

Combined Flood and Wind Mitigation for Hurricane Damage Prevention: The Case for Amphibious Construction

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Abstract

Some initiatives that are intended to mitigate extreme flood events do not fully consider the impact of less catastrophic but more commonly occurring wind-induced damage, which is a significant issue particularly in regions that are prone to hurricanes. The policies of the US Federal Emergency Management Agency (FEMA) encourage homeowners to implement permanent static elevation to increase their flood resilience. However, substantial elevation can increase a structure's vulnerability to wind. In effect, by protecting against a rare but catastrophic flood occurrence, these houses are made considerably more vulnerable to less severe but more regularly occurring wind events and thus face an increased likelihood of wind damage. This study introduces amphibious construction as an innovative retrofit flood mitigation and climate change adaptation strategy. It also evaluates the increased vulnerability to wind damage that accompanies permanent static elevation (PSE), to which amphibious retrofit construction is an alternative. The results of our investigation suggest that amphibious construction could provide a beneficial alternative solution to mitigating hurricane damage, as it is a strategy that can reduce vulnerability to flood damage without increasing vulnerability to wind damage.

Keywords: hurricane damage reduction; flood mitigation; wind damage; multi-hazard mitigation; permanent static elevation; amphibious construction; buoyant foundation; damage risk reduction; non-structural floodproofing; adaptive flood risk management; climate change adaptation.

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Introduction

In the U.S., more than 75% of all federal disaster declarations are related to flood events (Li and van de Lindt 2012). In flood-prone areas, the most recommended method to reduce flood-induced losses is elevating the building or building components to reduce the probability of contact with flood waters (Kreibich et al. 2005, Bin et al. 2008, Taggart and van de Lindt 2009). In order to retain eligibility for flood insurance provided by the National Flood Insurance Program (NFIP), homeowners are strongly encouraged to elevate their houses to comply with the NFIP flood map regulations issued by the US Federal Emergency Management Agency (FEMA).

However, permanently elevating houses creates new problems such as inconvenient access to living areas, poor accessibility for the elderly and others with restricted mobility, loss of neighborhood character, and increased vulnerability of the structure to wind damage. In some cases, homes are elevated by 7 meters or more, which exposes them to considerably stronger winds. By raising their houses to increase their resilience to catastrophic floods, homeowners are unwittingly increasing the wind exposure of their homes. All too often, as the focus is on mitigating flood damage rather than the potential for wind damage, the increased elevation is not accompanied by reinforcement of the roof to withstand the increased roof pressures, resulting in extensive roof damage (Figure 1).

Statically elevated buildings are subjected to greater wind speeds and hence wind pressures and forces, which are a function of the square of the wind speed, on a regularly occurring basis because of their increased height above the ground. The increased vulnerability of permanently elevated homes to wind damage is explained by the boundary layer wind gradient, as wind velocity increases with height above the surface of the earth (Cochran 2012). Sites that are exposed to hurricane hazards may be located in coastal regions, where the upwind fetch is often open water or flat, smooth terrain. In these areas of smooth fetch, lower surface roughness results in higher wind speeds with height than in areas with rougher terrain. Consequently, if a coastal community is required to elevate their homes high above the ground to comply with new Base Flood Elevation (BFE) requirements, their homes may be exposed to significantly higher wind speeds. The increases in wind speed that accompany permanent static elevation (PSE) expose the structure to exponentially higher wind forces, which may have significant impacts on building damage and economic loss (English et al. 2015).



Fig. 1 Statically elevated houses on the Gulf Coast with extensive roof damage (William Widmer; FEMA/ Greg Henshall)

Amphibious construction is a retrofit approach that offers an alternative to PSE. Amphibious construction refers to an innovative 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 (English 2009, English et al. 2016). 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 to avoid damage when flooding occurs.

This paper provides a general description of the components of amphibious construction, reviews the benefits of amphibious retrofit compared to PSE and explores the wind vulnerability of PSE homes as a result of the increased wind loads that accompany a permanent increase in elevation. Vulnerability to wind hazards is generally expressed either as a function of physical damage or in economic terms representing the repair or replacement of the wind-induced damage (i.e., loss). The increased vulnerability of PSE 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.

Amphibious Construction and Reduced Flood Damage

There are two fundamental components of an amphibious flood mitigation system. Basic amphibiation requires buoyancy to provide temporary flotation and vertical guidance to prevent lateral movement. The flexible elevation provides a house with greater resilience to flooding without permanently exposing the structure to increased wind forces. As the house remains close to the ground except during extreme flooding, any increase in wind velocity and force is minimal compared to the exponential increase in force that results from permanently elevating the house (Figure 2).

