A New Approach to Combined Flood and Wind Mitigation for Hurricane Damage Prevention

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ABSTRACT: As global climate change causes sea levels to rise and weather events to become increasingly extreme, the occurrence of severe floods and hurricanes will become more common around the world. In 2005, Hurricane Katrina had a devastating impact on New Orleans as eighty percent of the city was inundated. Many discussions and policies are being implemented to increase resilience to future weather-related disasters. However, while many of these initiatives are intended to mitigate extreme flood events, they do not fully consider less severe but more commonly occurring wind-induced damage. In accordance with regulations issued by FEMA, houses are commonly raised on stilts in an effort to increase resilience to flooding. However, drastic elevation increases the structure's vulnerability to wind. In effect, by protecting against a rare but catastrophic occurrence, houses are made considerably more vulnerable to less severe but more regularly occurring events with potential to cause wind damage. Amphibious construction provides an alternative solution to mitigating hurricane damage, as this strategy increases resilience to flooding without causing an increase in wind exposure.

KEY WORDS: ICWE14; Amphibious Architecture; Buoyant Foundation; Hurricane Damage Reduction; Wind Load; Flood Mitigation; Permanent Static Elevation; Climate Change Adaptation.

1 INTRODUCTION

In the aftermath of Hurricanes Katrina and Rita, many homeowners in south Louisiana are required to comply with new government regulations in order to retain their eligibility for flood insurance. For most, this means elevating their houses to comply with the new Base Flood Elevation (BFE) requirements issued by FEMA (the US Federal Emergency Management Agency) [1]. However, permanently elevating houses creates new problems such as inconvenient access to living areas, difficult access for elderly and handicapped residents, loss of neighborhood character, and increased vulnerability of the structure to wind damage. In some cases, homes are elevated by more than 7 meters, which exposes them to significantly greater wind speeds and exponentially greater wind forces.

2 PERMANENT STATIC ELEVATION AND INCREASED WIND VULNERABILITY

The increased vulnerability of permanently elevated homes to wind damage can be explained by the boundary layer wind gradient, as wind velocity increases with height above the surface of the earth. Sites that are exposed to hurricane hazards may be located in coastal regions, where the characteristic of the upwind fetch is open water or flat, smooth terrain. In these areas of smooth fetch, the gradient of the curve is especially steep. Consequently, if a coastal community is required to elevate their homes high above the ground to comply with new flood map regulations issued by FEMA, their homes may be exposed to significantly higher wind speeds. As the wind force exerted on a building is in proportion to the square of the wind speed, increases in wind speed as a result of elevation will expose the structure to higher wind forces, which may have significant impacts on building damage and economic loss [2].

2.1 Wind Speed

To calculate the increase in wind speed with increasing elevation, the most commonly used methods of estimating the vertical wind profile are the log law and the power law [3-5]. Both approaches are subject to uncertainty caused by the variable, complex nature of turbulent flows. The log law is based on boundary layer flow and is a combination of theoretical and empirical research (Equation 1) and the power law is an empirically developed relationship (Equation 2) [6, 7], where z_1 and z_2 (Equation

4) [8] are the target and reference heights, respectively; U_{z_1} and $U_{z_2}$are the target and reference height wind speeds; z_0 is the surface roughness length; and α is an empirical exponent (Equation 3) [8], where c_1 is 5.65. For a case of a low-rise building with a mean roof height of 4 meters being elevated to 10 meters, the increase in wind speed was calculated using the power law for a range of surface roughnesses (Table 1).

$$\frac{U_{z_1}}{U_{z_2}} = \frac{\ln\frac{z_1}{z_0}}{\ln\frac{z_2}{z_0}} \tag{1}$$

$$\frac{U_{z_1}}{U_{z_2}} = (\frac{z_1}{z_2})^{1/\mapsto} \tag{2}$$

$$\alpha = c_1 z_0{}^{-0.133} \tag{3}$$

Table 1. Ratio of 10 meter wind speed to 4 meter wind speed ($V_{10\text{ m}}/V_{4\text{ m}}$) calculated using the power law.

