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Introduction

When Cyclone Tracy roared ashore on Christmas Eve nearly 30 years ago, it created lasting impacts not only for the community of Darwin but for the international wind engineering community as well. It was a watershed event, leading to years of concentrated research efforts in the areas of wind effects on houses and other low-rise, 'ordinary' buildings, which had not previously received as much attention. Three decades later, we have a much greater understanding of building aerodynamics for low-rise buildings. In terms of reducing future losses to tropical cyclones, the larger challenges lie more in the areas of developing improved construction materials and methods, in education and training of design and construction professionals and tradesmen, and in improved codes and code enforcement.

This isn't to say that traditional wind engineering research is left out in the cold. There are still some significant research challenges left that are very important to the low-rise building stock that represents the vast majority of all construction. Understanding the vertical velocity profile and gust structure of winds in a tropical cyclone needs much additional work. For all the added insight that GPS dropwindsondes launched from hurricane hunter planes have provided in the past few years, the data has raised more questions than it has answered. Traditional boundary layer and gradient wind speed assumptions are clearly not applicable, but we still lack a better model. The boundary layer transition that occurs as the storm makes landfall is also not well understood. Most of the pressure and force coefficients in wind loading codes worldwide are based on wind tunnel test results of isolated buildings with very simple geometry, in flat open terrain. In actuality, the majority of real buildings and site locations are not so simplistic. Improved models are needed to better understand the aerodynamic complexities of structures in the real world.

New areas of research and practice have been opening up in recent years, on the boundaries of the field as wind engineering has begun to mature as a discipline. Integration and adaptation of wind engineering knowledge into emergency management and disaster response are rapidly expanding fields, which promise to help continue the trend of reducing tropical cyclone fatalities and property damage over time. The four phases of emergency management are Mitigation, Preparedness, Response, and Recovery. There are wind engineering applications for all of these phases, which will be discussed throughout the paper.

It has also become clearer in recent years that the fragmented approach of considering each cyclone hazard as an isolated phenomena does not satisfactorily address the situation. The wind engineering research community and practitioners rarely interact with the coastal (storm surge) flood community, which has minimal interaction with the freshwater (rainfall) flood community. However, all three of these hazards interact with each other and have impacts on the design of structures.

Tropical Cyclones – A Multihazard Environment

Tropical cyclones (variously called hurricanes, typhoons, and cyclones in different parts of the world) represent a significant hazard to the natural, built, and human environments, yet their unique nature is not generally accounted for in engineering education and design practices. These powerful storms present a wide array of hazards, in addition to extreme winds. The primary hazards listed in Table 1 are the major storm phenomena themselves and the immediately ensuing hazards. Secondary hazards result from interaction of the primary hazards with the natural and built environments. In order to build sustainable communities in hurricane-prone locations, all of these hazards must be considered in the planning and design of facilities ranging in scale from individual buildings to regional infrastructure systems.

Table 1. Tropical Cyclone Hazards

Primary Phenomena/Hazards	Secondary Hazards
Storm surge and waves/flooding	Fire
Extreme winds/tornadoes	Contaminated floodwaters/debris
Extreme rainfall/flooding	Combined environmental/technological hazards, e.g. hazardous materials releases caused by storm damage to pipelines, storage tanks, etc.
Windborne/floodborne debris	Electrocution (downed power lines)
Rain-induced landslides	Floodborne diseases
Erosion/scour/washover	
Wind-driven rain (economic hazard)	

One of the most distinguishing features that differentiates tropical cyclones from other natural hazards is the unique combination of potential for catastrophic loss of life and damage, over a large area, by a wide variety of hazards, *from an event that can be predicted with increasing accuracy a few days before it occurs*. This warning time provides an opportunity to save lives and property, if utilized properly. The most deadly natural disaster in American history is the Galveston Hurricane of 1900. Over 6000 people perished as a massive storm surge swept over the island, due to inadequate warning of the dangers of the storm.