Amphibious construction provides dramatically improved multi-hazard resilience in hurricane zones by being able to withstand both the occasional flood events and the more frequently occurring wind events that characterize hurricanes. This innovative technology allows homes and their contents to survive hurricanes undamaged, and such weather-related



Fig. 2 Amphibious houses in Maasbommel, The Netherlands, and Old River Landing, Louisiana (photos permission of Buoyant Foundation Project)



Fig. 3 Flood performance of amphibious houses in Maasbommel, The Netherlands, and Old River Landing, Louisiana (photos permission of Buoyant Foundation Project)

events become temporary inconveniences rather than catastrophes (English, 2014). As is the case with permanent static elevation (PSE), occupants are expected to evacuate for the duration of the event. If their house has been amphibiated, they may expect to return to a home with no significant damage. Maasbommel in the Netherlands and Old River Landing in Louisiana both experienced extreme flood conditions in 2011 (albeit without severe winds in these non-coastal locations). The amphibious houses in both of these situations successfully demonstrated the potential of this emerging technology (Figure 3).

In a severe event where flooding may reach unanticipated depths, the fixed height of PSE may prove to be inadequate. As climate change stimulates sea level rise and more extreme weather events, severe flooding is predicted to become more frequent as well. Community resilience will require holistic solutions to address this altered hazard landscape, as infrastructure may be overwhelmed by the changing hazard environment. However, 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 on the surface of the floodwater to the elevation necessary to keep the interior from flooding. As stronger hurricane winds exacerbate the impact of floods, flood mitigation strategies that rely on PSE will become inadequate when record floods reach heights beyond the levels that were anticipated at the time of construction (Figure 4).



Fig. 4 Comparison of flood performance of amphibious houses (undamaged) vs. PSE structures (damaged), Old River Landing, Louisiana (photos permission of Buoyant Foundation Project)

The Buoyant Foundation Project (BFP) is a non-profit research initiative that specializes in the design of retrofitted amphibious foundations for existing houses. Buoyant foundations work much like floating docks. With the installation of buoyancy elements, a structural sub-frame and vertical guidance posts, an “amphibiated” building is able to rise and descend on the surface of the water, but not to move horizontally. Underneath the house, the buoyancy elements displace water to provide flotation. Vertical guidance posts (VGPs) restrain lateral movement and rotation as required so that the building can only move straight up and down. A structural sub-frame reinforces the existing floor framing and supports the buoyancy elements, transferring their uplift forces to the reinforced first floor framing beams. It also provides the connection to the VGPs. It is beyond the scope of this paper to review the several options for each of these three basic components and the multiple ways in which they can be combined into a system that responds to the particular requirements and constraints of a specific context. Figure 5 illustrates one such possible configuration of the necessary components into a system.

Utility lines may be fitted with long, coiled “umbilical” lines for water and electrical supply, and self-sealing “breakaway” connections that disconnect sewer and natural gas lines when the house begins to rise. The cost of these minor adaptations to accommodate the utilities is minimal. There are more elaborate systems available at greater expense.

In addition to providing increased resilience to both flood and wind hazards, retrofitted buoyant foundations are also more environmentally and culturally sustainable than PSE. As a surface application that does not require replacement of the existing gravity-load-bearing foundation, retrofitted amphibious foundations have a lesser environmental impact. Amphibious foundations also preserve the traditional relationship of the house to the ground, supporting the cultural continuity of the community. On the other hand, PSE homes may drastically alter the appearance 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