Surface roughness, z_0 (m)	0.03	0.2	2
$V_{10\text{ m}}/V_{4\text{ m}}$	1.107	1.140	1.195

2.2 Wind Pressure

To calculate the wind pressure and increase in pressure with increasing mean roof height h, q_h (Equation 4) [8] is calculated, where K_z is the velocity pressure exposure coefficient calculated as $K_z = 2.01({}^{4.6}/_{z_g})^{2/\alpha}$ for z < 4.6 m and $K_z = 2.01({}^{z}/_{z_g})^{2/\alpha}$ for 4.6 m ≤ z ≤ z_g; K_{zt} is the topographic factor; K_d is the wind directionality factor; and V is the basic wind speed. Holding all other factors constant, the increase in wind pressure was calculated for the case of a low-rise building with a mean roof height of 4 meters being elevated to 10 meters for a range of surface roughnesses, shown in Table 2.

$$q_h = 0.613 K_z K_{zt} K_d V^2 \quad (\text{N/m}^2) \tag{4}$$

Table 2. Velocity pressure coefficients, K_z, and increase in velocity pressure with height.

Height above ground	Surface roughness, z_0 (m)		
	0.03	0.2	2
≤ 4.6 m	0.801	0.575	0.328
10 m	0.951	0.717	0.443
Increase in pressure	18.8%	24.8%	35.2%

2.3 Wind Damage and Loss

To calculate the increase in damage or loss with increasing elevation, expected annual loss (EAL) is a parameter to evaluate long-term risk from a probabilistic standpoint and calculated by convolving the continuous loss curve and continuous probability density function for annual wind maxima [9-12], where $E[L]$ is the expected loss, $f_V(v)$ is the probability density function (PDF) of wind maxima, and $L(v)$ is the loss curve as a function of wind speed, v (Equation 5).

$$E[L] = \int_0^\infty f_V(v) L(v) dv \tag{5}$$

To simulate economic lifecycle losses, extreme value probability functions are required to define the relationship between expected return period and wind speed intensity. Typically, Extreme Value Type I (Gumbel) and Extreme Value Type III (Weibull) distributions are used to predict wind speed extremes. Therefore, the probability of wind speed $F_V(v)$ is calculated by the cumulative distribution function (CDF) of the Gumbel distribution (Equation 6) or the two-parameter Weibull distribution (Equation 7).

$$F_V(v) = exp\{-exp[-(v-u)/a]\} \tag{6}$$

$$F_V(v) = 1 - exp[-(v/u)^a] \tag{7}$$

The parameters u and a are site specific, and can be determined from regression analysis of wind speeds corresponding to mean recurrence interval R in logarithmic format. Transforming Equations 6 and 7, wind speed v is calculated in terms of mean recurrence interval R for the Gumbel distribution (Equation 8) and Weibull distribution (Equation 9).

$$v = u + a\left\{-ln\left[-ln\left(1 - \frac{1}{R}\right)\right]\right\} \tag{8}$$

$$v = u\left[-ln\frac{1}{R}\right]^{\frac{1}{a}} \tag{9}$$

Monte Carlo simulation is used to convolve the damage or loss functions with the wind speed probability distribution function and accounts for wind speed uncertainty and ensures stability of results. For each simulation, a random number between zero and one is generated and used as input in the inverse of the wind speed CDF to calculate the annual extreme wind speed for each year. The annual wind speed maxima are then used as input into building vulnerability functions to calculate the loss for each simulation year. Using Monte Carlo simulation over N simulations, the expected annual loss for each direct economic loss function EAL_j (Equation 10) is the summation of total losses divided by the number of simulations, N, where i is the simulation counter from 1 to N, $F^{-1}[Ran(i)]$ is the inverse of the CDF of the wind speed for each simulation, $Ran(i)$ is a random number between 0 and 1 with continuous uniform distribution, and $L_j(v_i)$ is the economic loss corresponding to annual extreme wind speed v_i for function type j.

