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Mitigating wind and flood: The increased wind vulnerability of static elevation vs. amphibious retrofit

Elizabeth C. English [a], Fatemeh Orooji [b], Carol J. Friedland [c]

[a]University of Waterloo, Cambridge, ON, Canada, english@ecenglish.ca
[b]Louisiana State University, Baton Rouge, LA, USA, forooj1@lsu.edu
[c]Louisiana State University, Baton Rouge, LA, USA, friedland@lsu.edu

SUMMARY:
Hurricanes and severe storms expose structures to both wind and flood damage. Permanent static elevation as a flood mitigation strategy has the concomitant disadvantage of exposing a structure to higher wind forces. This paper introduces a methodology for the systematic quantification of the increase in expected loss due to wind damage as a result of the increased wind exposure due to significant static elevation in order to reduce flood risk. Results show that the expected wind loss as a percentage of building value over the lifecycle of the building is significantly increased for permanent static elevation in comparison to an amphibious retrofit. Amphibious construction is an alternative flood mitigation and climate change adaptation strategy that allows a structure to remain close to the ground except during a flood, thus avoiding the increased vulnerability to wind that accompanies permanent static elevation.

Keywords: Wind damage, expected loss, flood mitigation, static elevation, amphibious retrofit, buoyant foundation

1. INTRODUCTION

Holmes (1994) investigated the increase in wind loads due to permanent static elevation for a housing typology typical to the Gold Coast region of Australia. He concluded that the combined static and dynamic pressures for elevated homes may be 40-80% greater than for non-elevated buildings in the same windstorm. By being raised to increase their resilience to catastrophic floods (by 7 meters or more, in some cases), such statically-elevated buildings are subjected to greater wind speeds and forces on a regularly occurring basis because of their increased height above grade (Figure 1). Consequently, if a coastal community is required to elevate their homes

Figure 1. Increased exposure to wind with permanent static elevation

high above the ground to comply with new Base Flood Elevation (BFE) requirements as mandated by the US Federal Emergency Management Agency (FEMA), their homes are likely to 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 exponentially higher wind forces, which may in turn have significant impacts on building damage and economic loss (Cochran, 2012).

English et al. (2015) evaluated the change in vulnerability that would be expected by elevating a single story low-rise residential building (4 meter mean roof height) to a 10 meter mean roof height (MRH). They found an increase in MRH wind speed of approximately 11%, corresponding to an increase in wind pressure of 19%, and an increase in expected annual loss (EAL) of 75% for a one story single family residence with gable roof, located in open terrain on the 72 m/s (160 mph) ASCE 7-10 wind speed contour (ASCE, 2010). For non-statically-elevated amphibious foundations, the height of the building relative to the earth's surface does not change significantly, as the elevation of the building increases only with the rising surface of the floodwater and remains at an essentially constant height above the surface.

Amphibious construction refers to an innovative flood mitigation strategy that is an alternative to permanent static elevation. It allows an otherwise-ordinary structure to remain close to the ground under ordinary circumstances, but 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 (English, 2009). Vertical guidance posts prevent the house from moving laterally, and flexible elevation enables a house to avoid damage from flooding without permanently exposing the structure to stronger wind forces. 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 allowing the house to rise to exactly the elevation necessary to keep it safely above water. As global warming stimulates sea level rise and more extreme weather events, flood mitigation strategies that rely on permanent static elevation will become inadequate as record floods reach heights beyond the levels that were anticipated at the time of construction. Figure 2 illustrates the basic principle of amphibious flood mitigation.

Figure 2. Schematic diagram of a buoyant foundation (www.buoyantfoundation.org)

Figure 3. Application of a buoyant foundation to a New Orleans shotgun house (photo on left, render on right)

Figure 3 depicts the retrofit application of a buoyant foundation to a typical shotgun house in New Orleans, and Figure 4 shows the components of a retrofitted buoyant foundation system.

The increased vulnerability of permanently statically elevated homes to wind damage is easily understood as a function of the greater wind-load exposure of the structure; however, the increase in wind damage and loss for elevated vs. non-elevated buildings has not been robustly quantified to date. This paper will compare the relative wind vulnerability of a permanently-statically-elevated building to an otherwise identical non-elevated, buoyant-foundation-supported building, through convolution of wind hazard probability distributions with Hazus economic loss functions that have been adjusted to address the higher mean roof height wind speeds of statically elevated buildings. For both elevated and amphibious cases, building vulnerability is calculated over a variable building life cycle by considering the net present value of future loss. The results of the methodology will be presented for increasing building elevations located in multiple ASCE-7 wind exposures. Our work expands previous analyses through development of the building loss function adjustment methodology and by implementing the methodology for continuously increasing building elevations.