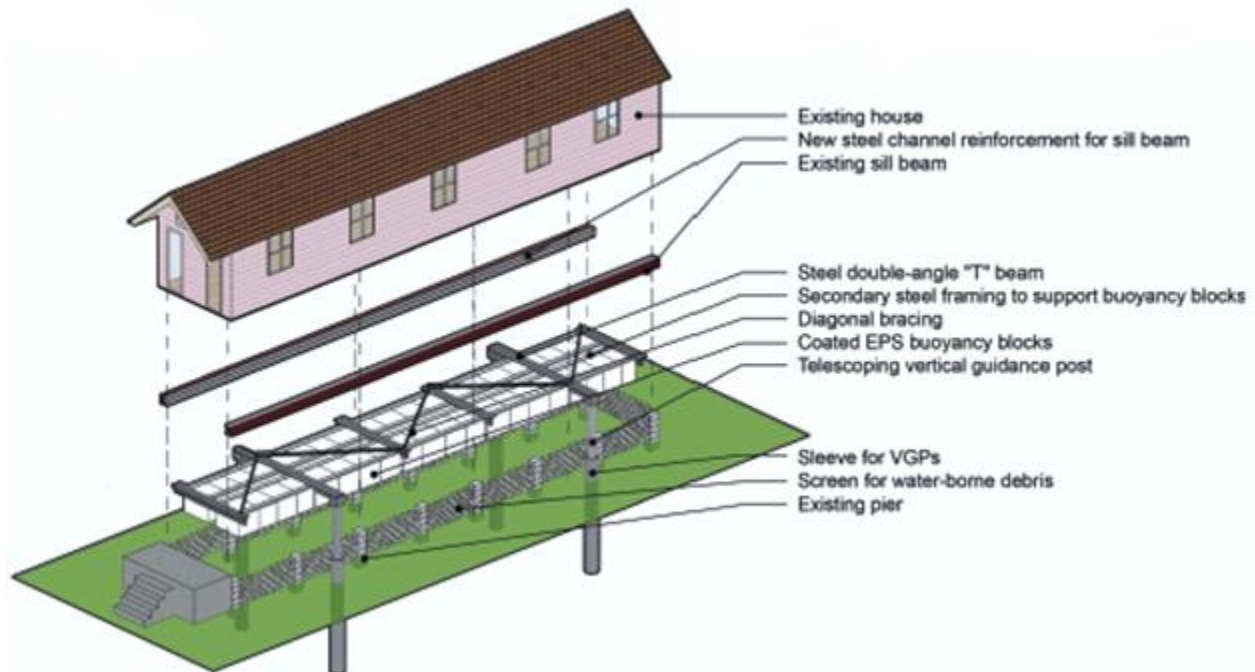


Fig. 5 Components of a retrofitted buoyant foundation (Buoyant Foundation Project)

neighborhood character and sense of community. Amphibious foundations alleviate the long-term degradation of flood protection that results from soil subsidence and elevated sea level due to climate change, an unwelcome loss of long-term effectiveness that PSE cannot avoid.

Buoyant foundations (retrofitted amphibious foundations) are also more economical for homeowners as their installation is considerably less expensive than PSE. This is in large part because PSE requires the replacement of the entire foundation system, whereas an amphibious retrofit retains the existing foundation, supplementing its ongoing gravity load-bearing function with a buoyancy system to provide uplift in the event of flooding and a vertical guidance system to resist lateral loads such as those generated by the forces of wind and flowing water. The expense associated with replacing the entire foundation system far exceeds what is required simply to add vertical guidance posts and buoyancy elements. Detailed cost comparisons show that amphibious retrofits generally range from one-quarter to one-half of the cost of PSE, and are typically around 30%. This emerging technology thus provides a holistic strategy for increasing the resilience of communities in the face of climate change, as it is environmentally, culturally, and economically sustainable.

Amphibious construction is not, however, a solution that is appropriate for all circumstances. Amphibious strategies as currently implemented are not intended for application in conditions where wave action or high velocity current is expected. For buildings exposed directly to wave impacts, horizontal wave forces are one of the primary drivers of building damage (Koshimura et al. 2009, Nadal et al. 2009, Tomiczek et al. 2013). Increased first floor elevation, or PSE, is currently considered the most effective mitigation for wave-induced damage (Tomiczek et al. 2013). Amphibious applications are at present more suitable for flooding due to rising water than for fast-flowing or wave-impacted flood conditions, and are appropriate for such locations as large, flat floodplain areas, regions that are protected by levees where flooding is due to overtopping, and coastal regions well-protected by barrier islands or peninsulas. Vertical guidance systems for BFP applications have to date been designed to withstand floodwater velocities of 1.5-2.0 mps, depending on local conditions.

Permanent Static Elevation and Increased Wind Vulnerability

It is well known that wind speed increases with increasing height above the ground. This behavior has been measured in the atmosphere and simulated in wind tunnel testing for building design, e.g., Mara (2015). Wind speeds at the earth's surface are slower and more turbulent due to friction from terrain obstacles. With increasing height, wind speeds are less affected by this friction and approach the gradient wind speed, which is assumed to be constant above the gradient height.