$$EAL_j = \frac{1}{N}\sum_{i=1}^{N} F^{-1}[Ran(i)] \times L_j(v_i) \tag{10}$$

For a case of a low-rise building with a mean roof height of 4 meters being elevated to 10 meters, the increase in wind loss was calculated using residential economic loss functions from FEMA's Hazus-MH [13] for a single story, gable roof single family residence with toe-nail roof to wall connections, no secondary water resistance on the roof sheathing seams, without shutters or garage door, and with 6d roof cover nails spaced at 0.15 m on the edge and 0.3 m in the field located in the 72 m/s ASCE 7-10 Occupancy Category II wind speed contour [8]. In open terrain (z_0 = 0.03 m), this building with 4 m mean roof height is expected to experience an annual loss (EAL) of 2.8%. By elevating the building to a mean roof height of 10 m, the EAL becomes 4.9%, an increase of 75%.

Based on our preliminary analysis, for a house with a 4 meter roof height, located in the 72 m/s ASCE 7-10 Occupancy Category II wind speed contour [8] that will be elevated to a 10 meter roof height, the increase in roof height wind speed is approximately 11%, corresponding to an increase in wind pressure of 19% and an increase in expected annual loss (EAL) of 75%. This effect becomes more exaggerated the higher the structure is raised above the ground. By raising houses to increase their resilience to catastrophic floods, homeowners are significantly increasing the exposure of their homes to much stronger wind forces. Our preliminary analysis suggests that some homes with high permanent static elevation may be more likely to suffer damaging losses from increased wind exposure than would be likely from a flood event had the house remained unelevated, as significant wind events have a much higher frequency of occurrence in the region.

3 AMPHIBIOUS ARCHITECTURE AND REDUCED FLOOD DAMAGE

Amphibious architecture refers to an alternative flood mitigation strategy that allows an otherwise-ordinary structure to float up on the surface of rising floodwater, as a means of protecting it against flood damage, rather than permanently raising the structure to a higher static elevation [14]. An amphibious foundation retains a structure's connection to the ground by resting firmly on the earth under usual circumstances, yet it allows a house to float as high as necessary when flooding occurs (Figure 1).

Vertical guidance posts prevent the house from moving laterally; it can only go straight up and down. The flexible elevation enables houses to become more resilient to flooding, without permanently exposing the structure to increased wind speeds and stronger wind forces. As the house remains close to the ground except during extreme flooding, the increase in wind velocity and force is not as dramatic as the exponential increase in force when the house is permanently elevated. Amphibious homes not only provide superior flood resilience, but are able to withstand both the occasional catastrophic flood events and the more frequently occurring but less severe wind events. This technology allows homes and their contents to survive hurricanes undamaged, and such weather-related events become temporary inconveniences rather than catastrophes [15].

