Performance-Based Comparison of Different Storm Mitigation Techniques for Residential Buildings

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Abstract: In recent years, severe hurricanes have caused enormous economic losses for society and placed tremendous burden on the insurance industry. As the number of residential buildings in hurricane prone regions continues to rise, hurricane hazard mitigation is of paramount importance for residential buildings. Although different retrofit measures are available to mitigate hurricane damage and to reduce the associated social and economic losses, choosing the most cost-effective ones is still an engineering challenge. This paper uses the performance-based hurricane engineering (PBHE) framework with multilayer Monte Carlo Simulation (MCS) for the loss analysis of residential buildings subject to hurricane hazard. A highly efficient modified version of the multilayer MCS technique based on copula is proposed for the faster re-evaluation of hurricane risk when different hurricane hazard mitigation strategies are considered for the same building. This technique is combined with cost-benefit analysis to provide effective decision making tools based on the performance comparison of different design and retrofit solutions. A realistic case study is presented to illustrate the proposed methodology by comparing the cost-effectiveness of several commonly used hurricane hazard mitigation techniques and design alternatives for a typical residential building.
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Introduction

Hurricanes are among the most costly natural hazards affecting communities worldwide, in terms of both property damage and loss of life. In the United States, the average annual economic loss attributable to hurricanes in the period 1900–2005 was about \$10 billion (normalized to 2005 USD), and placed a tremendous burden on the society and the insurance industry (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, and appropriate engineering criteria must be used to select the most cost-effective solutions for different conditions. In the case of residential buildings, hurricane risk mitigation is limited by the high upfront cost of common hurricane risk mitigation practices. 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 the last few decades, significant research was devoted to developing vulnerability models (also called fragility curves) for residential buildings subject to hurricane hazard. Leicester et al. (1980) developed global vulnerability curves (i.e., for the entire building) for various housing types based on cyclone damage surveys in different regions of Australia after Cyclone Tracy in 1974. Stubbs and Perry (1996) defined vulnerability models for different building components based on reliability analysis techniques and investigated the relative contribution from the damage of individual components to the total damage for buildings subject to extreme wind events. Huang et al. (2001) developed a hurricane damage model for single family housing units using event-based simulation and southeastern United States insurance data from Hurricanes Hugo and Andrew to predict the expected losses at a regional level. Pinelli et al. (2004) proposed a probabilistic model for hurricane vulnerability evaluation of residential structures using basic damage modes for individual structural and nonstructural components and combining them in possible damage states for specific building types. Grayson et al. (2013) proposed a modular framework for assessing the building envelope failures of light-frame wood construction subject to hurricane wind and windborne debris hazards, by providing the time evolution of building envelope damage for specific structures and the windborne debris impact vulnerability plots at different locations for given hurricane scenarios.

More recently, performance-based design approaches began to receive significant attention by researchers in wind and hurricane engineering. Ellingwood et al. (2004) proposed a fragility analysis approach for assessing probabilistically the achievement of specified performance objectives by light-frame wood constructions subject to extreme windstorms and earthquakes. Augusti and Ciampoli (2008) presented a general approach to performance-based design of buildings subjected to wind and earthquake hazards. van de Lindt and Dao (2009) proposed a performance-based wind engineering approach that included the development of fragility curves for different performance objectives applied to wood-frame buildings. Li and Ellingwood (2009) presented a multihazard risk assessment framework to compare the impact of hurricanes

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and earthquakes on wood-frame residential construction and the effectiveness of different mitigation strategies. Petrini (2009) proposed a performance-based wind engineering framework based on the total probability theorem for risk assessment of structures subjected to wind hazard. Barbato et al. (2013) developed a probabilistic performance-based hurricane engineering (PBHE) framework, also based on the total probability theorem, for the risk assessment and loss analysis of structural systems subject to hurricane hazard. This framework considers the multihazard nature of hurricane events, the interaction of different hazard sources (i.e., wind, windborne debris, flood, rain), and possible sequential effects of these distinct hazards.

In parallel with the development of performance-based design approaches, the last two decades have seen the advancement of risk-based cost-benefit analysis approaches in several subfields of structural engineering (e.g., Frangopol et al. 1997 for bridge engineering, and Porter et al. 2001 for earthquake engineering). Stewart et al. (2003) performed a hurricane damage risk-cost-benefit analysis proposing two scenario-based models to investigate the structural vulnerability change for the existing building stock attributable to improvements in the building envelope performance, and the effects over time of this change on expected insurance losses. Pinelli et al. (2009) analyzed the cost-effectiveness of various mitigation measures for different residential building typologies of different age and quality of construction. Li (2010) proposed a risk-cost-benefit framework for assessing the damage risk and cost-effectiveness of hurricane and earthquake mitigation strategies for residential buildings using life-cycle and scenario-case analysis. Li and van de Lindt (2012) proposed a loss-based formulation for residential buildings subject to multiple hazards, in which cost-benefit analysis was used to compare different design and retrofit options for multihazard mitigation.

In this paper, the PBHE framework (Barbato et al. 2013; Unnikrishnan and Barbato 2015) is adopted for the risk assessment of structural systems located in hurricane-prone regions. Multilayer Monte Carlo simulation (MCS) is employed to perform a loss analysis for residential buildings subject to hurricane hazard. A highly efficient modified version of multilayer MCS is proposed for faster re-evaluation of hurricane risk when different design alternatives and mitigation strategies are considered for the same building. These design alternatives and 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, Florida.

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

$$\begin{aligned} G(DV) = \int\int\int\int\int & G(DV|DM) \cdot f(DM|EDP) \\ & \cdot f(EDP|IM, IP, SP) \cdot f(IP|IM, SP) \cdot f(IM) \cdot f(SP) \\ & \cdot \mathrm{d}DM \cdot \mathrm{d}EDP \cdot \mathrm{d}IP \cdot \mathrm{d}IM \cdot \mathrm{d}SP \end{aligned} \tag{1}$$

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., parameters characterizing the environmental hazard); SP = vector of structural parameters (i.e., parameters describing the relevant properties of the structural system and nonenvironmental actions); IP = vector of interaction parameters (i.e., parameters describing the interaction phenomena between the environment and the structure); EDP = vector of engineering demand parameters (i.e., parameters describing the structural response for the performance evaluation); and DM = vector of damage measures (i.e., parameters describing the physical damage to the structure). 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.