Wind Speed

In the absence of flood conditions, PSE buildings are subjected to greater wind speeds on a daily basis because of their increased height. 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 (Equation 1) and the power law (Equation 2) (Panofsky and Townsend 1964, Peterson and Hennessey 1978, Ray et al. 2006):

$$\frac{U_{z_1}}{U_{z_2}} = \frac{\ln \frac{z_1}{z_0}}{\ln \frac{z_2}{z_0}} \quad (1)$$

$$\frac{U_{z_1}}{U_{z_2}} = \left(\frac{z_1}{z_2}\right)^{1/\alpha} \quad (2)$$

where z_1 and z_2 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; ASCE, 2010), where c_1 is 5.65.

$$\alpha = c_1 z_0^{-0.133} \quad (3)$$

For the case of a low-rise building with a mean roof height (MRH) of 4 meters that is elevated to MRH 10 meters, the increase in wind speed for a range of surface roughnesses can be calculated using the power law, as shown in Table 1.

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

Wind Pressure

There has been little experimental work investigating the effect of PSE on wind pressures and resulting wind loads. Holmes (1994) conducted a series of wind tunnel experiments to determine wind pressures induced on the exterior of walls and roofs (i.e., external wind pressure) for tropical-style single-story homes with gable-roof pitches ranging from 10° to 30° and with eave heights of 3.0 meters (non-elevated) and 5.1 meters (elevated) for wind mean directions of 0° , 60° , and 90° . Comparison of results for non-elevated and elevated houses demonstrated higher wall and roof mean pressure coefficient magnitudes for PSE houses. Mean wall pressure coefficients were found to be considerably higher on the windward wall and on windward edges of the side walls. Holmes' experimental tests also found that peak pressure coefficients are significantly higher for PSE homes and he concluded that the combined static and dynamic pressures for PSE homes may be 40-80% greater than for non-elevated buildings in the same windstorm.

To find the wind pressure and increase in pressure with increasing mean roof height h , q_h (Equation 4; ASCE, 2010) 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 $4.6 \text{ m} \leq z \leq z_g$; K_{zt} is the topographic factor; K_d is the wind directionality factor; and V is the basic wind speed.

$$q_h = 0.613K_zK_{zt}K_dV^2 \quad (\text{N/m}^2) \quad (4)$$

Holding all other factors constant, the increase in wind pressure was calculated for a range of surface roughnesses for the case of a low-rise building with a mean roof height of 4 meters that has been elevated to 10 meters. Mean roof height wind pressures were found to increase by

18.8% in open terrain and by 35.2% in urban terrain, as shown in Table 2.

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%

Internal wind pressures, which are produced on the interior of the building as a function of the porosity of the building envelope, affect the net (i.e., combined internal and external) wind pressures acting on walls and roofs. In some situations, such as low rise buildings with dominant openings, internal pressures can be significant (Holmes 2001). Regardless of coastal home foundation type (i.e., elevated or non-elevated), failures of roofs during severe windstorms often occur following window failure on the windward wall, resulting in substantial building damage and loss. The effects of internal wind pressure may be dramatically increased in PSE homes, which are exposed to higher wind velocity and wind pressure, significantly increasing the wind hazard vulnerability of these homes.

Economic Loss

Loss functions typically relate relative economic loss as a ratio of building value (i.e., 0 to 1.0) as a function of wind speed. To calculate the increase in economic loss with increasing elevation, expected losses are calculated by convolving two continuous curves, the fragility curve and wind speed probability density function (PDF) (Amoroso and Fennell 2008, Bjarnadottir and Stewart 2011, Li 2012, Li and Ellingwood 2006), where $E[L]$ is the expected annual loss, $f_V(v)$ is the probability density function (PDF) of annual wind maxima, and $L(v)$ is the loss curve as a function of wind speed, v (Equation 5).

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

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 non-exceedance 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).

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

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

A single-story, single-family residence is selected to demonstrate the expected increase in MRH wind speed and wind pressure, along with the associated increase in expected annual loss. The case study building is assumed to have a gable-roof, toe-nail roof to wall connections, no secondary water resistance on the roof sheathing seams, no 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 (160 mph) ASCE 7-10 Occupancy Category II wind speed contour (ASCE, 2010) in open terrain ($z_0 = 0.03$ m). The case study building is assumed to be elevated from an MRH of 4 meters to 10 meters, and residential economic loss functions from FEMA's Hazus-MH (FEMA, 2012) were used to calculate the building annual economic loss.

