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Cost-Benefit Assessment of Different Storm Mitigation Techniques for Residential Buildings using the PBHE Framework

Vipin U. Unnikrishnan
Graduate Student, Dept. of Civil Engineering, Louisiana State University, Baton Rouge, USA

Michele Barbato
Assoc. Professor, Dept. of Civil Engineering, Louisiana State University, Baton Rouge, USA

ABSTRACT: The resources available for hurricane risk mitigation of residential buildings are limited. Therefore, in order to have an optimum use of the available resources, the decision regarding the choice of mitigation/retrofit techniques for a specific project should be based on a performance-based approach. In this study, a probabilistic Performance-Based Hurricane Engineering (PBHE) framework is used to compare the effectiveness of different hurricane retrofit techniques for residential building from a cost-benefit point of view. A realistic case study is presented to illustrate the methodology and to evaluate the costs and benefits of different hurricane hazard mitigation techniques for residential buildings.

1. INTRODUCTION

Hurricanes are among the most costly natural hazards affecting communities worldwide, in terms of both property damage and loss of life. In the U.S., the average economic loss due to hurricanes in the period 1900-2005 was about $10 billion (normalized to 2005 USD) per year (Pielke et al. 2008). As the population tends to concentrate on coastal regions and the number of residential buildings in hurricane-prone areas continues to rise, the societal vulnerability to hurricanes is increasing, with the prospect of even higher damages and losses in the future (Li and Ellingwood 2006). Hence, hurricane hazard mitigation is of paramount importance for residential buildings located in hurricane-prone regions. Many mitigation measures are available to reduce the social and economic losses that are associated with hurricane damage. Thus, appropriate engineering criteria must be used to select the most cost-effective solutions for different conditions. In the case of residential buildings, the resources available for hurricane risk mitigation are limited by high upfront cost of common mitigation practices. In order to reduce the societal risk posed by hurricane events in a cost-effective manner, appropriate decision-making tools must be developed based on a rigorous performance-based cost-benefit evaluation of different mitigation techniques for residential buildings.

In this paper, the PBHE framework (Barbato et al. 2013) is adopted for the risk assessment of structural systems located in hurricane-prone regions. Multi-layer Monte Carlo Simulation (MCS) is employed to perform a loss analysis for residential buildings subject to hurricane hazard and different mitigation strategies are compared using a risk-based cost-benefit analysis. A realistic case study is presented to illustrate the adopted methodology by comparing the cost-effectiveness of different hurricane hazard mitigation techniques applied to a typical house of an actual residential development located in Pinellas County, FL.

2. SUMMARY OF PBHE FRAMEWORK

The PBHE framework proposed in Barbato et al. (2013) disaggregates the performance assessment procedure for structures subject to hurricane hazard into elementary phases that are carried out in sequence. The structural risk within the PBHE framework is expressed by the probabilistic description of a decision variable, *DV*, which is defined as a measurable quantity that describes the cost and/or benefit for the owner, the users, and/or the society resulting from the structure under consideration. The fundamental relation for the PBHE framework is given by:

$$G(DV) = \int\int\int\int\int G(DV|DM)\cdot f(DM|EDP)\cdot f(EDP|IM,IP,SP)\cdot f(IP|IM,SP)\cdot\ f(IM)\cdot f(SP)\cdot \mathrm{d}DM\cdot \mathrm{d}EDP\cdot \mathrm{d}IP\cdot \mathrm{d}IM\cdot \mathrm{d}SP \quad (1)$$

where $G(\bullet)$ = complementary cumulative distribution function, and $G(\bullet|\bullet)$ = conditional complementary cumulative distribution function; $f(\bullet)$ = probability density function, and $f(\bullet|\bullet)$ = conditional probability density function; *IM* = vector of intensity measures (i.e., the parameters characterizing the environmental hazard); *SP* = vector of structural parameters (i.e., the parameters describing the relevant properties of the structural system and non-environmental actions); *IP* = vector of interaction parameters (i.e., the parameters describing the interaction phenomena between the environment and the structure); *EDP* = engineering demand parameter (i.e., a parameter describing the structural response for the performance evaluation); and *DM* = damage measure (i.e., a parameter describing the physical damage to the structure). In Eq. (1), *IM* and *SP* are assumed as uncorrelated and independent of *IP*, while *IP* is dependent on both *IM* and *SP*. By means of Eq. (1), the risk assessment is disaggregated into the following tasks: (1) hazard analysis, (2) structural characterization, (3) interaction analysis, (4) structural analysis, (5) damage analysis, and (6) loss analysis.