Since the advent of weather-monitoring satellites in the 1960's, hurricanes no longer strike land without warning. This has drastically reduced the number of hurricane-induced casualties in most instances in the developed world, but the potential for mass fatalities still exists. Lack of warning was not the problem during Hurricane Camille in 1969, where 259 people perished. Many of those deaths occurred at the infamous Richeliu Apartments in Pass Christian Mississippi, where legend has it that residents decided to throw a hurricane party instead of evacuating. They drowned in the surge as their building collapsed around them. There are two very important lessons to be learned here: 1) the lack of understanding of the relative seriousness of the hazard compared to the safety afforded them by their apartment building led these people to make a very bad decision, which cost them their lives; and 2) warned or not, when people remain in areas subject to significant storm surge there will be a need to break out the body bags (for those bodies that can even be found).

The vastly improved detection of tropical cyclones, prediction of storm tracks, and communication of this information to the public over the past four decades are countered by the concurrent population boom in high-risk coastal areas and the lack of significant growth in transportation infrastructure. Put another way, the amount of time needed to evacuate our increasingly urbanized coastal areas is escalating as fast or faster than the amount of warning time provided by improvements in storm tracking and prediction. This scenario could spell disaster for many coastal cities, as happened in the October 1999 super cyclone that struck Orissa India, which claimed well over 10,000 lives and left millions homeless.

Evacuation

There are two basic options (and several variations of each) for people in the way of an approaching cyclone. The first is evacuation to a place far enough inland to be beyond the reach of the storm surge and extreme winds. However, even moving hundreds of kilometers inland does not necessarily 'guarantee' safety, as storm hazards including extreme rainfall, rainfall flooding, tornadoes, and downed power lines from even moderate strength winds can all occur far inland. The second main option is seeking shelter in buildings within the high hazard coastal area. This can be in one's own home or business, or at other local facilities. An apparent third option, doing nothing, becomes in essence a choice of sheltering in place or seeking local shelter at the very last minute, but with less forethought, planning and preparation than the second option. Physical safety is generally the most important concern for families making a decision on how they will respond to the approaching storm, but there are many others including availability of transportation, economic situation, job responsibilities, and concern for property and pets. Evacuation advisories and orders from local officials play a significant role in the decision-making process. However, even in areas where officials order a mandatory evacuation, there is usually no enforcement and some people choose to stay behind.

"Run from water, Hide from wind." In heavily populated areas in the United States where evacuation clearance times exceed available warning times, emergency management agencies have begun optimizing evacuation plans. They have begun ordering mandatory evacuations of only those areas expected to receive significant flooding, since most hurricane deaths are water-related. This does not mean the wind threat is not significant, but rather it is a strategy to 'reserve' transportation infrastructure capacity for evacuation of those most at risk.

The geographic extent of areas subjected to storm surge and severe rainfall flooding are generally much smaller than those that will experience damaging winds. This means that potentially large areas and populations will be under 'voluntary' evacuation orders, accentuating the importance of the 'go or stay' decision. Exceptions exist in locations of wide and shallow continental shelves having extensive low-lying coastal areas, where topographies barely above (or below) sea level extend far inland, such as the broad river deltas of Louisiana and Bangladesh. Storm surge flooding in these locations can inundate hundreds of km^2, making evacuation less viable as a tool for protecting the whole populace in locations having large populations and/or limited transportation resources.

<u>Wind-Related Aspects of Evacuation</u>

There are several areas where additional wind engineering research can and will improve evacuation planning and operations (which are aspects of emergency management phases of preparedness and response, respectively). In the United States, evacuations are generally halted so that all vehicles can be clear of the road before the arrival of tropical storm force winds, defined as sustained (one-minute) winds of 17.4 m/s. This criterion is based on a perception of vehicle safety and stability by the emergency management community, with no input from the engineering community. Several studies of vehicle stability in cross winds are now underway at Louisiana State University, Florida Tech, and Kent State University, to provide criteria with a scientific basis. If vehicles can be shown to be stable at higher wind speeds, evacuations could be allowed to proceed longer, allowing more people out.