A Monte Carlo simulation with 50,000 iterations was used to convolve the Hazus loss functions with the wind hazard curve to ensure the stability of the results. From Tables 1 and 2, the increase in MRH wind speed is approximately 11%, corresponding to an increase in wind pressure of 19%. With a 4 m MRH, the case study building has an expected annual loss of 2.8%. By elevating the building to a MRH of 10 m, the EAL becomes 4.9%, an increase 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. This 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, particularly in regions where significant wind events occur more regularly. Clearly, a flood mitigation strategy such as amphibiation that is not accompanied by increased wind vulnerability could be advantageous.

Discussion

The most important considerations in determining the vertical wind speed profile are the surface roughness (i.e., terrain) and the height above the earth's surface. The calculations for the wind speed profile are very straightforward; however, when floodwaters cover large land areas, both of these variables may change dramatically. Surface roughness may be significantly reduced as vegetation and other obstacles are covered by virtually flat floodwaters, thus tending to increase wind speeds. At the same time, the height of a PSE building above the earth's now water-covered surface decreases as the floodwater rises, which would otherwise tend to decrease wind speeds. For amphibious foundations, the height of the building relative to the earth's surface does not change considerably with flooding, as the building rises only with the rising surface of the floodwater and remains at a constant height above the water's surface.

A limitation of the quantitative methodology to calculate expected wind loss for PSE buildings is that it does not consider the reduction in mean roof height of a PSE building as a result of rising floodwaters. To include this aspect requires location-specific knowledge of the joint wind and flood hazard distribution, which is not considered in this paper but is a topic of future work. Final determination of the relative wind and flood vulnerability of PSE buildings versus those that are provided with buoyant foundations and only temporarily elevated during a flood requires analysis of the underlying hazards, their return period distributions, and the extent of damage and loss associated with each hazard (e.g., loss functions).

Conclusions

Global climate change and warmer ocean temperatures are anticipated 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 it is essential to develop sustainable strategies that will allow coastal communities to become more resilient.

Amphibious construction is a low-impact hurricane mitigation strategy that provides flood protection without increasing exposure to strong winds. It is an innovative approach that is rapidly gaining acceptance and finding application around the globe. While the new BFE requirements issued by FEMA aim to provide increased resilience to floods, the increased static elevation levels are problematic in that permanently elevated structures are exponentially more vulnerable to wind damage. In addition, PSE is more expensive, disrupts the visual coherence of traditional neighborhoods, and may not provide sufficient elevation when an extreme flood exceeds the predicted levels for which the elevation height was determined.

Amphibious foundations provide an alternate hurricane mitigation and climate change adaptation 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 an efficient, entirely passive solution that works in synchrony with floodwater instead of resisting it. This low-impact technology thus provides houses with an even greater resilience to rising flood levels than PSE, without increasing the exposure of the structure to the more regularly occurring strong winds.

A simple case study was presented that demonstrated increases in wind speeds, wind pressures and expected annual wind losses of 11%, 19%, and 75%, respectively, when elevating a single family home from a 4 m MRH to a 10 m MRH. Future work 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 determine 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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References