3. CASE STUDY

This paper uses the PBHE framework to compare different storm mitigation and retrofit techniques based on a realistic case study in which both wind and windborne debris hazards interact. A residential development in Pinellas County, located in South Florida and composed by 201 similar gable roof wooden residential buildings (see Figure 1) is considered. The roof covers are considered as debris sources, whereas the windows and doors are considered as debris impact vulnerable components. The value of the target building is assumed to be \$200,000 and the contents are valued at \$100,000.

Figure 1: Plan view of the residential development (Source: Google Maps)

3.1. Hazard Analysis

In this study, the 3-second wind speed (V) recorded at 10 m above the ground is considered as the *IM* for wind hazard. Among the different wind field models available in the literature (Batts et al. 1980, Peterka and Shahid 1998, Li and Ellingwood 2006), the Weibull distribution is adopted here to describe the hurricane wind speed variability. The two-parameter Weibull cumulative distribution function is given by:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{a}\right)^b\right] \quad (2)$$

The two shape parameters *a* and *b* are site specific and are determined for sixteen different wind directions by fitting to a Weibull distribution the hurricane wind speed records for the corresponding directions provided by the National Institute of Standards and Technology (NIST). The NIST wind speed records contain data sets of simulated 1-minute hurricane wind speeds at 10 m above the ground in an open terrain near the coastline, for locations ranging from milepost 150 (near Port Isabel, TX) to milepost 2850 (near Portland, ME), spaced at 50 nautical mile intervals (92,600 m). Considering South Florida as the location for the case study, the dataset corresponding to milepost 1400 is used for fitting the distribution.

The parameters needed to describe the windborne debris are: (1) the relative distribution of different debris types, e.g., compact-type, rod-type, and sheet-type debris (Wills et al. 2002); (2) the physical properties of the debris, e.g., for sheet-type debris, M_{d} = mass per unit area of the debris, and A_{d} = area of the single debris; (3) the resistance model for the debris sources (which contributes to determine the number of windborne debris generated by a given source under a specified wind speed); and (4) the trajectory model for the debris (which describes the debris flight path).

In residential developments, the windborne debris are predominantly sheet-type, e.g., roof shingles and sheathing (Holmes 2010), hence this paper focuses on sheet-type debris. The area and mass per unit area of debris are assumed to follow a uniform distribution defined in the range [0.108, 0.184] m^2 and [10.97, 14.97] kg/m^2, respectively.

The debris generation model employed by the Florida Public Hurricane Loss Model (Gurley et al. 2005) is adopted. This model is a component-based pressure-induced damage model, which provides the number of debris generated from each source house as a function of (1) the percentage of roof cover damage for a given 3-second gust wind speed, and (2) the geometry of the house.

The debris trajectory model provides the landing position of the debris as identified by the random variables X = along-wind flight distance, and Y = across-wind flight distance. These random variables are modeled using a two-dimensional Gaussian distribution (Lin and Vanmarcke 2008) described by the following parameters: μ_X = mean along-wind flight distance; μ_Y = 0 m = mean across-wind flight distance; $\sigma_X = \sigma_Y = 0.35\mu_X$ = standard deviation of the along-wind and across-wind flight distance, respectively. The parameter μ_X is computed as (Lin and Vanmarcke 2008):