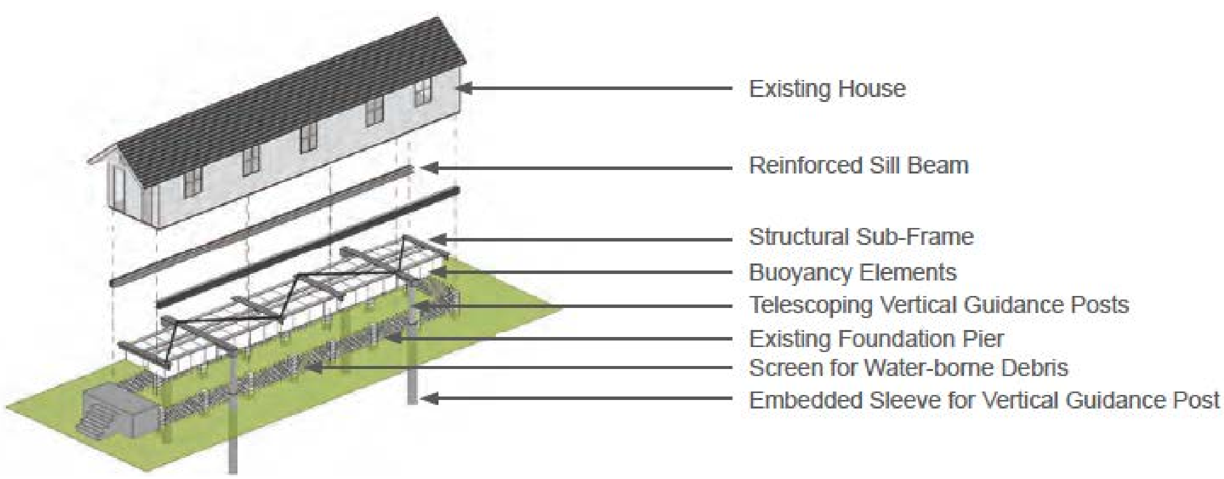

Figure 4. Components of a typical retrofitted buoyant foundation system

2. WIND LOSS MODELLING

The probability of wind speed v is expressed using the two-parameter Weibull cumulative distribution, where α and u are site-specific parameters determined by fitting return period wind speed data to a Weibull distribution (Equation 1), which is transformed in terms of wind speed v and mean recurrence interval R (Holmes, 2001; Equation 2).

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

$$v = u\left[-\ ln\frac{1}{R}\right]^{\frac{1}{\alpha}} \tag{2}$$

Mean roof height wind pressure q_h is calculated using Equation 3 (ASCE, 2010), 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.

$$q_h = 0.613 K_z K_{zt} K_d V^2 \quad (N/m^2) \tag{3}$$

Expected wind loss $E[L]$ is calculated by convolving the continuous wind speed probability density function $f_V\ (v)$ with building fragility curves $L(v)$ expressed as a function of wind speed, v (Equation 4).

$$E[L] = \int_0^{\infty} f_V\ (v) L(v) dv \tag{4}$$

To model expected annual loss (EAL) for statically elevated buildings, the MRH wind speed is calculated using the power law, and the corresponding loss is derived from published Hazus loss functions modified to account for increased MRH wind speed. Monte Carlo simulation is used to convolve fragility curves with the wind hazard probability curve to ensure result stability. This process is repeated for increasing top of first floor elevations, beginning at ground level. EAL is calculated for buoyant-foundation-supported buildings using the standard Hazus loss functions, as any increase in building elevation would result from an increase in local water elevation, resulting in an essentially consistent relative MRH.

3. CASE STUDY AND RELEVANCE

The case study considers 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 (ASCE, 2010).

Considering a 4 m MRH elevated to a maximum 10 m MRH, the increase in wind speed is calculated using the power law for the range of surface roughness lengths used within FEMA's Hazus-MH (FEMA, 2012), shown in Figure 5. Depending on exposure, MRH wind speeds increase by 8% for Exposure D to 19% for Exposure A when the MRH is elevated from 4 m to 10 m. The increase in wind speed becomes more exaggerated the higher the structure is raised above the ground, and these increased wind speeds result in increases in the velocity pressure coefficient, K_z, in the range of 15%-35% depending on exposure (Figure 6). By raising houses to increase their resilience to catastrophic floods, homeowners are significantly increasing the exposure of their homes to stronger wind forces and pressures and thus increasing the likelihood of wind damage.

