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Analytical Damage Quantification Method for Residential Developments Subjected to Hurricane Wind Hazards

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ABSTRACT: Hurricanes, typhoons, and cyclones (hereafter referred to as “hurricanes”) continue to have a significant impact on residential developments around the world. As more populations continue to migrate into the path of these costly natural hazards, it is becoming increasingly important to develop new methods to quantify damage to residential developments in order to increase the resilience of communities. One way to increase community resilience from a structural engineering standpoint is to limit the damage incurred by a residential development subjected to a hurricane wind event. Previous post-hurricane damage assessments have illustrated the integrity of the building envelope plays a key role in reducing or even eliminating the significant losses typically associated with hurricane wind hazards. In order to assess the post-hurricane state of a residential development, three failure modes common to residential building envelopes are implemented using the axioms of probability to implement an analytical damage quantification method. Results illustrating the implementation of the proposed method will be presented using a probabilistic building envelope failure assessment model applied to a residential development subjected to ten synthetic hurricane events each with a maximum mean wind speed equivalent to a 700-year return period wind speed. Benefits are twofold, as this research provides (1) a useful tool for assessing the state of physical residential developments with information readily available after post-hurricane damage assessments, and (2) the ability to determine the temporal status of a residential development during the recovery process, which is crucial to implement community life-cycle resilience assessments.

1. INTRODUCTION

Socioeconomic loss due to hurricane wind hazards is a topic that has received a significant amount of attention since the landfall of Hurricane Hugo (1989) in South Carolina and Hurricane Andrew (1992) in southern Florida. However, the National Science Board (NSB) (2007) acknowledges that, despite advances in hurricane research, there is still significant research that needs to be conducted in order to reduce the socioeconomic impact of hurricanes. The NSB assigns a high priority to quantifying hurricane/structure interactions, noting that current risk prediction models are overly simplified in many cases. Additionally, the NSB states that assessing and improving the resilience of civil infrastructure from an engineering and socioeconomic perspective is extremely important to response and recovery efforts, especially pertaining to identifying and prioritizing the most cost-effective hurricane mitigation techniques.

There have been studies performed that quantify residential damage incurred during extreme wind events (e.g., Gurley et al. 2005; Li and Ellingwood 2009; Lin 2010; Vickery et al. 2006; Yau et al. 2011). However, few of these studies have investigated residential developments subjected to hurricane wind hazards in an effort to capture the synergistic relationships between homes within a residential development. These relationships between individual homes within a residential development are due to their interaction through wind-borne debris impacts, which can cause significant damage similar to that of direct wind loading (Holmes 2010).

Considering that approximately 90% of residential structures in the United States (U.S.) consist of light-frame wood construction, coupled with the annual U.S. coastal population growth (U.S. Census Bureau 2011; NOAA 2011), it intuitive that there will continue to be an increase in socioeconomic losses due to hurricanes and other extreme wind events. Post-hurricane damage assessments have illustrated that losses experienced by residential housing during a hurricane can be attributed to breach of the building envelope by wind and wind-driven rain (Rosowsky and Schiff 2003; Gaynor and Simiu 2007), which further emphasizes the need for building envelope failure research.

Gaynor and Simiu (2007) state that loss estimation methodologies on the community scale are a necessary evolution of hazard-based research. Therefore, the mechanics-based building envelope failure assessment (BEFA) model developed by Grayson et al. (2013) integrates the performance of building envelope components in order to consider the synergistic effects of wind-borne debris explicitly. However, the integration of building components through a first principles model has its own challenges with respect to placing the damage contributed by several different failure modes of the building envelope into similar categories. This requires a novel analytical damage quantification method rooted in probability to combine the damage effects from the failure modes of the building envelope.