In addition to vehicle stability on the roadways – populated coastal areas often have major evacuation routes that include high rise bridge segments. State Police Officials in Louisiana are so concerned about local conditions at bridges that they have issued hand-held anemometers to state troopers assigned to monitor traffic at these bridges. Unfortunately, they do not have adequate criteria for what to do with this wind speed information with regard to closing a bridge. It remains to the trooper's judgment. Steve Cai at Louisiana State University is developing a model of wind-bridge-vehicle interaction that accounts for dynamic interaction between the vehicle and vibrating bridge deck. This type of analysis, coupled with aerodynamic stability data for various types of passenger and emergency response vehicles, will allow for optimization of evacuation speed and safety. Maximum safe driving speeds could be determined for each bridge based on its wind performance characteristics at different wind speeds, and then manually programmed electronic speed limit signs could be employed to post these speeds for the evacuees. Such a system could even be automated, using wind sensors at the bridge location to automatically feed into a program and then electronically display appropriate speed limits or notify of need to close the bridge. Steve Cai is also investigating the use of portable, truck mounted tuned mass dampers that could be deployed on bridges used in critical evacuation routes, to reduce bridge vibrations and allow for faster evacuating vehicle throughput and lengthening of time that the bridge could remain open.

Sheltering

Selection of the appropriate tropical cyclone intensity (including wind speeds and storm surge potential) to be used as an ultimate design event for shelters and other buildings in hurricane-prone coastal community needs to be thought out. Consideration of the consequences, including evacuation clearance times, would produce a more risk-consistent design from a life safety standpoint (consequence-based engineering). The currently used design wind speeds, which account for tropical climatology and the geomorphology of the coast, produce a risk-consistent design from the standpoint of wind damage potential to the buildings, but do not consider anthropogenic factors. Since the ultimate goal of building codes is protection of life safety, consideration of the likelihood that people are in the building when it experiences the hurricane winds becomes important.

As an example of including consequence assessment into the process, consider two different sections of the Florida coast. The three counties in Southeast Florida (Miami-Dade, Broward, and Palm Beach) are home to five million people. Under the best of circumstances, there is not enough warning time and transportation capacity to evacuate more than a fraction of this population. The Everglades provide a barrier, meaning that most of the population can't even locally evacuate to more than 25 miles from the coast – therefore, millions of people will be forced to shelter in their own homes and businesses. Contrast this with a similar length of coast in northeast Florida (Volusia, Flagler, and St. Johns counties). The combined population of this region is only 600,000, with better transportation infrastructure for evacuations. This section of coastline can be much more easily evacuated. In most cases, sheltering in place would be based on individual choice, not on necessity. Given these two scenarios, is consistency of risk of structural failure an appropriate criterion? Structural failures in these two cases would have significantly different implications for life safety.

Selection of the minimum design storm for different locations should therefore be made after consideration of the hurricane climatology as well as the consequences. Consider a location like New Orleans that is highly vulnerable to storm surge flooding, where it takes upwards of 72 hours to evacuate the city. Estimates are that even under the best circumstances, only two thirds of the metropolitan area population of 1.3 million can or will evacuate. Hundreds of thousands of people will remain in the city, many not by their own choice, and need to shelter in place or seek refuge. In this case, consideration of upping the design wind speed above the that specified in the US wind loading standard (ASCE, 2002), which is approximately equivalent to Saffir Simpson Category 2 storm, would be appropriate.. Other areas with long evacuation times that may warrant increasing the design event storms above current code minimums include South Padre and Galveston Islands in Texas, Mobile Alabama, several of the larger cities in northern and western Florida, Charleston South Carolina, and Wilmington North Carolina. A thorough analysis of current and future projected evacuation time requirements (considering population trends over the next few decades) and comparisons with minimum available warning times for a rapidly developing storm would be needed to make these decisions.

A US national standard for the design and construction of storm shelters is under development. It will address both residential and community shelters, and hurricanes and tornados. This standard will address all of the storm hazards, not just wind. The author chairs this committee, which will likely have a draft available for public review and comment by the end of next year. More information is available on the International Code Council's web site (ICC, 2004).