Multilayer Monte Carlo Simulation

Similar to the Pacific Earthquake Engineering Research Center performance-based earthquake engineering framework equation (Cornell and Krawinkler 2000; Porter 2003), Eq. (1) can be solved using different techniques, e.g., closed-form analytical solutions (Jalayer and Cornell 2003), direct integration techniques (Bradley et al. 2009), and stochastic simulation techniques (Porter et al. 2001). In PBHE, analytical solutions and direct integration techniques require the knowledge of the joint probability density function of the component losses, which is usually very difficult to obtain for real-world applications. Thus, in this study, a multilayer MCS technique (Conte and Zhang 2007) is adopted and specialized to efficiently perform loss analysis for residential buildings subject to hurricane hazard. The result of the PBHE equation [Eq. (1)] is the annual loss curve, $G(DV)$, i.e., the complementary cumulative distribution function of the annual losses for the residential building under consideration owing to hurricane events.

Fig. 1 shows the flowchart of the general multilayer MCS technique applied to PBHE considering a one-year time interval. Multilayer MCS takes into account the uncertainties from all six phases of the PBHE framework. Each of these analysis phases is performed in two steps: (1) a sample generation step of random parameters with known probability distributions, which are needed to describe the uncertainties in environmental actions, structural properties, interaction phenomena, analysis techniques, and cost estimates; and (2) an analysis step based on a deterministic model, which is used to propagate the uncertainties from input to output parameters of each analysis phase. It is noted here that the analysis steps are usually more computationally intensive than the corresponding sample generation steps. Thus, it is useful to identify specific conditions under which one or more of the analysis steps can be avoided to reduce the computational cost of the multilayer MCS approach.

In particular, this study focuses on hurricane loss analysis for low-rise residential buildings such as single-family houses. For this specific building typology, component strength statistics are commonly available as functions of the environmental action intensity. In fact, most of these structures are constructed based on design models, and their components consist of products that are certified based on building code requirements (NAHB 2000). Under these conditions, the damage analysis phase can be performed without requiring the statistical description of the structural response of the building, because the probabilistic description of the strength for the building components subject to damage (i.e., windows,

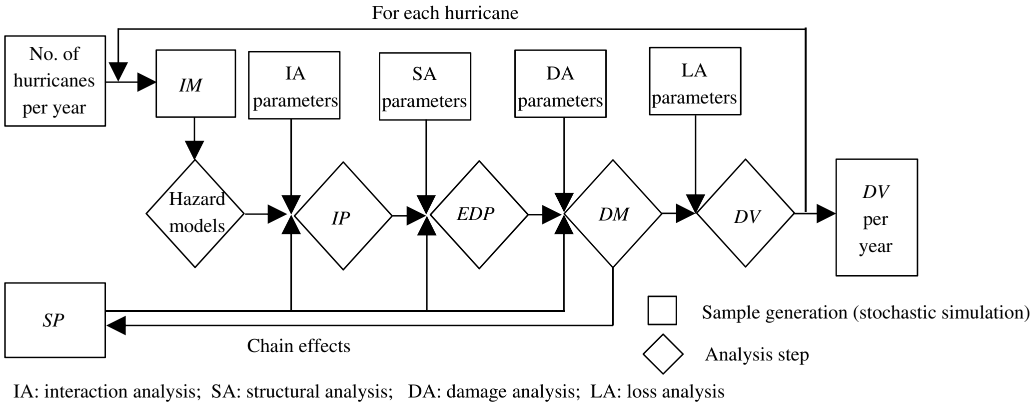

Fig. 1. Multilayer MCS approach for PBHE framework (reprinted from Unnikrishnan and Barbato 2015, © ASCE)

doors, walls, roof) can be obtained from empirical relations available in the literature as a function of opportunely chosen *IP*. Thus, it is computationally convenient to eliminate the structural analysis phase from the multilayer MCS procedure. Fig. 2 shows the flowchart for the multilayer MCS technique specialized for probabilistic hurricane loss estimation of low-rise residential buildings, and provides the list of analysis parameters involved in each analysis phase. As noted above, the structural analysis phase is not performed explicitly to derive the probabilistic description of the *EDPs* that are related to structural damage. This simplification considerably reduces the computational cost of the multilayer MCS approach for probabilistic hurricane loss analysis of low-rise residential buildings. The following sections of this paper describe in detail the PBHE phases for the proposed specialized multilayer MCS technique. It is noted here that, for simple structures of risk categories I and II (ASCE 2010), such as single-family residential buildings, simplified and computationally inexpensive models are often appropriate to perform the analysis steps required by the PBHE methodology.

Hazard Analysis Phase

The focus of this paper is on the effects of mitigation techniques for wind and windborne debris hazards. Thus, the results presented in this paper are valid for residential buildings that are sufficiently far from water bodies and for which flood hazard mitigation is not required. The general multilayer MCS methodology presented in this study can include also flood and rainfall hazard. However, this generalization is outside the scope of this paper.

Wind Hazard Characterization

The first step in the proposed multilayer MCS approach is the simulation of the number of hurricanes affecting the considered structure in a given year, e.g., according to a Poisson occurrence model (Russel 1971; Chouinard and Liu 1997). For each of these hurricanes, a corresponding wind field needs to be simulated to characterize the wind hazard. Three methodologies of increasing accuracy and computational cost can be adopted to define the hurricane wind field (FEMA 2007): (1) deriving the statistical description of the 3-s gust wind velocity, V, at the building site from existing peak wind speed data (Batts et al. 1980; Li and Ellingwood 2006); (2) using site-specific statistics of fundamental hurricane parameters to obtain a mathematical representation of a hurricane at the building location, including the statistics of the wind speed (Batts et al. 1980; Vickery and Twisdale 1995); and (3) modeling the full track of a hurricane from its initiation over the ocean until final dissipation and using appropriate wind field models to obtain the wind speed statistics corresponding to the specified track at the building site (Vickery et al. 2000).

In this paper, the first methodology (i.e., using existing peak wind speed data at the building sites to derive the statistical description of the 3-s gust wind velocity) is adopted to reduce the computational cost of the proposed procedure. However, for important structures, one of the more accurate procedures would be more