2. METHODOLOGY

2.1. Quantification of building envelope damage

The BEFA model was implemented to determine the overall performance of a residential development subjected to hurricane wind hazards at various levels of vulnerability. However, it was necessary to establish a metric to quantify the amount of damage incurred by the individual building envelopes during a hurricane wind event. This was accomplished by adapting the damage state descriptions for residential housing defined within the HAZUS-MH model (Vickery et al. 2006) to delineate between specific damage states. Table 1 lists the damage state descriptors that correspond to each damage state of the building envelope, and the values of these damage descriptors presented as a number or percentage of failed building envelope components and wind-borne debris impacts.

*Table 1: Damage state descriptions within HAZUS **

Failure type	Damage state	Descriptor values
Roof covering	Very minor	≤ 2%
	Minor	> 2% and ≤ 15%
	Moderate	> 15% and ≤ 50%
	Severe	> 50%
	Destruction	> 50%
Windows/ Doors (WD)	Very minor	0
	Minor	1 window or door
	Moderate	> 1 and ≤ max(20%, 3 WD)
	Severe	> max(20%, 3 WD) and ≤ 50%
	Destruction	> 50%
Sheathing loss	Very minor	0 panels
	Minor	0 panels
	Moderate	1 to 3 panels
	Severe	> 3 panels but ≤ 25% of sheathing
	Destruction	> 25% of sheathing
Impacts	Very minor	0 impacts
	Minor	< 5 impacts
	Moderate	5-10 impacts
	Severe	10-20 impacts
	Destruction	> 20 impacts

* Taken from Vickery et al. (2006)

2.2. Determination of damage state thresholds

The BEFA model is capable of determining the percentage of the building envelope penetrated by window, door, and sheathing failures, and the percentage of roof covering that is missing from the underlying roof sheathing. The damage state descriptor values from Table 1 had to be converted to a common measure as a percentage of building envelope damage. Roof covering was already given as a percentage and did not need to be further converted. However, window/door failures and sheathing failures for some damage states were given as a number of failed components rather than a percentage of the components that make up that portion of the building envelope. Average component areas typical to residential developments were used to determine the percentage of building envelope represented by each component in order to convert the number of failed components into a percentage of the specific failure type.

In addition to determining the contribution of individual building envelope components, wind-borne debris impacts that contributed to the damage of the building envelope needed to be determined on a percentage basis. However, little research has sought to quantify the number of impacts required for complete destruction of the building envelope of a structure. Therefore, at this point it was assumed that the total number of impacts that would cause complete destruction of a building envelope is seventy-five impacts. This value was chosen to provide building envelope damage percentages that are comparable to the other failure types within each damage state. Once the damage state descriptor values were determined on a percentage basis, threshold values for each of the damage states were determined for each of the four identified failure types as shown in Table 2.

The BEFA model is capable of measuring each of these failure types. However, it was necessary to determine how these failure types contribute to an overall building envelope damage value. The four failure types defined in Tables 1 and 2 were grouped into three failure modes and ranked based on their damage potential to the building envelope (see Table 3). This approach required that two of the failure types identified by Vickery et al. (2006) (i.e., sheathing failure, and window and door failure) were combined into a single failure mode that represented an actual penetration of the building envelope. Determination of the failure mode 3 contribution from each of these two failure types consisted of weighting the damage of the two failure types based on the percentage of the building envelope that they occupy on average as shown in Eq. (1):

$$\psi_{3_i} = \lambda_{vc}\psi_{vc_i} + \lambda_{sh}\psi_{sh_i} \tag{1}$$

where, λ_{vc} and λ_{sh} are the fraction of the building envelope occupied by the vulnerable components (i.e., windows and doors) and sheathing, respectively, and ψ_{vc_i} and ψ_{sh_i} are the damage values for the vulnerable components and sheathing for damage state *i* (i.e., the damage states identified in Tables 1 and 2), respectively.