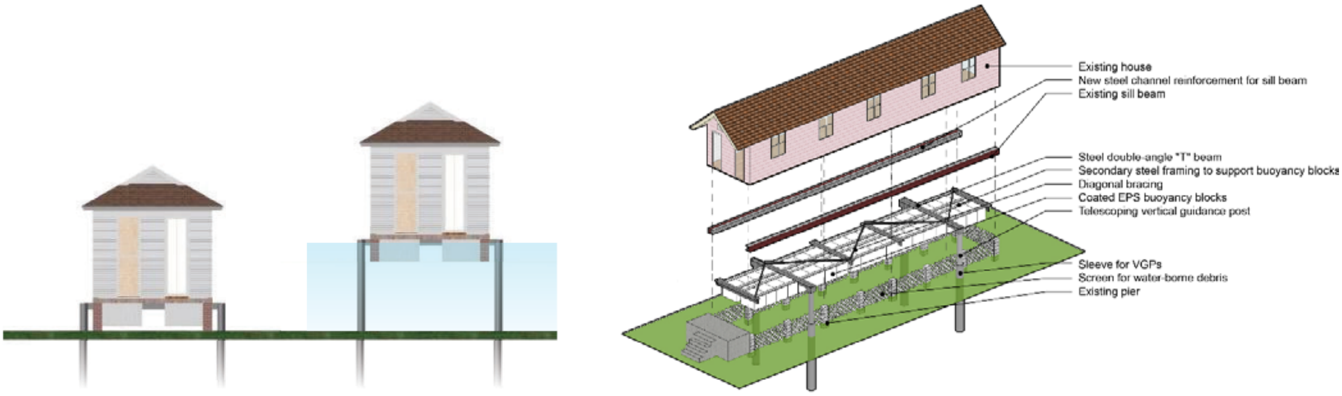

Figure 1. Components of a buoyant foundation. The amphibious structure provides temporary elevation when needed to prevent flood damage without increasing vulnerability to hurricane wind damage.

Amphibious construction is suitable for new buildings or as a retrofit to an existing structure. Successful amphibious foundation systems have been functioning for over thirty years at Old River Landing in Pointe Coupee Parish, Louisiana, where they provide more reliable and more convenient flood protection than can be obtained from permanent static elevation. Successful amphibious housing projects or prototypes have also been constructed in the Netherlands, the UK, Bangladesh, Thailand, and Vietnam.

In a severe event where flooding may reach unanticipated depths, the fixed height of permanent static elevation may prove to be inadequate. The variable elevation provided by amphibious foundations accommodates not only short-term extreme flood levels but long-term land subsidence and sea level rise as well, by lifting the house to the elevation necessary to keep it safely above water. As global warming stimulates sea level rise and more extreme weather events, severe flooding is predicted to become more frequent as well. As stronger hurricane winds exacerbate the impact of floods by increasing wave heights and driving floods further inland, a flood mitigation strategy that relies on permanent static elevation will become inadequate when record floods reach heights beyond the levels that were anticipated at the time of construction. Maasbommel in the Netherlands (Figure 2) and Old River Landing in Louisiana (Figure 3) both experienced extreme flood conditions in 2011, and the amphibious houses in both of these locations successfully demonstrated the reliability of this emerging technology.

In addition to providing increased resilience to both flood and wind damage, amphibious homes are also more environmentally and culturally sustainable than permanent static elevation. As a surface application, buoyant foundations are a low impact and thus more environmentally sustainable hurricane resilience alternative. Buoyant foundations also preserve the traditional relationship of the house to the ground, supporting the cultural continuity of the community. On the other hand, statically elevated homes completely alter the character of the neighborhood, in addition to creating less convenient access to living areas, and a displaced relationship between the street and the home, amounting to a loss of neighborhood character and sense of community. Buoyant foundations alleviate long-term degradation of flood protection that results from soil subsidence and elevated sea level due to climate change, something that permanent static elevation cannot avoid. Buoyant foundations are also more economical for homeowners as their installation is considerably less expensive than permanent static elevation. This emerging technology thus provides a holistic sustainable solution to increasing the resilience of communities in the face of climate change, as they are environmentally, culturally, and economically sustainable.

Figure 2. Amphibious housing in Maasbommel, Netherlands, undamaged in winter 2011 Maas River flood.

Figure 3. Undamaged amphibious houses in Old River Landing, Louisiana, after spring 2011 Mississippi River floods, adjacent to severely damaged static elevated houses (note high water lines, HWL, on the static houses).

4 THE BUOYANT FOUNDATION PROJECT

The Buoyant Foundation Project (BFP) is a non-profit research initiative founded in 2006 at the LSU Hurricane Center with the goal of designing and implementing retrofittable buoyant foundations for New Orleans "shotgun" houses. The organization aims to provide inexpensive retrofits to existing houses that will allow property and possessions to survive both repetitive seasonal and occasional extreme flooding [16].

In 2007 a team of LSU Hurricane Center faculty and students successfully constructed and tested a full-scale prototype buoyant foundation system installed on a platform structure representing the full width (4 meters) and forty percent (8 meters) of the full length (approximately 20 meters) of a typical New Orleans shotgun house (Figure 4). Dead load was simulated using water-filled barrels, and live load by sand bags. The amphibious foundation prototype was verified to work in a series of tests, confirming both its buoyancy and rotational stability.