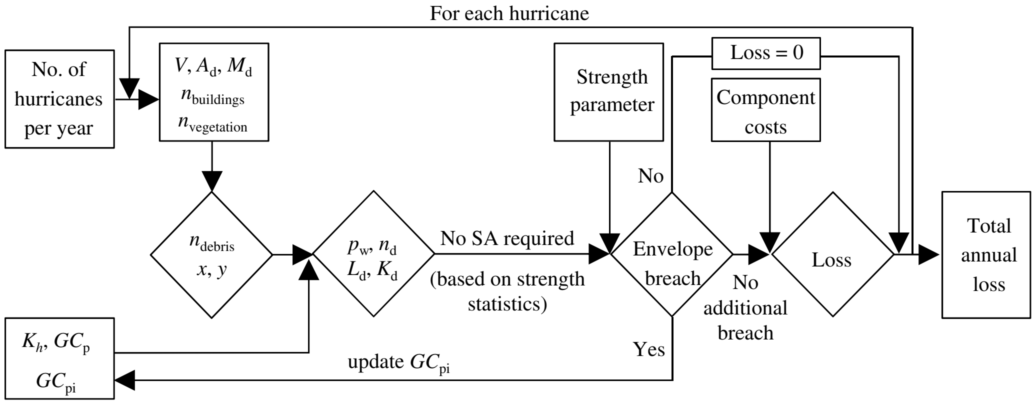

Fig. 2. Multilayer MCS approach for probabilistic hurricane loss estimation of nonengineered residential buildings (adapted from Unnikrishnan and Barbato 2015, © ASCE)

appropriate and should be selected. It is also noteworthy that, when the number of hurricanes per year is equal to zero, the proposed PBHE framework reduces to the performance-based wind engineering framework proposed in Petrini (2009), and can be used to assess the performance of structures subject to nonhurricane wind actions. When the number of hurricanes per year is larger than zero, the procedure shown in Fig. 1 or Fig. 2 is always performed first for nonhurricane wind actions, and then repeated for hurricane actions a number of times equal to the simulated number of hurricanes.

Windborne Debris Hazard Characterization

The windborne debris hazard is described by the wind field intensity (which is also needed to describe the wind hazard) and the characteristics of the windborne debris that can affect the structure under study. 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 density of debris sources, e.g., the building density (applicable for expanding residential developments), $n_\mathrm{buildings}$, and the vegetation density, $n_\mathrm{vegetation}$, at the building site; (4) the resistance model for the debris sources (which determines the number of windborne debris generated by a given source under a specified wind speed); and (5) the trajectory model for the debris (which describes the debris flight path).

The relative distribution of the debris types and the statistical description of the variables defining the physical properties of the debris can be obtained either from the literature or through damage surveys at the site from previous hurricane events. 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 debris source's density can be obtained from direct observation of the building site, and from development and/or urban planning documents. Several debris generation models are available in the literature, e.g., component-based pressure-induced model (Gurley et al. 2005), and empirical models based on damage surveys (FEMA-325 2007b). In this paper, the debris generation model employed by the Florida public hurricane loss model (FPHLM) is adopted (Gurley et al. 2005). 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-s gust wind speed, and (2) the geometry of the house.

Two different types of debris trajectory models are available in the literature to estimate the debris flight path: (1) models that investigate the two-dimensional motion of debris in uniform wind flow using simplified dimensionless equations of motion (Holmes 2004; Baker 2007; Lin et al. 2007), and (2) models that consider the debris trajectory in a three-dimensional space through the numerical integration of the three- or six-degree-of-freedom debris equations of motion (Twisdale et al. 1996; Grayson et al. 2012). To reduce the computational cost of windborne debris hazard analysis, a 2D model using simplified dimensionless equations of motion proposed by Lin et al. (2007) is adopted in this study to estimate the debris flight trajectory. This model provides the landing position of the debris in terms of two statistically independent Gaussian random variables, i.e., X = along-wind flight distance and Y = across-wind flight distance, which are described by their means (μ_X and $\mu_Y = 0$ m) and standard deviations ($\sigma_X = \sigma_Y = 0.35\mu_X$). The parameter μ_X is expressed as a function of the normalized flight time, $\tilde{T}$, and the Tachikawa number, $K = \rho_\mathrm{a} \cdot V^2 \cdot \ell^2 / m_\mathrm{d} \cdot g$ (in which ρ_a = air density, ℓ = characteristic dimension of the debris, $m_\mathrm{d} = M_\mathrm{d} \cdot A_\mathrm{d}$ = mass of the debris, g = gravity constant), using nondimensional coefficients that depend on the shape of the debris and were calibrated using wind tunnel tests (Lin et al. 2007).

Interaction among Hazards in the Hazard Analysis Phase

The interaction among different hazard sources acting during a hurricane event can take place in the form of: (1) interacting hazards, and (2) hazard chains. The PBHE framework accounts for the former type of interaction within the hazard analysis phase by considering two modes of interaction: (1) different hazards described using shared *IM*s (e.g., wind and windborne debris hazards require the description of the wind field, which is common to both hazards for a given hurricane event); and (2) one or more hazards described by statistically dependent *IM*s, which can be modeled using joint probability density functions (e.g., Myers and Ho 1975). In this study, the *IM*s used to describe the wind field and the debris properties are assumed as independent random variables.

Structural Characterization Phase

The structural characterization phase provides the probabilistic description of the SP vector, which includes the random structural properties that can influence the loading applied to the structure and/or its components through the IP vector. These properties can include, e.g., geometrical properties, such as position and dimensions of windows and doors, and the dimensions of the building (length, width, and height); mechanical properties, such as natural period and damping; and other parameters that determine the intensity of the wind effects on the structure and its components (e.g., pressure coefficients). Geometrical properties can usually be treated as deterministic quantities, because they can be directly measured for existing structures or are characterized by a small variability. In general, the variability of the mechanical properties of a low-rise residential building has a negligible effect on the performance of the building itself and can also be neglected. The statistical characterization of the other parameters affecting the intensity of the wind effects can be obtained through wind tunnel tests or from appropriate statistical distributions available in the literature. The latter approach is followed in this study. It is noteworthy that the statistical distributions of these parameters usually change any time the building envelope is breached. Thus, it is important to account for these changes to properly evaluate the effects of hazard chains (Barbato et al. 2013). In this paper, the following random structural parameters are considered: wind pressure exposure factor (evaluated at h = height of the target building), K_h; external pressure coefficient for the j-th building component, $GC_{\mathrm{p},j}$; and internal pressure coefficient for the j-th building component, $GC_{\mathrm{pi},j}$ ($j = 1, \ldots, n_\mathrm{c}$, where n_c = number of building components). The variability of the wind gust factor G is incorporated in that of external and internal pressure coefficients because it is usually small for the building typology considered in this study (Li and Ellingwood 2006).

Interaction Analysis Phase

The choice of the IP vector is crucially dependent on the hazard sources, limit states, and performance levels of interest for both structural and nonstructural 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, $p_{\mathrm{w},j}$. In this study, the wind pressure acting on the j-th component of the building is computed as (ASCE 2010)

$$p_{\mathrm{w},j} = q_h \cdot (GC_{\mathrm{p},j} - GC_{\mathrm{pi},j}) \tag{2}$$

in which the velocity pressure evaluated at h, q_h, is given by

$$q_h = 0.5 \cdot \rho_{\mathrm{a}} \cdot K_h \cdot K_{\mathrm{zt}} \cdot V^2 \tag{3}$$

where K_{zt} = topographic factor.