Table 2: Damage state threshold values

Failure type	**Damage state**	**Threshold (%)**
Roof covering	Very minor	2
	Minor	15
	Moderate	50
	Severe	> 50
	Destruction	> 50
Windows/ Doors (WD)	Very minor	0
	Minor	5
	Moderate	20
	Severe	50
	Destruction	> 50
Sheathing loss	Very minor	0
	Minor	0
	Moderate	6
	Severe	25
	Destruction	> 25
Impacts	Very minor	0
	Minor	7
	Moderate	13
	Severe	27
	Destruction	> 27

Table 3: Ranking the building envelope failure modes

Failure type	**Failure mode**	**Ranking**
Sheathing/window/ door failures	Building envelope (BE) penetration	3
Wind-borne debris impacts	Potential for BE penetration	2
Roof covering loss	No BE penetration	1

Using the residential development modeled in this study as an example, the vulnerable components occupied approximately ten percent (i.e., $\lambda_{vc} = 0.10$) and the sheathing occupied the remaining ninety percent (i.e., $\lambda_{sh} = 0.90$) of the building envelope surface area. Combining the sheathing, window, and door failure types into a single failure mode provided the damage state threshold values for the three failure modes as shown in Table 4.

Table 4: Failure mode damage threshold values (ψ)

Failure mode	Damage state	Value
1: No BE penetration (i.e., roof covering loss)	Very minor	2
	Minor	15
	Moderate	50
	Severe	> 50
	Destruction	> 50
2: Potential BE penetration (i.e., wind-borne debris impact)	Very minor	0
	Minor	7
	Moderate	13
	Severe	27
	Destruction	> 27
3: BE penetration (i.e., sheathing/window/door failure)	Very minor	0
	Minor	0.5
	Moderate	7.4
	Severe	27.5
	Destruction	> 27.5

2.3. Calculation of building envelope damage

Figure 1 provides the general logical relationships between each of the failure modes identified in Table 4. It is assumed that these three failure modes are the only failures modes possible for the building envelope of a home based on the results of Vickery et al. (2006). Figure 1 provides a reasonable assumption for the failure modes given that each of the three failure modes can occur to a home without one or both of the other failure modes occurring. For example, wind-borne debris impacts can occur to a home within a residential development without any roof covering, sheathing, or window/door failures occurring to that particular home).

Vickery et al. (2006) assumes that a building is classified in a particular damage state if it exceeds the criteria of any one of the failure types for the corresponding damage state. This permits the building envelope damage caused by the three failure modes to be calculated as the union of the three events:

$$BED_{n,t} = FM_{1,n,t} \cup FM_{2,n,t} \cup FM_{3,n,t} \tag{2}$$

where $BED_{n,t}$ is the building envelope damage for house *n* at time step *t*, and $FM_{j,n,t}$ is the damage determined by the BEFA model for failure mode *j* at time step *t*.

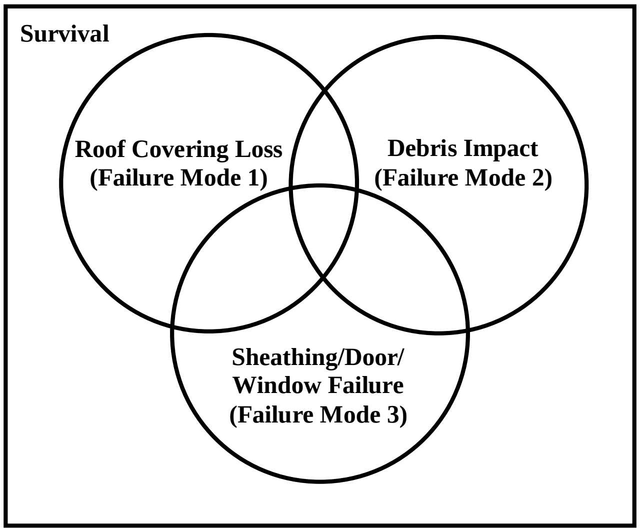

Figure 1: Venn diagram illustrating the general logical relationship between the failure modes for an individual home within a residential development (not to scale).