$$\mu_X = \frac{2M_{\mathrm{d}}}{\rho_{\mathrm{a}}} \cdot \left[\frac{1}{2} C \cdot \left(K \cdot \tilde{T} \right)^2 + c_1 \cdot \left(K \cdot \tilde{T} \right)^3 + c_2 \cdot \left(K \cdot \tilde{T} \right)^4 + c_3 \cdot \left(K \cdot \tilde{T} \right)^5 \right] \tag{3}$$

in which ρ_{a} = 1.225 kg/m^3 = air density; $K = \frac{\rho_{\mathrm{a}} \cdot V^2}{2M_{\mathrm{d}} \cdot g}$ = Tachikawa number; $\tilde{T} = \frac{g \cdot T}{V}$ = normalized time; g = gravity constant; T = flight time in seconds; C, c_1, c_2, and c_3 = non-dimensional coefficients that depend on the shape of the debris. The flight time is assumed to follow a uniform distribution with range [1, 2.5] seconds. For the sheet-type debris considered in this study, C = 0.91, c_1 = -0.148, c_2 = 0.024, and c_3 = -0.0014.

3.2. Structural Characterization

The structural characterization phase provides the probabilistic description of the *SP*s. The *SP*s represent the geometrical and/or mechanical proprieties of the structure which influence the loading applied on the structure and, thus, the *IP*s. Geometrical properties can usually be treated as deterministic quantities, since they can be directly measured for existing structures or are characterized by a small variability. Table 1 shows the parameters corresponding to the target residential building (Gurley et al. 2006)

Table 1. Structural parameters of target building

Structural Parameter	*Dimension*
Length	60 ft
Width	4 ft
Height of wall	10 ft
Roof Pitch	5/12
Eave overhang	2 ft
Space between roof trusses	2 ft
Roof sheathing panel dimension	8 ft X 4 ft

The position and dimension of the windows and doors of the target building are shown in Figure 2.

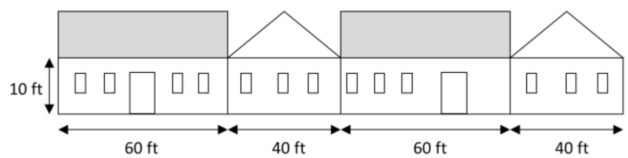

Figure 2. Unfolded view of target building

The *SP*s considered in this case study also include: (1) the wind pressure exposure factor (evaluated at *h* = height of the target building), K_h; (2) the external pressure coefficient, GC_p; and (3) the internal pressure coefficient, GC_{pi}. The pressure coefficients include the effects of the gust factor *G*. The value of the topographic factor, K_{zt}, is assumed deterministically equal to one. The *SP* K_h is assumed as normally distributed with a mean value of 0.71 and a coefficient of variation (COV) of 0.19 (Lee and Rosowsky 2005). The statistical characterization of the external and internal pressure coefficients is given in Table 2 (Li and Ellingwood 2006).

Table 2. Structural characterization of external and internal pressure coefficients

	Location/ Condition	*Mean*	*COV*	*Distrib.*
GC_p	Roof (near ridge)	-0.86	0.12	Normal
	Roof (away from ridge)	-1.62	0.12	Normal
	Roof (corner)	-2.47	0.12	Normal
	Windward Wall	0.95	0.12	Normal
	Leeward wall	-0.76	0.12	Normal
	Side wall	-1.05	0.12	Normal
GC_{pi}	Enclosed	0.15	0.33	Normal
	Breached	0.46	0.33	Normal

3.3. Interaction Analysis

The choice of the *IP* vector is crucially dependent on the hazard sources, limit states, and performance levels of interest for both structural and non-structural elements. In this study, the *IP* vector is selected to represent the effects of wind and windborne debris hazard on the different limit states of interest for low-rise residential buildings.