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, e.g., aluminum storm panels (Herbin and Barbato 2012; Alphonso and Barbato 2014).

The analysis step of the interaction analysis phase requires an impact model to estimate 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 impact with the target building. In the event of an impact, it uses the horizontal component of the missile velocity and data relative to the missile size and mass (obtained from the debris generation model) to compute the impact linear momentum and kinetic energy of the missile, which are given by

$$\begin{aligned} L_{\mathrm{d}} &= M_{\mathrm{d}} \cdot A_{\mathrm{d}} \cdot u_{\mathrm{d}} \\ K_{\mathrm{d}} &= \frac{1}{2} M_{\mathrm{d}} \cdot A_{\mathrm{d}} \cdot u_{\mathrm{d}}^2 \end{aligned} \tag{4}$$

in which u_{d} = debris horizontal velocity at impact and is given by (Lin and Vanmarcke 2008)

$$u_{\mathrm{d}} = V \cdot [1 - \exp(-\sqrt{2 \cdot C \cdot K \cdot x})] \tag{5}$$

in which $x = g \cdot X/V^2$ = dimensionless horizontal flight distance of the debris, and $C = 0.911$ for sheet-type windborne debris.

Damage Analysis Phase

In the methodology proposed here for low-rise residential buildings, the structural analysis phase is not performed explicitly and the strength of vulnerable components is directly compared to the corresponding IP. 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.

$$LSF_j = DM_j - IP_j \tag{6}$$

where DM_j corresponds 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 IPs are compared with the limit state capacity of different components of the building, and if the IPs 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 interaction and damage analysis phases are repeated with updated SPs until there is no further additional breach (Fig. 2).

Loss Analysis Phase

The loss analysis phase gives the estimate of the annual probability of exceedance of the DV. The DV can be chosen as, e.g., the repair cost related to the hurricane induced damage, or the total cost of the structural system during its design lifetime, which includes construction and maintenance costs, repair costs, economic losses attributable to structural and content damage, and loss of functionality (Bjarnadottir et al. 2011). The statistical description of the repair cost for each of the building components can be obtained from the literature and/or market, and the loss can be calculated as a function of the percentage of component damage. Repair costs depends on local labor cost, availability of materials, and local construction practices. Loss data from insurance companies can also be used to derive an appropriate probabilistic description of losses.

Faster Reanalysis Multilayer MCS Method

The ordinary multilayer MCS method proposed here for risk assessment of residential buildings can be modified to achieve an improved computational efficiency when numerous performance assessment analyses are required for the same building (e.g., when comparing different design alternatives and hazard mitigation strategies). For this type of problem, the hazard and interaction analysis phases remain the same as long as the location and geometry of the building do not change. Under these conditions, the computational effort of the multilayer MCS procedure can be significantly reduced by randomly generating the IPs based on their statistical description obtained from a first application of the multilayer MCS technique (e.g., on an unmitigated structure), thus avoiding the repetition of the hazard and interaction analysis phases.

The statistical description of the IPs consists of the marginal probability distributions and the correlations between pairs of IPs. Thus, the random generation of the IPs requires the joint probability distribution of the random variables that describe the IPs. Different techniques are available in the literature to generate the joint probability distribution of random variables given their marginal distributions and correlations, e.g., the Chow-Liu tree (Chow and Liu 1968), the Nataf transformation (Der Kiureghian and Liu 1986), and the copula approach (Nelsen 2007). In this study, the copula approach is adopted to model the joint probability distribution of the IPs in conjunction with the faster reanalysis multilayer MCS method.

A copula is a multivariate joint distribution defined on the n-dimensional unit cube $[0{,}1]^n$ such that every marginal distribution is uniform on the interval [0, 1] (Sklar 1959; Nelsen 2007). According to Sklar's theorem (Sklar 1959), the multivariate joint cumulative distribution function (CDF) of n random variables, $X_1, \ldots\ldots, X_n$, can be expressed as

$$F(X_1, \ldots, X_n) = C[F_1(X_1), \ldots, F_n(X_n)] = C(U_1, \ldots, U_n) \tag{7}$$

where $F(X_1, \ldots, X_n)$ = joint CDF of variables $X_1, \ldots, X_n$; $U_i = F_i(X_i)$ = marginal CDF of $X_i (i = 1, \ldots, n)$; and $C(U_1, \ldots, U_n)$ = copula function. The joint CDF of $X_i (i = 1, \ldots, n)$ can be determined by Eq. (7) if the marginal distributions of the random variables and the copula function are known. Different types of copulas can be used to describe the dependence between the random variables (Tang et al. 2013). In this study, a Gaussian copula is adopted to model the dependence between the variables. The investigation of the efficiency of different copulas in modeling the dependence structure of the variables, albeit important, is out of the scope of this study.

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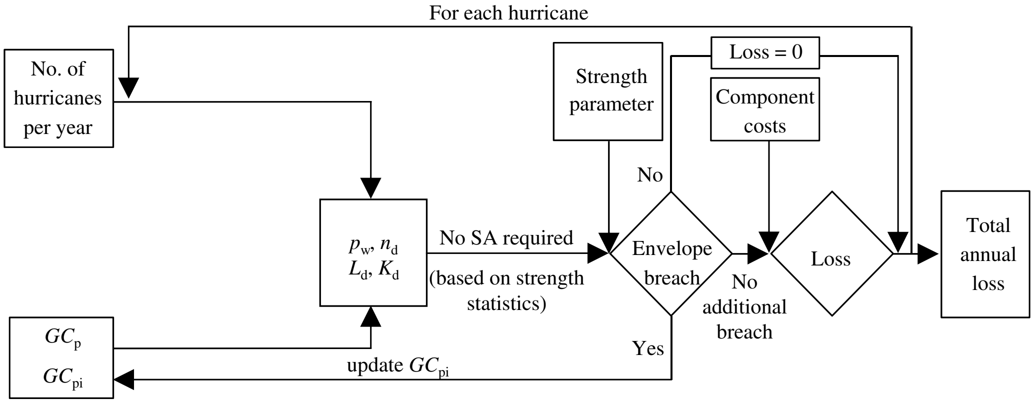

Fig. 3. Modified multilayer MCS approach for probabilistic hurricane loss estimation of nonengineered residential buildings requiring multiple reanalyses