Other Wind Engineering Applications to Mitigation and Emergency Response and Recover

Loss estimation models have long been used by insurance companies to help determine their risk and exposure and set rates. In the past few years, there has been a major effort in the US to develop publicly available loss tools. Major initiatives have been funded by the State of Florida and the Federal Emergency Management Agency. These tools have application in mitigation, response and recovery from hurricanes. FEMA has just recently released its HAZUS Multihazard software program, with a new hurricane module (FEMA, 2004). This GIS-based software provides simulation capability for hurricane landfalls, and produces estimates of damage to the building stock. It also allows users to do 'what-if' scenarios, investigating the effectiveness of code changes such as requiring debris impact resistant shutters or glazing.

HAZUS can also be used in a response mode during a real hurricane. By entering the forecast track and intensity of a storm nearing landfall, the software will produce GIS-based estimates of which areas will be most severely damaged. This information can be used by emergency managers to effectively preposition response assets and assist with search and rescue operations. It can also be used by wind damage investigators, to have a better idea of where the most severe damage was likely to occur. John Holmes and I met with Larry Twisdale (lead developer of HAZUS hurricane model) in Raleigh North Carolina on September of 2003, as Hurricane Isabel was making landfall about 200 km away. He provided us with maps of estimated maximum wind speeds that would be experienced across North Carolina in the next few hours, and detailed damage estimates for areas of the state. John and I used this information to help target our storm damage investigations on the following few days. The software also develops detailed estimates of volume of debris generated. This is critical for post-storm operations, as the recovery phase of the disaster cannot begin until the debris is cleaned up. Use of wind damage estimation tools for emergency response is just in its infancy, but will be expanding rapidly at the emergency management community becomes more technology savvy.

Role of Engineering Education in Cyclone Hazard Mitigation

As mentioned at the beginning of the paper, Hurricanes are among the most devastating of all catastrophic natural hazards. Surprisingly, there is not a single engineering program that educates its students to deal with the multiple threats posed by these powerful storms. There are no textbooks on the subject, and only limited amounts of curricular materials of any kind. Buildings and infrastructure in hurricane-prone regions are not generally designed for the full range of hurricane effects, including extreme winds, windborne debris, storm surge, river flooding, rain-induced landslides, wind-driven rain, and other hazards. A major reason for this anomaly is that engineers and architects are not trained to understand and deal with hurricane threats as regular parts of their curricula.

This is in sharp contrast with earthquakes. In California and Japan and other areas with significant seismic risk, all structures, from buildings to highways to utilities, are designed from the ground up with earthquakes in mind. A number of US Pacific coast universities have undergraduate courses in earthquake engineering, and/or include various aspects of earthquake engineering in their analysis and design courses. Engineers are trained to understand the multi-hazard nature of threats related to earthquakes and design accordingly (e.g. ground motion, landslides, liquefaction, etc.). The better job done by the seismic community in educating engineers is certainly one reason that earthquakes kill and injure fewer people and cause less damage than hurricanes do in this country.

It is interesting to note that most of the universities teaching earthquake or wind engineering, at either the undergraduate or graduate level, are schools with active research programs in those areas. The disparity between the numbers of courses offered in the two areas may simply be a reflection of the disparity in available research funding and corresponding numbers of faculty working in the two areas. Annual funding for earthquake engineering research in the US exceeds $100 million, while funding for wind engineering is only $5 million (Hight, 1999).

The disparity of educational offerings in earthquake- and hurricane-related fields is reflected in the availability of textbooks and general engineering reference books on the subjects. A January 2000 keyword search of "Earthquake Engineering" on VarsityBooks.com (one of the nation's largest online textbook retailers) yielded 14 available, pertinent books, including three textbooks. A keyword search of "Seismic Design" yielded an additional eight relevant titles (including two more texts). Less restrictive searches yielded additional relevant titles. These texts and reference books addressed a wide range of issues. Some were very specific, dealing only with certain types of structures (e.g.,