The BFP aims to reduce environmental vulnerability and improve the quality of life for culturally rich and vibrant communities in contextually specific locations. For each project, design strategies are modified in order to respond to the specific contexts of each site. For example, Figure 5a illustrates an urban application where, for aesthetic reasons, the vertical guidance posts are designed to telescope out of the ground. In a rural context surrounded by trees, however, where the appearance of poles above the ground is less objectionable, the vertical guidance posts manifest as static poles with sleeves that slide vertically (Figure 5b). The BFP has also undertaken design projects in indigenous communities including locations such as Kashechewan in northern Ontario, Pinaymootang in central Manitoba, Isle de Jean Charles in coastal Louisiana and Malacatoya in Nicaragua. In these contexts, strong cultural ties to the land and a lack of resources to relocate as a community leave the remaining band members vulnerable to increasing risks of flooding. By implementing cost-effective, flexible amphibious retrofits to the community, the BFP seeks to secure a continued safe and affordable living space for the at-risk citizens. The Buoyant Foundation project promotes the understanding of how to build strong, flood-resilient housing that is equally responsive to climate change and cultural values in order to enable both well-off and impoverished communities that live with the threat of flood to develop and to thrive.

Figure 4. Full-scale prototype buoyant foundation system.

Figure 5. In an urban application (left) vertical guidance posts may telescope out of the ground. In a rural context surrounded by trees (right), the vertical guidance posts are static poles with sleeves that slide vertically.

The scope of the BFP has also expanded to participation in design competitions, covering a geographic range of applications from Louisiana to Vancouver, Nova Scotia, New York, Jamaica, Nicaragua, Colombia, Bangladesh and Thailand. In August 2015, the BFP will be joining other sponsors to host ICAADE 2015, the first International Conference on Amphibious Architecture, Design, and Engineering, in Bangkok, Thailand [17]. The second of these conferences, ICAADE 2017, is being planned for summer 2017 in Ontario, Canada.

5 CONCLUSIONS

Global climate change and warmer ocean temperatures will lead to more frequently occurring, and increasingly intense, storm activity. The strong winds of hurricanes propagate a series of hazards beyond increased wind forces, including wind-induced storm surges that amplify wave action and drive floods further inland. These weather occurrences can cause significant damage to structures and possessions, and as the likelihood of these events increases, it is essential to develop sustainable strategies that will allow coastal communities to become more resilient. Amphibious construction is a sustainable low-impact hurricane mitigation strategy that provides flood protection without increasing exposure to strong winds. It is rapidly gaining acceptance and finding application around the globe. While the new Base Flood Elevation requirements issued by FEMA aim to provide increased resilience to floods, raised static elevations are problematic in that permanently elevated structures are exponentially more vulnerable to wind damage. In addition, permanent static elevation is more expensive and disrupts the visual coherence of traditional neighborhoods. Amphibious foundations provide an alternate hurricane mitigation strategy by resting on the earth most of the time, but floating the house as high as necessary when flooding occurs. They can provide temporary elevation as needed, when needed, and do so with a sustainable solution that works in synchrony with floodwater instead of resisting it. This low-impact technology thus provides houses with a greater resilience to rising flood levels, without compromising the structure's ability to withstand the more frequently occurring wind hazards.

Future work in this area is needed to focus on additional quantification of increased wind speeds, wind forces, and wind-induced damage and loss, including expansion of the loss estimation methodology to damage and loss functions that consider uncertainty. To address the avoided flood losses that may be achieved through the use of buoyant foundations, additional research is needed to implement a probabilistic loss estimation framework for flood hazards that considers flood magnitude, frequency, and loss functions. By considering the individual and joint probabilities of wind and flood hazards, more robust estimates of expected losses can be achieved for hurricane environments and other areas subjected to wind and flood hazards.

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