The *IP*s obtained from the interaction analysis are $p_{w,j}$ for each building component, n_d, and L_d and K_d for each impact. The wind pressure values depend on the velocity pressure,q_h, and on the *SP*s through Eq. (2). Based on the results obtained from numerous applications of the multilayer MCS method, it is assumed that, for a given wind velocity, both L_d and K_d follow a lognormal distribution, which is completely characterized by its mean and standard deviation (i.e., μ_{L_d} and σ_{L_d} for L_d, and μ_{K_d} and σ_{K_d} for K_d). These means and standard deviations are modeled as random variables, each described by an empirical CDF. It is further observed that the correlation coefficients between μ_{L_d} and μ_{K_d}, and between σ_{L_d} and σ_{K_d} are very close to 1. Thus, a Gaussian copula function is generated for variables q_h, n_d, μ_{L_d}, and σ_{L_d}, based on the marginal distributions and correlation coefficients obtained in the first application of the multilayer MCS method. In the subsequent reanalyses, the hazard analysis and interaction analysis phases are substituted in the modified multilayer MCS method by a sample generation step (Fig. 3), in which: (1) variables q_h, n_d, μ_{L_d}, and σ_{L_d} are sampled from the joint probability distribution constructed using the previously obtained copula function; (2) for each of the n_d impacts, variables L_d and K_d are sampled from the corresponding lognormal distributions with means and standard deviations μ_{L_d} and σ_{L_d}, and μ_{K_d} and σ_{K_d}, respectively; and (3) variables $GC_{p,j}$ and $GC_{pi,j}$ are sampled for each building component and variables $p_{w,j}$ are obtained from Eq. (2).

Cost-Benefit Analysis

Cost-benefit analysis can be used to compare the cost of different storm mitigation techniques and the benefits achieved from improved performance of the building over its entire design life. Cumulative monetary damages or losses over a specific period of time are of interest to decision-makers and can be estimated based on the expected annual loss. The relationship between the cost of mitigation tactics and its benefits are explicitly quantified and thereby facilitate effective decision making for investment in the safety of buildings (Liel and Deierlein 2013). The expected present value of economic benefit of a hurricane mitigation technique (B) can be expressed as

$$B = \sum_{n=0}^{t} \frac{EAL_u - EAL_r}{(1+\rho)^n} - C_r \tag{8}$$

where EAL_u = expected annual loss for the unretrofitted structure; EAL_r = expected annual loss after retrofit; ρ = discount rate; t = planning period; and C_r = present cost of the retrofit. The expected annual loss (EAL) is defined as the average economic loss that occurs every year in the building and is equal to the area under the corresponding annual probability of exceedance curve. The retrofit or redesign is financially viable if the corresponding expected value of economic benefit is greater than zero.

Case Study

A realistic case study of a single-family house subject to wind and windborne debris hazards is presented here to illustrate the proposed PBHE framework and to compare the costs and benefits of different storm mitigation techniques and/or design alternatives when applied to a given structure. The house is located in a residential development in Pinellas County, Florida, which contains 201 similar gable roof wooden residential buildings (Fig. 4). The roof covers were considered as debris sources, whereas the walls, windows, and doors were considered as debris impact vulnerable components. The value of the target structure was taken as $200,000. and the content value was assumed equal to $100,000.

Map data ©2015 Google

Fig. 4. Plan view of the benchmark residential development (map data © 2015 Google)

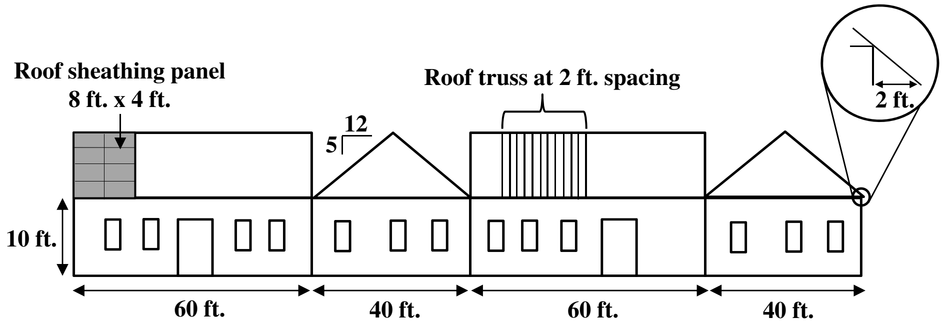

Fig. 5. Unfolded view of target building (adapted from Unnikrishnan and Barbato 2015, © ASCE)

Hazard Analysis

The number of hurricanes per year was simulated using a Poisson occurrence model, with an annual hurricane occurrence rate $\nu_{\text{hurricane}} = 0.52$ obtained from the National Institute of Standards and Technology (NIST) database (NIST 2005). The 3-s wind speed (V) recorded at 10 m above the ground was adopted as IM for wind hazard. The hurricane wind speed variability was described by using a two-parameter Weibull distribution, the parameters of which were fitted for 16 different wind directions through maximum likelihood estimation of the hurricane wind speed records provided by NIST for milepost 1,400 (Unnikrishnan 2015). The NIST wind speed records contain data sets of simulated 1-min hurricane wind speeds at 10 m above the ground in an open terrain near the coastline (NIST 2005). Before fitting, the wind speed data were multiplied by a factor equal to 0.89, to obtain the corresponding 3-s wind speeds for exposure category B (Lungu and Rackwitz 2001). Nonhurricane wind hazard was also considered in addition to hurricane wind hazard. The daily maximum 3-s wind speeds at the building location were obtained from the Iowa Environmental Mesonet (IEM) database for the 1971–2013 period (IEM 2001). The historical hurricane tracks that passed within a 250-mile radius from the site during the same 1971–2013 period were obtained from the National Oceanic and Atmospheric Administration (NOAA) database and were used to separate the nonhurricane wind speeds from the hurricane wind speeds. The yearly maximum nonhurricane 3-s wind speeds were then obtained and fitted to a lognormal distribution, with a mean of 18.34 m/s and a standard deviation of 1.08 m/s.

The IMs considered for windborne debris hazard were area of debris, A_d, and mass per unit area of debris, M_d. They were assumed to follow uniform distributions defined in the range $[0.108, 0.184]$ m^2 and $[10.97, 14.97]$ kg/m^2, respectively (Gurley et al. 2005). The FPHLM debris generation model was used to simulate the number of debris originating from the source houses.

Description of Base Structure and Hazard Mitigation Techniques

Fig. 5 provides an unfolded view of the target residential building, including its (deterministic) geometric parameters, and the position and dimensions of windows and doors (Gurley et al. 2005). The wind pressure exposure factor K_h was assumed as normally distributed with a mean value of 0.71 and a coefficient of variation (COV) of 0.19. The topographic factor was modeled as a deterministic quantity with value $K_\text{zt} = 1$. The statistical characterization of the external and internal pressure coefficients is given in Table 1 (Li and Ellingwood 2006), and the roof zones for the external pressure coefficients are shown in Fig. 6.