The interaction analysis for the wind hazard provides the statistical characterization of the wind pressure acting on the different components of the buildings, p_w. In this study, the wind pressure acting on the *j*-th component of the building is computed as (ASCE 2010)

$$p_{w,j} = q_h \cdot \left(GC_{\mathrm{p},j} - GC_{\mathrm{pi},j} \right) \tag{4}$$

where the velocity pressure, q_h, evaluated at *h*, is given by

$$q_h = 0.613 \cdot K_h \cdot K_{\mathrm{zt}} \cdot V^2 \tag{5}$$

The relevant *IP* components controlling the effects of windborne debris impact are: (1) number of impacting debris, n_d; (2) impact linear momentum, L_d; and (3) impact kinetic energy, K_d. The impact linear momentum is well correlated with the damage to envelope components with a brittle behavior (e.g., glazing portions of doors and windows (Masters et al. 2010), whereas the impact kinetic energy is better correlated with the damage to envelope components with a ductile behavior such as aluminum storm panels (Herbin and Barbato 2012, Alphonso and Barbato 2014).

The analysis step of the interaction analysis phase requires an impact model to evaluate n_d, L_d, and K_d (Barbato et al. 2013). The debris impact model uses the debris flight path obtained from the trajectory model to check for any windborne debris impact with the target building. In the event of an impact, the horizontal component of the missile velocity and data relative to the missile size and mass (obtained from the debris generation model) are used to compute the impact linear momentum and kinetic energy of the missile (i.e., the linear momentum corresponding to the windborne debris velocity component orthogonal to the impacted surface, conditional to the event of at least one impact on vulnerable components). The impact linear momentum and kinetic energy are given by

$$L_d = M_d \cdot A_d \cdot u_d$$
$$K_d = \frac{1}{2} M_d \cdot A_d \cdot u_d^2 \qquad (6)$$

The debris horizontal velocity at impact, u_d, is a function of the wind velocity and the distance travelled by the debris (determined by its landing position), and is given by (Lin and Vanmarcke 2008)

$$u_d = V \cdot \left[1 - \exp\left(-\sqrt{2 \cdot C \cdot K \cdot x}\right)\right] \qquad (7)$$

in which $x = \frac{g \cdot X}{V^2}$ = dimensionless horizontal flight distance of the debris.

3.4. Structural Analysis/Damage Analysis

In this study, the structural analysis phase is not performed explicitly and the strength of vulnerable components is directly compared to the corresponding *IP*. This approach is computationally convenient and is appropriate for non-engineered and pre-engineered structures. Following a procedure commonly used in performance-based earthquake engineering, the physical damage conditions are represented using a limit state function *LSF* for each damage limit state, i.e.,

$$LSF_j = DM_j - IP_j \qquad (8)$$

in which DM_j correspond to the limit state capacity of the component *j*, for the given damage limit state. The limit states generally considered for residential buildings are: (1) breaking of annealed glass windows/doors, (2) uplift of the roof sheathings, (3) uplift of the roof covers, (4) roof truss failure, and (5) wall failure. The *IP*s are compared with the limit state capacity of different components of the building, and if the *IP*s assume values larger than the corresponding limit state capacity of the building component, the component is assumed to fail. In case of any breach in the building envelope, the iteration is repeated with updated *SP*s until no additional breach is observed (see Figure 3). The statistics of the limit state capacity for different components of the building and their corresponding limit states are shown in Table 3 (Datin et al. 2010, Gurley et al. 2005, Masters et al. 2010).

Table 3: Statistics of the limit state capacity for different components

Component	*Limit State*	*Mean*	*COV*	*Distrib.*
Roof cover (asphalt shingle)	Separation or pull off	3.35 kN/m^2	0.19	Normal
Roof cover (clay tile)	Separation or pull off	5.25 kN/m^2	0.2	Normal
Roof sheathing (8dC6/12)	Separation or pull off	6.20 kN/m^2	0.12	Log-normal
Roof sheathing (8dR6/6)	Separation or pull off	12.08 kN/m^2	0.07	Log-normal
Door	Pressure failure	4.79 kN/m^2	0.2	Normal
Windows	Pressure failure	3.33 kN/m^2	0.2	Normal
Windows	Impact failure	4.72 kg-m/s	0.23	Log-normal
Aluminum hurricane panels	Impact failure	12.7 cm	0.15	Log-normal
Roof to wall connections	Tensile failure	16.28 kN	0.2	Log-normal
Wall	Lateral Failure	5.4 kN	0.25	Normal
	Uplift Failure	9 kN/m	0.25	Normal