De Morgan’s law states that the complement of the union of events can be calculated as the intersection of the complement of the individual events:

$$\overline{E_1 \cup E_2 \cup \ldots \cup E_n} = \overline{E_1} \cap \overline{E_2} \cap \ldots \cap \overline{E_n} \tag{3}$$

where E represents a generic event. Substituting the failure mode damages (*FM*) for the generic events provided the building envelope survival for house *n* at time step *t*:

$$BES_{n,t} = \overline{FM_{1,n,t}} \cap \overline{FM_{2,n,t}} \cap \overline{FM_{3,n,t}} \,. \tag{4}$$

The individual failure modes for a single home shown in Eq. (4) have the potential to be conditional upon one another during the passage of the hurricane event. For example, a loss of sheathing can be due to the internal pressurization of the home caused by wind-borne debris impact. However, the conditional probabilities for each of the failure modes are small at any given time step compared to the probability of occurrence of an individual failure mode. Since the conditional probability of a failure mode reduces to the probability of an individual failure mode in the absence of dependence, it was assumed that the intersection of the individual failure mode complements was simply the product of the failure mode complements. Therefore, the building envelope survival became:

$$BES_{n,t} = \prod_{j=1}^{k=3}\left(1 - FM_{j,n,t}\right) \tag{5}$$

where $BES_{n,t}$ is the building envelope survival for house n at time step t. Damage to the building envelope was treated as a fraction of the entire building envelope; therefore, each failure mode required a corresponding damage factor (φ) that weighted the failure mode damage relative to their potential for penetration of the building envelope (see Table 3). The failure mode damage factors are calculated by Eq. (6) and are provided in Table 5.

$$\varphi_j = \frac{\text{Rank of failure mode } j \text{ (from Table 4.3)}}{\text{Number of failure modes (i.e., } k = 3)} \tag{6}$$

Table 5: Failure mode damage factors (φ)

Failure mode	**Rank**	**Damage factor**
Building envelope (BE) penetration	3	1
Potential BE penetration	2	0.67
No BE penetration	1	0.33

Thus, the damage contributed to a building envelope by each failure mode becomes:

$$FM_{j,n,t} = \varphi_j \psi_{j,n,t} \tag{7}$$

where φ_j is the damage factor for failure mode j, and $\psi_{j,n,t}$ is the damage value for failure mode j provided by the BEFA model for each house n at each time step t.

Substituting the results of Eqn. (7) into Eqn. (5) the building envelope survival for each house n at each time step becomes:

$$BES_{n,t} = \prod_{j=1}^{k=3}\left(1 - \varphi_j \psi_{j,n,t}\right). \tag{8}$$

The time evolution of the building envelope survival for the entire residential development was calculated as the arithmetic mean of the results from Eq. (8):

$$BES_t = \frac{1}{N}\sum_{n=1}^{N} BES_{n,t}\ . \tag{9}$$

2.4. Calculation of the damage state boundaries

The only difference between the calculation of the actual building envelope survival and the calculation of the damage state boundaries is that the failure mode damage values provided by Table 4 were used in place of the BEFA model output in Eq. (10):

$$BES_i = \prod_{j=1}^{k=3}\left(1 - \varphi_j \psi_{j,i}\right) \tag{10}$$

where BES_i is the value of the damage state boundary corresponding to damage state i, and $\psi_{j,i}$ is the failure mode values corresponding to damage state i. An example of the delineated damage state boundaries can be seen in Figures 2 and 3.

3. APPLICATION OF THE METHOD

In order to illustrate the analytical damage quantification method, the BEFA model was utilized to subject a representative 38-home residential development near Moncks Corner, South Carolina (SC) to a suite of synthetic hurricane events. The selected events possessed a maximum mean wind speed equivalent to a 700-year return period wind speed. The 700-year return period was selected to coincide with the design-level wind event stipulated by the American Society of Civil Engineers (ASCE) 7-10 *Minimum design loads for buildings and other structures* standard (ASCE 2010) for residential structures (i.e., Risk Category II). The purpose of using the design-level wind event was to investigate the response of the residential development to hurricane wind events that would affect the building envelope components, but not necessitate the evaluation of the main wind-force resisting systems of the homes.

