of transport of the shingles by wind rather than by water.

Beach sand likewise does not float; however, throughout the Mississippi coast it was carried several hundred feet inland by action of the storm surge and was found around the foundations of many damaged or destroyed buildings. The presence of beach sand around the base of one damaged beachfront structure in Mississippi prompted the hypothesis that the sand had been transported there by wind action, and furthermore that the presence of “loose sand debris” in the wind so increased the density of the air as to cause destruction of [only] the lowest floor of the building, leaving the second floor walls unscathed. While wind can also entrain and transport sand, it is all the more difficult when the sand is not only wet from rainfall but also submerged beneath 10 ft of storm surge.
MEASURING WITH THE RIGHT TOOL

The Saffir-Simpson Hurricane Scale [17] has long been the official scale for measuring U.S. hurricane intensity and remains so for the time being. Categories 1-5 (ranging from 74 mph to over 155 mph) are assigned based solely on sustained (1-minute) winds speeds over water. General descriptions of damage and potential surge levels that can typically be expected with the various hurricane categories are also included in the scale. Hurricane Katrina was quite atypical in that it had been a Category 5 storm with sustained winds exceeding 165 mph and measured wave heights as high as 55 ft some 18 hours prior to final landfall along the Louisiana/Mississippi border [18]. The windspeeds diminished rapidly to the Category 3 level prior to landfall, yet the storm surge (having approximately 800 times the density of the wind) retained significant momentum and did not diminish as rapidly as the windspeeds. Thus, the storm surge at landfall was consistent with Category 5 levels (exceeding 18 ft) suggested by the Saffir-Simpson Scale, while the landfalling hurricane was classified as Category 3 based on maximum sustained winds. Because storm-surge levels of a hurricane diminish more slowly than windspeeds, it is possible for a hurricane such as Katrina to maintain prior storm-surge potentials consistent with Category 5, although windspeeds have weakened to that of a Category 3 at the time of landfall. The potential surge levels in the Saffir-Simpson Scale therefore may significantly underestimate the actual surge levels experienced. Future efforts in predicting damage from storm surge and windspeeds in hurricanes are likely to address modified or new scales for hurricane destructive potential, with emphasis on the history of pre-landfall intensities and the resulting effect on storm surge.

Additional methods for predicting damage from hurricanes have also been suggested and implemented in other applications [19, 20]. Other scales have sought to correlate windspeeds with wind effects or wind damage, but not all are applicable to hurricanes. Included in this list are the Beaufort Scale and Enhanced Fujita Scale, both of which are addressed subsequently.

The Beaufort Scale enables the estimation of windspeeds based on verbal descriptions of wind effects and has proven useful to mariners (and later to landlubbers) since its introduction over 200 years ago [21]. The Beaufort Scale, however, is pushed beyond its usefulness when employed as justification that structures could be damaged by relatively low hurricane windspeeds. The operational version in the U.S. [22] extends only to the lowest level of hurricane windspeeds and merely states that windspeeds above 63 knots (above 73 mph) are considered “hurricane force” characterized by “widespread damage” and are “very rarely experienced on land.” The self-evident truth is that the scale makes no distinction between the destructive potential of hurricanes of various strengths and therefore is not helpful for predicting actual wind damage in hurricanes, especially when we recall that a two-fold increase in windspeed (e.g., from 75 mph to 150 mph) corresponds to a four-fold increase in pressures acting on structures.

THOU SHALT NOT TAKE FUJITA’S SCALE IN VAIN

The National Weather Service implemented the Enhanced Fujita Scale (EF Scale) in 2007 as the official measure of tornado intensity in the U.S. A recommended EF Scale [23] was developed under the direction of the Wind Science and Engineering Research group at Texas Tech University (TTU) to address concerns raised by the engineering and meteorological communities over use of the original Fujita Scale (F Scale) [24]. Notably, the EF Scale provides expected ranges of tornado windspeeds corresponding to levels of damage severity, termed Degrees of Damage (DODs), for various Damage Indicators (DIs), such as buildings, other structures, and
trees. The DODs follow the general progression of damages with increasing winds speeds, based on engineering-oriented studies of tornado damage over the previous three decades [25, 26, 27].

As widespread measurements of tornado winds speeds were not available, the developers of the EF Scale used an elicitation process, comprised of experts in the study of tornado damage (including co-author Smith), to develop estimates of windspeed ranges associated with each DOD for each damage indicator [25, 26, 27]. The windspeed ranges of the EF Scale thus represent the best estimates of the engineering and meteorological communities at the time of its development.

Although Dr. Fujita apparently intended the original F Scale to be used both for tornadoes and hurricanes [24], the Enhanced Fujita Scale was developed specifically for tornado (and not hurricane) winds [28]. It is significant that the vast majority of the engineering-oriented studies in the TTU tornado damage archives were directed at severe tornadoes in the Midwestern U.S, and not coastal areas, and thus the experiences with damaged buildings largely reflected construction practices employed away from the hurricane coast [28].

Since the development of the EF Scale, the question has arisen as to whether the EF Scale can be reliably used to predict the amount of wind damage based on known hurricane winds speeds. In contemplating such use of the EF Scale, Womble et al. [28] examine separately its two primary components: (1) Degrees of Damage and (2) ranges of tornado winds speeds associated with these damage levels. Engineering investigations of tornado and hurricane damage suggest that the appearance and progressive severity of damage from both hurricane and tornado winds have a similar appearance [14]; and therefore the Degrees of Damage in the EF Scale properly describe the general progression of damage to structures with increasing winds speeds in both tornadoes and hurricanes [1]. However, the winds speeds associated with various DODs are expected to be different for structures exposed to hurricanes and tornadoes. This difference stems from inherent variances in both the wind loading imparted by hurricanes and tornadoes and in the wind resistance of building stocks in tornado- and hurricane-prone areas of the United States. As a result, the EF-Scale is prone to over-predicting damage for given winds speeds in hurricane-prone coastal regions, and use of a known or assumed hurricane windspeed to determine the level of wind damage can lead to large errors [28].

Much anecdotal evidence exists for the improper use of EF Scale in hurricanes to determine the extent of wind damage occurring before the subsequent destruction by storm surge [28]. For instance, for pier-and-beam residences removed their foundations by storm surge during Hurricane Katrina, forensic reports have reasoned that the damage was consistent with EF Scale DOD 5 for a single-family residence [23]: “Entire house shifts off foundation.” Yet the shingles on these residences experienced little-if-any damage. It is unlikely for such structures to be moved by wind action without first experiencing lesser DODs (e.g., loss of roof coverings and decking). Storm-surge action, however, can be expected to move inadequately founded pier-and-beam residences without major damage to roof coverings or to nearby trees.

Even in attempting to establish wind action as the damage causation using the DODs and winds speeds of the EF Scale, other nearby DIs must also be investigated, e.g., hardwood and softwood trees. In such situations, even trees surrounding the floated residences did not exhibit damage characteristic of winds speeds suggested by the DOD 5 for single-family residences, and therefore the EF Scale could not even be uniformly applied in these instances in support of wind-induced transport of the residence.
CONCLUSION
Since the actions of wind and water and the associated structural responses can be counted upon to obey the laws of physics, it is imperative that engineers have a clear understanding of these laws and their manifestations in cases of severe loading. The propagation of misconceptions concerning these actions provides a disservice to all parties. The experiences and recommendations recounted herein are offered as encouragement for engineers to continuously seek and utilize only credible, standardized data; to fully investigate failure theories supported by fundamental physical principles and available evidence; and to impartially pursue accurate determinations of wind/water damage causation.

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REFERENCES