The base structure is characterized by (1) roof cover made of asphalt shingles, (2) nailing pattern 8d C6/12 (i.e., 8 mm diameter smooth shank nails, with a spacing of 6 in. at the center and 12 in. at the edge) for the roof sheathing, (3) unprotected windows and doors, and (4) wooden walls. Table 2 shows the statistics of the limit state capacity for the different components of the base building and their corresponding limit states (Gurley et al. 2005; Datin et al. 2010; Masters et al. 2010). The normal distributions reported here are truncated with a lower bound of zero for the corresponding quantity.

The following storm mitigation techniques and design alternatives were considered: (1) using clay tiles as roof cover instead of asphalt shingles; (2) using an improved roof nailing pattern of 8d C6/6 (i.e., 8 mm diameter smooth shank nails, with a spacing of 6 in. in both directions) or 8d R6/6 (i.e., 8 mm diameter ring shank nails, with a spacing of 6 in. in both directions) instead of the traditional 8d C6/12 pattern; (3) using aluminum hurricane protection

Table 1. Statistical Characterization of External and Internal Pressure Coefficients (reprinted from Unnikrishnan and Barbato 2015, © ASCE)

Pressure coefficient	Location/condition	Mean	COV	Distribution
GC_p	Roof (zone 1)	−0.855	0.12	Normal
	Roof (zone 2)	−1.615	0.12	Normal
	Roof (zone 3)	−2.470	0.12	Normal
	Windward wall	0.950	0.12	Normal
	Leeward wall	−0.760	0.12	Normal
	Side wall	−1.045	0.12	Normal
GC_pi	Enclosed	0.150	0.33	Normal
	Breached	0.460	0.33	Normal

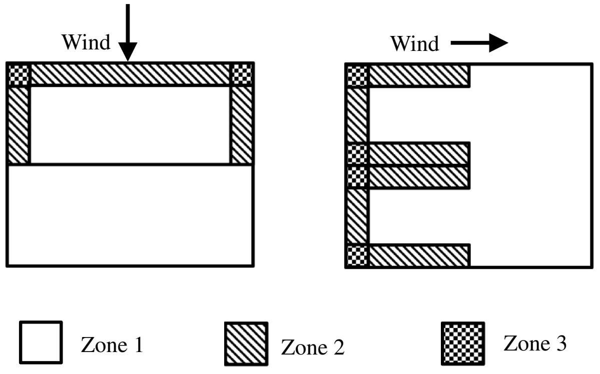

Fig. 6. Roof zones for external pressure coefficients

Table 2. Statistics of the Limit State Capacity for Different Components of the Base Structure

Component	Limit state	Mean	COV	Distribution
Roof cover (shingles)	Separation or pull off (R_{cover1})	$3.35\ \text{kN/m}^2$	0.19	Normal
Roof sheathing (nailing pattern 8d C6/12)	Separation or pull off (R_{sh1})	$6.20\ \text{kN/m}^2$	0.12	Lognormal
Doors	Pressure failure (R_{door})	$4.79\ \text{kN/m}^2$	0.20	Normal
Windows	Pressure failure ($R_{\text{w,pressure}}$)	$3.33\ \text{kN/m}^2$	0.20	Normal
	Impact failure ($R_{\text{w,impact}}$)	$4.72\ \text{kg m/s}$	0.23	Lognormal
Wall sheathing	Pressure failure ($R_{\text{wsh,pressure}}$)	$6.13\ \text{kN/m}^2$	0.40	Normal
	Impact failure ($R_{\text{wsh,impact}}$)	$642.00\ \text{kg m}^2/\text{s}^2$	0.07	Lognormal
Roof to wall connections (wood)	Tensile failure ($R_{\text{wcon,wood}}$)	16.28 kN	0.20	Lognormal
Wall (wood)	Lateral failure ($R_{\text{wall,wl}}$)	5.40 kN[a] 3.53 kN[b]	0.25	Normal
	Uplift failure ($R_{\text{wall,wu}}$)	9.00 kN/m[a] 5.80 kN/m[b]	0.25	Normal

[a] Toe nail connection.

[b] Sheathing nail connection.

Table 3. Statistics of Limit State Capacity for Different Storm Mitigation Techniques and Design Alternatives

Component	Limit state	Mean (kN/m^2)	COV	Distribution
Roof cover (tiles)	Separation or pull off (R_{cover2})	$5.25\ \text{kN/m}^2$	0.20	Normal
Roof sheathing (nailing pattern 8d C6/6)	Separation or pull off (R_{sh2})	$9.83\ \text{kN/m}^2$	0.10	Lognormal
Roof sheathing (nailing pattern 8d R6/6)	Separation or pull off (R_{sh3})	$12.08\ \text{kN/m}^2$	0.07	Lognormal
Windows with hurricane panels	Impact failure ($R_{\text{panel,impact}}$)	0.496 kJ	0.15	Lognormal
Roof to wall connections (masonry)	Tensile failure ($R_{\text{wcon,masonry}}$)	18.68 kN	0.20	Lognormal
Wall (masonry)	Combined uplift and bending failure ($R_{\text{wall,masonry}}$)	18.00 kN 1.31 kN m	0.20	Normal

panels for windows; and (4) using masonry walls instead of wooden walls. The statistics of the limit state capacity for the different storm mitigation techniques and design alternatives, and their corresponding limit states are shown in Table 3 (Gurley et al. 2005; Datin et al. 2010; Alphonso and Barbato 2014). Also in this case, the normal distributions reported in this table are truncated with a lower bound of zero for the corresponding quantity. The combination of different storm mitigation techniques and design alternatives were considered, giving a total of 24 configurations (i.e., Case #1 through Case #24) including the base structure (corresponding to Case #1).

The total loss during a 30-year design lifetime for the building (given by the sum of the repair cost and the content loss) was assumed as DV. The repair costs of each damaged component were generated based on a lognormal distribution, with mean given by the percentage of damage of the given component multiplied by its total cost (expressed as a percentage of the building cost), and COV equal 0.1 (Gurley et al. 2005).

The content loss was estimated using the approach followed in *HAZUS-MH* (FEMA 2012), i.e., by using empirical functions that express the content loss associated with the damage of each individual component as a percentage of the total value of the content. The content loss was sampled from a lognormal distribution with mean equal to the highest loss estimate obtained from the *HAZUS-MH* content loss functions and COV equal to 0.1. The total loss was calculated by adding up all the losses attributable to the damage of various components and the content damage.

To accurately estimate the annual probability of exceedance of the total loss (which coincides with the complementary cumulative distribution function of the DV), 100,000 samples were used for all results presented in this study. Three sets of results are presented here: (1) the hurricane loss analysis for the base structure; (2) the validation of the proposed faster reanalysis method; and (3) the cost/benefit comparison of different storm mitigation strategies and design alternatives.