3.1. Application scenarios

For this example, four retrofits were utilized to vary the percentage of homes retrofitted within the residential development from 0%, 25%, 50%, 75%, and 100%. This was done to account for vulnerability present in residential developments due to homes built to a newer code coexisting with homes grandfathered in to the new code. The four retrofits considered in this study were:

- roof sheathing supplemented with closed-cell spray foam,
- three-tab asphalt shingles replaced with Class H wind-resistant shingles,
- personnel/garage doors upgraded for increased pressure capacity, and
- impact protection systems (i.e., shutters) covering all windows.

Capacities for each of the four retrofits are shown in Tables 6 and 7. The homes that receive the retrofits for the 25%, 50% and 75% cases were selected from a uniform distribution without replacement in order to remove the influence of the spatial location of the homes with the retrofits.

The synthetic hurricane events used in this example were selected from a synthetic hurricane database generated by Liu (2014) that utilized the hurricane simulation procedure presented by Vickery et al. (2000; 2009). Slight discrepancies between the ASCE 7-10 design wind speed maps and the generated synthetic hurricanes were attributed to differences in the methods and algorithms employed by Liu (2014) within the simulation modules. However, the wind speeds generated for the synthetic hurricane events at the location of this study were reasonably comparable to those obtained with the ASCE 7-10 wind speed maps. The ten synthetic hurricane events, each with a maximum mean wind speed equivalent to a 700-year return period wind speed, were selected from 50,000-year subsets of a 500,000-year synthetic hurricane database to incorporate the probabilistic nature of the hurricane wind events. Accounting for the probabilistic nature of the hurricane wind events was done to remove the influence of the inherent random variables associated with a hurricane event (e.g., eye landfall location, translational speed, central pressure, etc.).

Table 6: Unretrofitted building component capacities

Component	Capacity	COV	Distribution	
Roofs				
Sheathing	2610 Pa	0.11	Lognormal	[a]
Covering	3350 Pa	0.40	Normal	[b]
Walls				
Sheathing	2610 Pa	0.11	Lognormal	[a]
Doors				
Personnel	2390 Pa	0.20	Normal	[a]
Garage	957 Pa	0.20	Normal	[a]
Windows				
Small	5000 Pa	0.20	Normal	[b]
Medium	3330 Pa	0.20	Normal	[b]
Tall	2500 Pa	0.20	Normal	[b]
Picture	1780 Pa	0.20	Normal	[b]
Impact	68 N-m	Deterministic		[a]

[a] Vickery et al. (2006)
[b] Gurley et al. (2005)

Table 7: Retrofitted building component capacities

Component	Capacity	COV	Distribution	
Roofs				
Sheathing	9090 Pa	0.11	Lognormal	[c]
Covering	6220 Pa	0.40	Normal	[d]
Walls				
Sheathing	2610 Pa	0.11	Lognormal	[a]
Doors				
Personnel	4780 Pa	0.20	Normal	[a]
Garage	2490 Pa	0.20	Normal	[a]
Windows				
Small	5000 Pa	0.20	Normal	[b]
Medium	3330 Pa	0.20	Normal	[b]
Tall	2500 Pa	0.20	Normal	[b]
Picture	1780 Pa	0.20	Normal	[b]
Impact	475 N-m	Deterministic		[a]

[a] Vickery et al. (2006)
[b] Gurley et al. (2005)
[c] Datin et al. (2011)
[d] Grayson (2014)

3.2. Results

Figures 2 and 3 illustrate the results from the five retrofit scenarios using the developed analytical method to quantify the damage experienced by the residential development. Note that the delineated damage state boundaries in these figures are as calculated by Eqn. (10).