3.5. Loss Analysis

The loss analysis phase gives the estimate of the annual probability of exceedance of the *DV* (herein taken as the total loss including content loss). This quantity can be used for informed risk-management decisions. Computation of the *DV* annual probability of exceedance requires knowledge of the joint probability density function of the component losses, which is very difficult to obtain. To overcome this difficulty, a very efficient multilayered Monte Carlo simulation (MCS) approach is used in this study to estimate the loss hazard curve (see Figure 3). The multilayered MCS is able to account for the uncertainties in all analysis parameters (Conte and Zhang 2007).

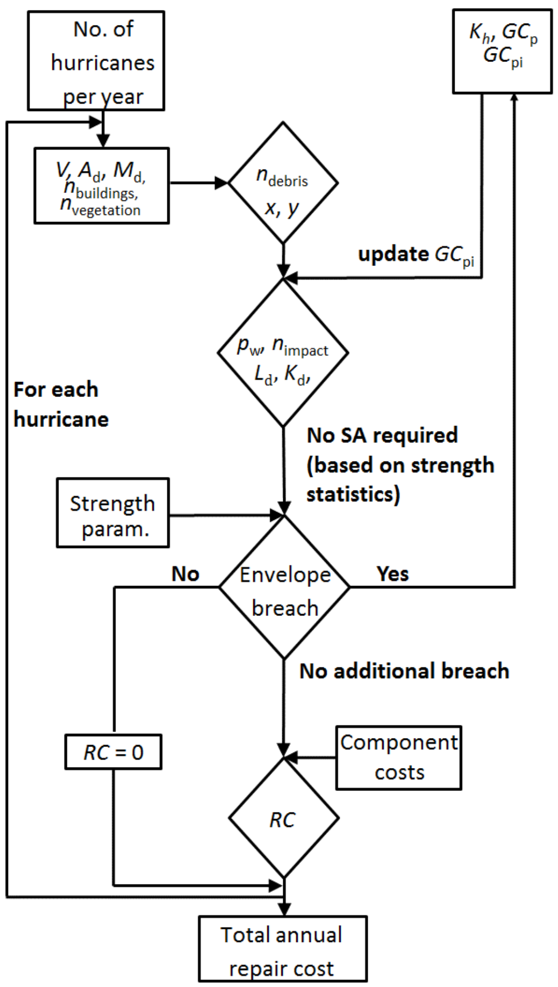

Figure 3: Multilayered MCS approach for probabilistic hurricane loss estimation of residential buildings

The number of hurricanes in each year is simulated according to a Poisson random occurrence model with annual occurrence rate obtained from the NIST database. For each generated hurricane, a peak wind speed, V, is generated randomly according to the Weibull distribution. For this value of V, the wind pressure is calculated using Eq. (4) and the number of debris impacts are calculated by comparing the flight trajectory with the position of the target house. For each debris impact, the corresponding linear momentum and kinetic energy are calculated using Eq. (6). The *IP*s are then compared with the limit state capacity of different components of the building, and if the *IP*s assume values larger than the corresponding limit state capacity of the building component, the component is assumed to fail. The building envelope is checked for any breach, in the event of which the internal pressure is modified. The remaining undamaged building components are checked for further damage due to the modified pressure. The repair cost of each damaged component are then generated using an appropriate distribution. For this case study, the repair cost is assumed to follow lognormal distribution with mean as shown in Table 4 (Gurley et al. 2005) and a COV of 0.1.