Loss Analysis Results for the Base Structure

Fig. 7 plots, in a semi-logarithmic scale, the annual probabilities of exceedance of the loss for the target building for different hazard scenarios. It also provides the EAL and standard deviation of loss (SDL) for each of the hazard scenarios considered.

From the results presented in Fig. 7, it is observed that for hurricane induced losses, the loss attributable to windborne debris hazard is predominant for losses lower than approximately $15,000, whereas the loss attributable to wind hazard is predominant for

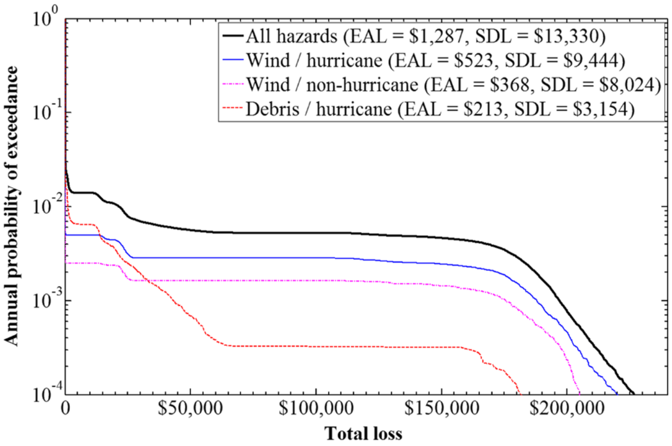

Fig. 7. Annual probabilities of loss exceedance for base building under different hazard scenarios

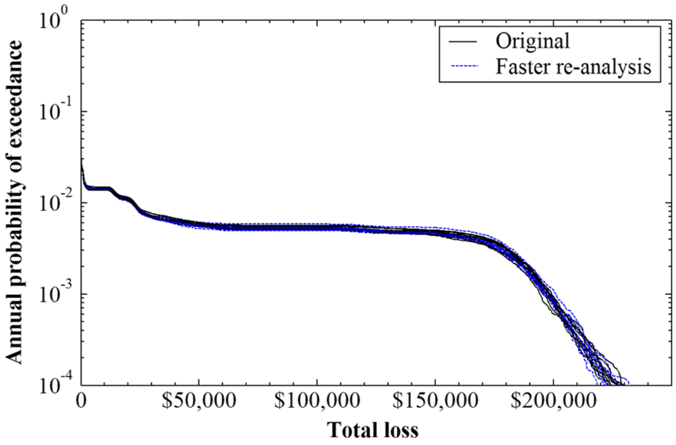

Fig. 8. Comparison of original and faster reanalysis multilayer MCS approaches

losses higher than approximately $15,000. This result is attributable to the fact that, at lower wind speeds, the probability of damage to the windows resulting from windborne debris is higher than that attributable to wind pressure. For nonhurricane winds, the loss owing to wind hazard is predominant, whereas the loss attributable to windborne debris is negligible (i.e., zero loss over the 100,000 samples), because for nonhurricane winds the number of generated windborne debris and, thus, the number of debris impacts is generally very small. It is also observed that the EAL attributable to the interaction of all hazards is approximately 15% higher than the sum of the EALs owing to each individual hazard. This result suggests a significant level of interaction among the different hazards for the case study considered here. In addition, it is observed that for all the hazard scenarios, the SDL is significantly higher than the EAL, which indicates that the annual loss is characterized by a high dispersion. Therefore, the EAL is not sufficient alone to describe the loss analysis results.

Validation of the Faster Reanalysis Multilayer MCS Procedure

To validate the newly proposed faster reanalysis multilayer MCS procedure, the hurricane loss analysis for the base structure (Case #1) was repeated 10 times using both the original and faster reanalysis multilayer MCS procedures. The results from the different runs were compared in terms of annual probabilities of loss exceedance (which are plotted in Fig. 8), and of EAL and SDL. Using a workstation with an Intel quad core Q6600 2.4 GHz and 4 GB RAM, the computational time for the 10 runs of the original multilayer MCS procedure varied between 2,880 and 3,027 s, whereas the computational time for the 10 runs of the faster reanalysis algorithm varied between 207 and 222 s, i.e., the reanalysis algorithm was approximately 13–14.5 times faster than the original algorithm.

From the results presented in Fig. 8, it is observed that the annual probability of exceedance curves obtained using the proposed reanalysis approach based on copula are similar to those obtained using the original multilayer MCS method, with a variability between the different repetitions of the two methods that is very close to the variability observed among different repetitions obtained from the same method. Additionally, a 95% confidence interval was calculated for the sample means and standard deviations of EAL and SDL for the original and faster reanalysis multilayer MCS method (Unnikrishnan 2015). The computed sample means and standard deviations for the faster reanalysis multilayer MCS method were within the confidence interval for the sample means and standard deviations of the original method, and vice-versa, which indicated that the differences between the means and standard deviations of the two sets of samples are not statistically significant. Therefore, it is concluded that the proposed faster reanalysis approach can be used with good accuracy for problems that require risk reassessment.

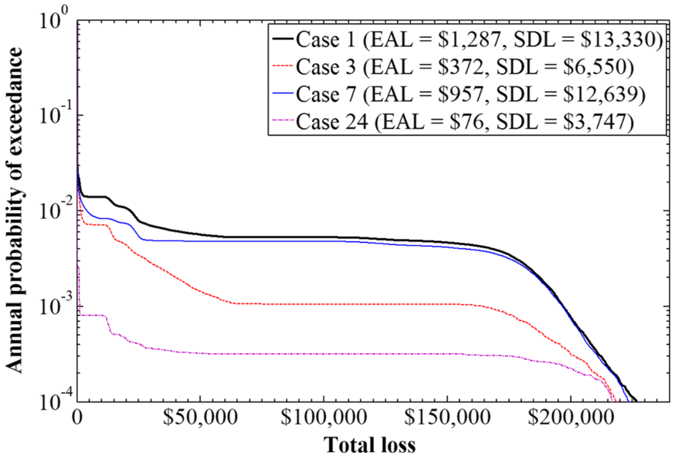

Fig. 9. Annual probability of loss exceedance for different hazard mitigation scenarios

Cost/Benefit Comparison of Different Hazard Mitigation Techniques

The annual probabilities of loss exceedance for the base structure and each of the 23 mitigation scenarios considered in this study were calculated using the faster reanalysis multilayer MCS method. Some of these curves are shown in Fig. 9 using a semilogarithmic scale, together with the corresponding EAL and SDL.