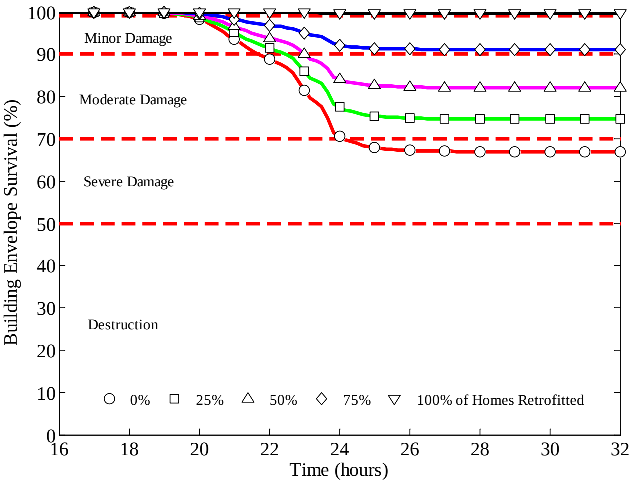

Figure 2: Building envelope survival of the residential development.

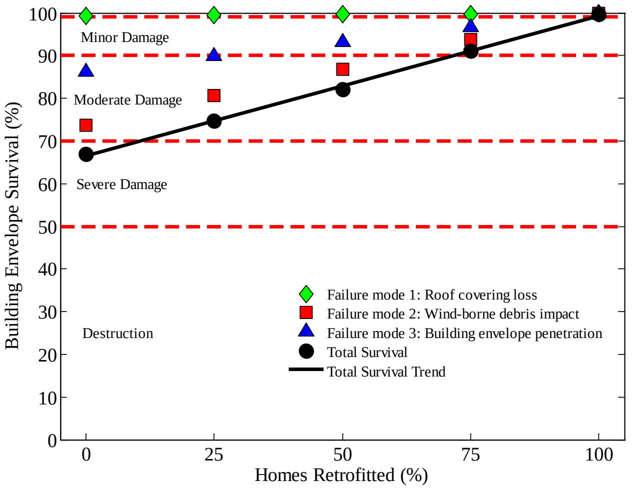

Figure 3: Final building envelope survival failure mode contributions.

The overall performance of the residential development to the ten synthetic hurricane events increased linearly with a linear increase in the percentage of homes retrofitted within the residential development (see Figure 2). It had been assumed that the wind-borne debris released in the residential development at lower retrofit percentages would manifest as a nonlinear trend on the overall performance of the residential development. However, it was possible that this trend was lost due to the contributions of failure modes 1 and 3. However, the individual contributions of each failure mode to the overall residential development damage did not reveal any significant nonlinearities due to a subsequent increase in the percentage of homes retrofitted. This could be due to the use of the failure mode damage factors, which were based on the potential of a failure type to penetrate the building envelope, masking the true contribution of the final building survival trend.

Reasons for the low contribution of failure mode 1 (i.e., roof covering loss) in Figure 3 are due to the failure mode damage factor, the pressure capacity of the roof covering that was determined for use on unretrofitted homes, and the implementation of an “all or nothing” approach in the application of the retrofits. The BEFA model only considers roof-covering loss that left roof sheathing exposed in the damage calculations at the end of each time step. Therefore, if an area of the roof experienced covering loss in addition to sheathing failure, the damage was considered as failure mode 3 (i.e., building envelope penetration) and not failure mode 1. Table 8 provides the individual failure mode results that correlate to Figure 1.

Table 8: Individual failure mode results

	Failure mode damage			**Overall**
Scenario	**1**	**2**	**3**	**Survival**
1	0.007	0.238	0.139	0.670
2	0.005	0.181	0.101	0.747
3	0.004	0.126	0.069	0.821
4	0.002	0.061	0.033	0.911
5	0.001	0.002	0.001	0.997

4. CONCLUSIONS

This research developed an analytical damage quantification method for residential developments subjected to hurricane wind hazards. This method was needed to quantify the overall performance of a light-frame wood construction residential development within a mechanics-based building envelope failure assessment model. Future studies will need to consider investigating the combinations of retrofits available to the homeowner as opposed to the "all or nothing" approach, in addition to validating the assumptions used to determine the failure mode damage values and the contributions of wind-borne debris impact to the damage imparted to a building envelope.