Table 4: Sub-assembly cost ratios

Sub-assembly	*Average cost (% of total building cost)*
Site Work	1%
Foundation	13%
Exterior Wall	22%
Framing	8%
Roof Sheathing	5%
Roof covers	7%
Interiors	40%
Windows & doors	4%

The single-year simulation described above is repeated a large number of times (e.g., in this example, 100,000 samples are used) to estimate the annual probability of exceedance (which coincides with the complementary cumulative distribution function of the *DV*) of the total loss. This methodology is used for the comparison of the performance of different storm mitigation techniques. The different storm mitigation techniques considered in this study are: (1) using clay tile as roof cover, (2) using aluminum hurricane protection panels for windows, (3) using an improved roof nailing pattern of 8dR6/6 (i.e., 8 mm diameter ring shank nails, with a spacing of 6 inches). The annual probabilities of exceedance of the loss for the target building for each mitigation scenarios are calculated and shown in Figure 4, using a semi-logarithmic scale.

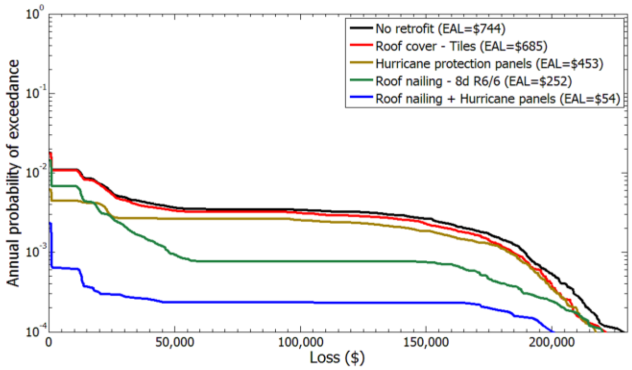

Figure 4: Annual probability of exceedance of loss for different storm mitigation scenarios

3.6. Cost-Benefit Analysis

Cost benefit analysis is used here to compare the cost of different storm mitigation techniques and the benefits achieved from improved performance of the building. The relationship between the cost of mitigation techniques and its benefits can be explicitly quantified and thereby facilitate effective decision making for investment in the safety of buildings (Liel and Deierlein 2013). The expected value of economic benefit of retrofit or redesign (B) is expressed as

$$B = \sum_{n=0}^{t} \frac{EAL - EAL_{\mathrm{r}}}{(1+\rho)^{n}} - C_{\mathrm{r}} \qquad (9)$$

where EAL = expected annualized repair cost before retrofit, EAL_{r} = expected annualized repair cost after retrofit, ρ = discount rate, t = planning period, and C_{r} = initial cost of the retrofit. The retrofit or redesign is financially viable if the expected value of B is greater than zero. In this study, discount rate and planning period are assumed as 3% and 30 years respectively. The cost-benefit analysis was conducted for different mitigation techniques. The cost of retrofit includes the cost of the materials and the labor cost, and is obtained from local manufacturers and contractors. The mean loss for 30 years for each retrofit case is calculated using Eq. (9). The cost of retrofitting, the mean loss for 30 years assuming a discount rate of 3%, and the corresponding savings for each mitigation scenarios are shown in Table 5.

Table 5: Cost-benefit analysis for different retrofit scenarios

Retrofit/ Improvement	*Cost of retrofit*	*Loss (30 years)*	*Savings*
Base Structure	-	$15,020	-
Roof cover (tiles)	$11,000	$13,830	-$9,810
Aluminum hurricane panels	$1,800	$9,145	$4,075
Roof re-nailing	$6,000	$5,087	$3,933
Roof re-nailing + hurricane panels	$7,800	$1,090	$6,130

It is observed that the use of aluminum storm panels for protection of windows is the most effective solution to reduce hurricane risk among the techniques considered in this study. The use of roof tiles is not a financially viable approach to reduce hurricane risk. In addition, the combination of aluminum storm panels and improved roof nailing pattern can reduce considerably the expected total loss due to hurricanes.

4. CONCLUSION

In this paper, the performance-based hurricane engineering (PBHE) framework is used to compare the performance of different mitigation techniques for wind and windborne debris hazards in terms of costs and benefits. An actual residential development located in Pinellas County, FL, is considered as a realistic case study.

It is observed that, for the specific example considered here, the most effective mitigation technique is the use of aluminum hurricane protection panels. The proposed PBHE methodology can be effectively used to improve the design or select appropriate hurricane hazard mitigation techniques for a specific residential building.

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