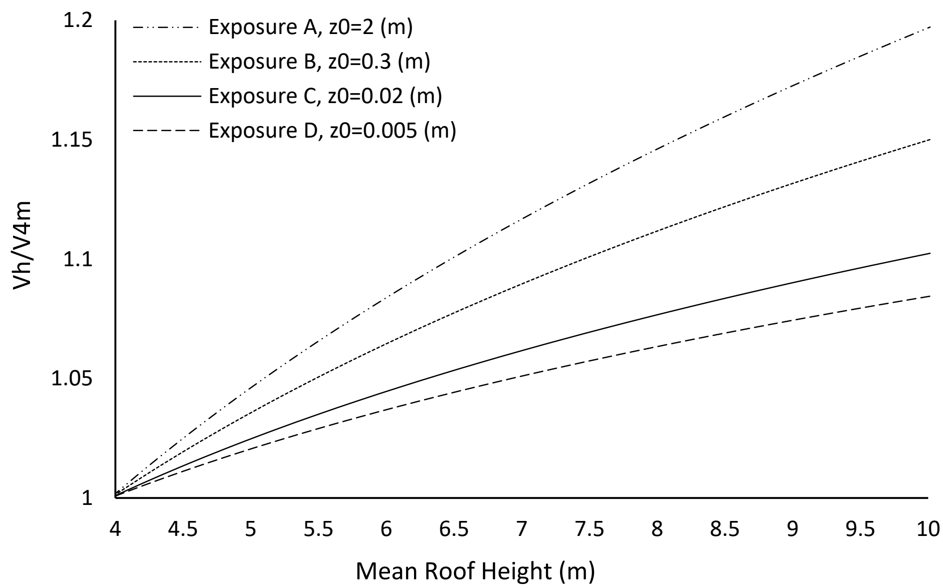

Figure 5. Ratio of mean roof height wind speed to 4m wind speed

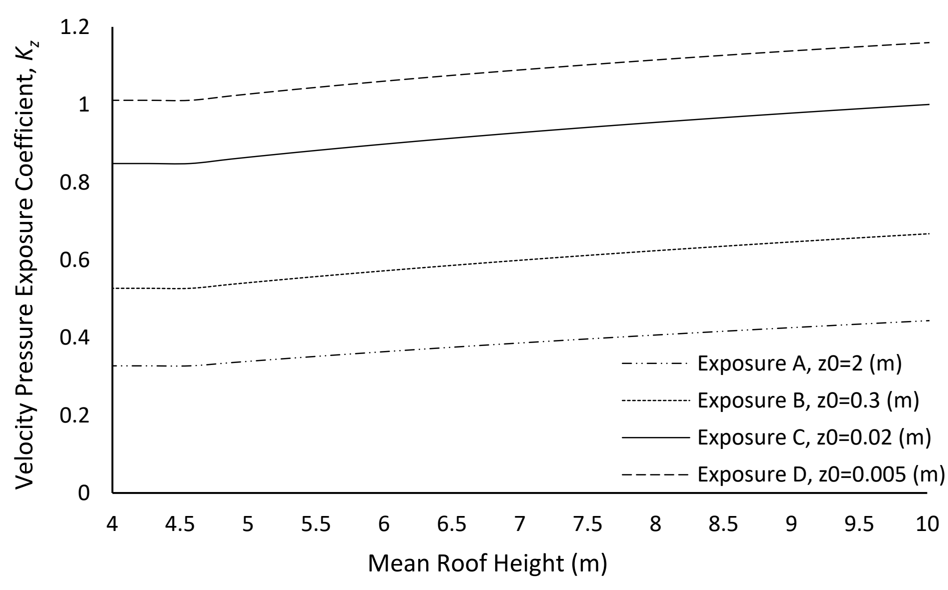

Figure 6. Velocity pressure exposure coefficient as a function of mean roof height

In open terrain (z_0 = 0.03 m), for example, this building with a 4 m MRH is expected to experience an annual loss (EAL) of 2.8%. By elevating the building to an MRH of 10 m, the EAL becomes 4.9%, an increase of 75%. This effect becomes more pronounced as the terrain roughness increases.

The full case study we are developing compares building vulnerability for statically-elevated and buoyant-foundation-retrofitted low-rise residential buildings located across multiple ASCE 7-10 wind speed contours. The full case study results will present EAL data over the range of elevations that are expected to comply with FEMA base flood elevation (BFE) requirements.

Preliminary analyses suggest 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 regions surrounding the Gulf of Mexico that are the focus of our investigation. Implementing flood mitigation by amphibiation eliminates the increase in expected wind damage loss that accompanies permanent static elevation. The methodology developed in this paper and the results of the case studies will improve our understanding of the relationship between elevation above ground level and expected wind loss, which ultimately will support improved decision-making for loss reduction for combined wind and flood hazards.

4. CONCLUSIONS

Global climate change and warmer ocean temperatures are expected to 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 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 retrofit construction is a low-impact hurricane mitigation strategy that provides flood protection to an existing building without increasing its exposure to strong winds. This is an innovative flood mitigation and climate change adaptation strategy that 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 subjected to higher wind speeds and pressures, and therefore become more vulnerable to wind damage. In addition, retrofitting with permanent static elevation is a much more expensive option, at roughly twice the cost of an amphibious retrofit. Static elevation also disrupts the visual coherence of an existing neighborhood, which is a particularly important consideration for neighborhoods where historic preservation is an issue.

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 combined wind and flood hazards.

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