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6. REFERENCES

American Society of Civil Engineers. (2010). *Minimum design loads for buildings and other structures*, ASCE/SEI 7-10, Reston, VA: ASCE.

Datin, P.L., Prevatt, D.O., and Pang, W. (2011). "Wind-uplift capacity of residential wood roof-sheathing panels retrofitted with insulating foam adhesive." *J. Archit. Eng.*, 17 (4), 144-154.

Gaynor, J., and Simiu, E. (2007). "The NIST-NOAA resilient communities cooperative initiative and its contribution to coastal community resilience." *Marine Tech. Soc. J.*, 41 (1), 26-32.

Grayson, J. M., Pang, W., and Schiff, S. (2013). "Building envelope failure assessment framework for residential communities subjected to hurricanes." *Eng. Struct.*, 51, 245-258.

Grayson, J. M. (2014). "Building envelope failure assessment of residential developments subjected to hurricane wind hazards." Doctoral Dissertation, Clemson Univ., Clemson, SC.

Gurley, K., Pinelli, J.-P., Subramanian, C., Cope, A., Zhang, L., Murphree, J., et al. (2005). *Florida public hurricane loss projection model engineering team. Final report*, International Hurricane Research Center, Florida International Univ., Miami, USA.

Holmes, J.D. (2010). "Windborne debris and damage risk models: a review." *Wind and Struct.*, 13(2), 95-108.

Li, Y., and Ellingwood, B.R. (2009). "Framework for Multihazard risk assessment and mitigation for wood-frame residential construction." *J. Struct. Eng.*, 135 (2), 159-168.

Lin, N. (2010). "Multi-hazard risk analysis related to hurricanes." Doctoral dissertation, Princeton Univ., Princeton, NJ.

Liu, F. (2014). "Projections of future U.S. design wind speeds and hurricane losses due to climate change." Doctoral Dissertation, Clemson Univ., Clemson, SC.

National Oceanic and Atmospheric Administration (NOAA). (2011). "Communities: The U.S. population living at the coast." <http://stateofthecoast.noaa.gov/population/> Last accessed: 12/19/2014.

National Science Board (NSB). (2007). "Hurricane warning: The critical need for a national hurricane research initiative." NSB-06-115. National Science Foundation.

Rosowsky, D.V., and Schiff, S.D. (2003). "What are our expectations, objectives, and performance requirements for wood structures in high wind regions?" *Nat. Hazards Rev.*, 4 (3), 144-148.

U.S. Census Bureau. (2011). Census 2010. <http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml> Last accessed: 4/21/2014.

Vickery, P. J., Skerlj, P. F., and Twisdale, L. A. (2000). "Simulation of hurricane risk in the U.S. using empirical track model." *J. Struct. Eng.*, ASCE, 126(10), 1222–1237.

Vickery, P.J., Skerlj, P.F., Lin, J., Twisdale, L.A., Young, M.A., and Lavelle, F.M. (2006). "HAZUS-MH hurricane model methodology II: Damage and loss estimation," *Nat. Hazards Rev.*, 7 (2), 94-103.

Vickery, P. J., Wadhera, D., Twisdale, L. A., and Lavelle, F. M. (2009). "U.S. hurricane wind speed risk and uncertainty." *J. Struct. Eng.*, ASCE, 135(3), 301–320.

Yau, S.C., Lin, N. and Vanmarcke, E. (2011). "Hurricane damage and loss estimation using an integrated vulnerability model." *Nat. Hazards Rev.*, 12 (4), 184-189.