- Amoroso, S. D., and Fennell, J. P. (2008). "A rational benefit/cost approach to evaluating structural mitigation for wind damage: Learning "the hard way" and looking forward." *Proc., Structures Congress 2008*, Vancouver, British Columbia, Canada.
- ASCE (American Society of Civil Engineers). (2010). "Minimum design loads for buildings and other structures" *ASCE/SEI 7-10*. Reston, VA.
- Bin, O., Kruse, J. B., and Landry, C.E. (2008). "Flood hazards, insurance rates, and amenities: Evidence from the coastal housing market." *Journal of Risk and Insurance* 75(1), 63-82.
- Bjarnadottir, S., Li, Y., and Stewart, M. G. (2011). "A probabilistic-based framework for impact and adaptation assessment of climate change on hurricane damage risks and costs." *Structural Safety*, 33(3), 173-185. doi: <http://dx.doi.org/10.1016/j.strusafe.2011.02.003>.
- Buoyant Foundation Project. (2016). Website: www.buoyantfoundation.org.
- Cochran, L., ed. (2012). *Wind Issues in the Design of Buildings*. American Society of Civil Engineers, Reston, VA.
- English, E. C. (2009). "Amphibious foundations and the buoyant foundation project: Innovative strategies for flood resilient housing." *International Conference on Urban Flood Management*, UNESCO-IHP and COST Action C22, Paris, France. Available from: http://www.buoyantfoundation.org/pdfs/ECenglish_ParisUFMpaper_nov2009.pdf
- English, E. C. (2014). "Amphibious architecture: An innovative strategy for flood resilient housing." *HazNet* 6(1), 20-22.
- English, E. C., Friedland, C. J., and Orooji, F. (2015). "Amphibious construction vs. permanent static elevation: Flood resilience without increased vulnerability to wind." *Proc. First International Conference on Amphibious Architecture, Design and Engineering (ICAADE 2015)*, Bangkok, Thailand.
- English, E. C., Klink, N. E. and Turner, S. (2016). "Thriving with water: Developments in amphibious architecture in North America." *Proc. Floodrisk Conference*, Lyon, France, in press.
- FEMA. (2012). HAZUS MH MR2 multi-hazard loss estimation methodology: Hurricane model technical manual. Washington, D.C., FEMA.
- Holmes, J. D. (1994). "Wind pressures on tropical housing." *Journal of Wind Engineering and Industrial Aerodynamics*, 53(1), 105-123.
- Holmes, J. D. (2001). *Wind loading of structures.*, CRC Press, London, U.K.
- Hsu, S. A., Meindl, E. A., and Gilhousen, D. B. (1994). "Determining the power-law wind-profile exponent under near-neutral stability conditions at sea." *Journal of Applied Meteorology*, 33(6), 757-765.
- Koshimura, S., Oie, T, Yanagisawa, H., and Imamura, F. (2009). "Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia." *Coastal Engineering Journal* 51(03), 243-273.
- Kreibich, H., Thieken, A. H., Petrow, T., Müller M., and Merz, B. (2005). "Flood loss reduction of private households due to building precautionary measures--lessons learned from the Elbe flood in August 2002." *Natural Hazards and Earth System Science* 5(1), 117-126.
- Li, Y. (2012). "Assessment of damage risks to residential buildings and cost-benefit of mitigation strategies considering hurricane and earthquake hazards." *Journal of Performance of Constructed Facilities*, 26(1), 7-16.

- Li, Y., and Ellingwood, B. R. (2006). "Hurricane damage to residential construction in the US: Importance of uncertainty modeling in risk assessment." *Engineering Structures*, 28(7), 1009-1018.
- Li, Y., and van de Lindt, J. W. (2012). "Loss-based formulation for multiple hazards with application to residential buildings." *Engineering Structures* 38, 123-133.
- Mara, T. G. (2015). "Modern and unique architecture: A perspective from the wind tunnel." *Proc., AEI Conference 2015*, American Society of Civil Engineers, Milwaukee, WI.
- Nadal, N. C., Zapata, R. E., Pagan, I., Lopez, R. and Agudelo, J. (2009). "Building damage due to riverine and coastal floods." *Journal of Water Resources Planning and Management* 136(3), 327-336.
- Panofsky, H. A., and Townsend, A. A. (1964). "Change of terrain roughness and the wind profile." *Quarterly Journal of the Royal Meteorological Society*, 90(384), 147-155. doi: 10.1002/qj.49709038404
- Peterson, E. W., and Hennessey, J. P. (1978). "On the use of power laws for estimates of wind power potential." *Journal of Applied Meteorology*, 17(3), 390-394. doi: 10.1175/1520-0450(1978)017<0390:OTUOPL>2.0.CO;2.
- Pinelli, J.-P., Simiu, E., Gurley, K., Subramanian, C., Zhang, L., Cope, A., Filliben, J. J. and Hamid, S. (2004). "Hurricane damage prediction model for residential structures." *Journal of Structural Engineering* 130(11), 1685-1691.
- Pita, G. L., Pinelli, J.-P., Gurley, K. R., and Hamid, S. (2013). "Hurricane vulnerability modeling: Development and future trends." *Journal of Wind Engineering and Industrial Aerodynamics* 114, 96-105.
- Ray, M. L., Rogers, A. L., and McGowan, J. G. (2006). "Analysis of wind shear models and trends in different terrains." *Proc., Windpower 2005*, American Wind Energy Association Pittsburgh, PA.
- Taggart, M., and van de Lindt, J. W. (2009). "Performance-based design of residential wood-frame buildings for flood based on manageable loss." *Journal of Performance of Constructed Facilities* 23(2), 56-64.
- Tomiczek, T., Kennedy, A., and Rogers, S. (2013). "Collapse limit state fragilities of wood-framed residences from storm surge and waves during Hurricane Ike." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 140(1), 43-55.