A cost-benefit analysis was carried out to compare the cost effectiveness of different retrofit techniques and design alternatives. In this study, discount rate and planning period were assumed as 3% and 30 years, respectively. The cost of retrofit includes the cost of the materials and the cost for the installation of the retrofits, and was obtained as the mean values of the quotes obtained by directly contacting several local suppliers and contractors. Table 4 provides EAL, SDL, cost of retrofit, discounted mean loss in 30 years, and discounted expected savings in 30 years for each mitigation scenario when compared with the base structure.

From the results presented in Table 4, it is observed that roof renailing using 8d R6/6 can result in an overall savings of $12,472 and is the most effective solution to reduce hurricane risk among the mitigation techniques considered in this study. Similarly, the use of aluminum panels for window protection can provide savings of approximately $5,000. The design alternative of using masonry or clay 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 owing to hurricanes, resulting in savings of approximately $15,000.

Conclusions

In this paper, the performance-based hurricane engineering (PBHE) framework is specialized for hurricane risk assessment of low-rise residential buildings. The focus of this paper is on the hurricane

Table 4. Cost/Benefit Comparison of Different Retrofit Scenarios

Materials	Window protection	Roof cover	Roof nailing pattern	Case number	Loss analysis		Cost/benefit analysis		
					EAL($)	SDL($)	Cost($)	Loss($)	Saving($)
Wood	No	Shingles	8d C6/12	1	$1,287	$13,330	—	$25,982	—
			8d C6/6	2	$394	$6,656	$5,800	$7,954	$12,228
			8d R6/6	3	$372	$6,550	$6,000	$7,510	$12,472
		Tiles	8d C6/12	4	$1,184	$13,286	$11,000	$23,903	-$8,921
			8d C6/6	5	$379	$6,559	$16,800	$7,651	$1,531
			8d R6/6	6	$363	$6,507	$17,000	$7,328	$1,654
	Yes	Shingles	8d C6/12	7	$957	$12,639	$1,800	$19,320	$4,862
			8d C6/6	8	$170	$5,011	$7,600	$3,432	$14,950
			8d R6/6	9	$130	$4,451	$7,800	$2,624	$15,558
		Tiles	8d C6/12	10	$901	$12,201	$12,800	$18,189	-$5,007
			8d C6/6	11	$151	$4,864	$18,600	$3,048	$4,334
			8d R6/6	12	126	$4,395	$18,800	$2,543	$4,639
Masonry	No	Shingles	8d C6/12	13	$1,093	$13,069	$19,200	$22,065	-$15,283
			8d C6/6	14	$291	$5,627	$25,000	$5,874	-$4,892
			8d R6/6	15	$278	$5,499	$25,200	$5,612	-$4,830
		Tiles	8d C6/12	16	$1,003	$13,010	$30,200	$20,249	-$24,467
			8d C6/6	17	$281	$5,528	$36,000	$5,672	-$15,690
			8d R6/6	18	$263	$5,392	$36,200	$5,309	-$15,527
	Yes	Shingles	8d C6/12	19	$888	$12,115	$21,000	$17,927	-$12,945
			8d C6/6	20	$100	$4,399	$26,800	$2,018	-$2,836
			8d R6/6	21	$90	$4,112	$27,000	$1,816	-$2,834
		Tiles	8d C6/12	22	$871	$12,064	$32,000	$17,584	-$23,602
			8d C6/6	23	$81	$3,870	$37,800	$1,635	-$13,453
			8d R6/6	24	$76	$3,747	$38,000	$1,534	-$13,552

loss analysis of residential buildings and the effects of mitigation techniques for wind and windborne debris hazards on the structural performance. The problem of risk assessment is disaggregated into the following basic probabilistic components: (1) hazard analysis, (2) structural characterization, (3) interaction analysis, (4) structural analysis, (5) damage analysis, and (6) loss analysis. A highly efficient modification of the multilayer Monte Carlo simulation (MCS) technique based on copula is proposed for faster reevaluation of hurricane risk. The proposed faster reanalysis multilayer MCS method is used in conjunction with cost/benefit analysis to compare different hazard mitigation techniques and design alternatives.

A realistic case study consisting of an actual residential development located in Pinellas County, Florida, is presented to illustrate the framework. The annual probabilities of exceedance of the loss for the target building for different hazard scenarios are calculated. It is found that for hurricane induced loss, the loss attributable to windborne debris hazard is predominant for lower loss levels, whereas the loss attributable to wind hazard is predominant for higher loss levels; whereas, for nonhurricane induced loss, windborne debris hazard is negligible. The proposed faster reanalysis approach is validated based on the corresponding results obtained using the original multilayer MCS. The cost-effectiveness of different hurricane hazard mitigation techniques and design alternatives typically used for low-rise residential buildings are compared. For the specific application example considered here and among the different types of retrofits compared in this study, the most economically viable form of retrofit is the use of roof renailing with an 8d R6/6 pattern, and the least is the use of masonry walls.

It is concluded that the PBHE methodology, in conjunction with the faster reanalysis multilayer MCS method proposed here and cost/benefit analysis, can be effectively used to improve the design or select appropriate hurricane hazard mitigation techniques for a specific low-rise residential building. It is noteworthy that the presented probabilistic methodology differs from the *HAZUS-MH* approach because it is concerned with the design and/or retrofit of specific buildings and structures, whereas *HAZUS-MH* focuses on loss analysis at a regional level.

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References

Alphonso, T. C., and Barbato, M. (2014). "Experimental fragility curves for aluminum storm panels subject to windborne debris impact." *J. Wind Eng. Ind. Aerodyn.*, 134, 44–55.

ASCE. (2010). "Minimum design loads for buildings and other structures." Reston, VA.

Augusti, G., and Ciampoli, M. (2008). "Performance-based design in risk assessment and reduction." *Probab. Eng. Mech.*, 23(4), 496–508.

Baker, C. J. (2007). "The debris flight equations." *J. Wind Eng. Ind. Aerodyn.*, 95(5), 329–353.

Barbato, M., Petrini, F., Unnikrishnan, V. U., and Ciampoli, M. (2013). "Performance-based hurricane engineering (PBHE) framework." *Struct. Saf.*, 45, 24–35.

Batts, M. E., Cordes, M. R., Russell, L. R., Shaver, J. R., and Simiu, E. (1980). "Hurricane wind speeds in the United States." *Rep. No. BSS-124*, National Bureau of Standards, U.S. Dept. of Commerce, Washington, DC.

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." *Struct. Saf.*, 33(3), 173–185.

Bradley, B. A., Lee, D. S., Broughton, R., and Price, C. (2009). "Efficient evaluation of performance-based earthquake engineering equations." *Struct. Saf.*, 31(1), 65–74.

Chouinard, L., and Liu, C. (1997). "Model for recurrence rate of hurricanes in Gulf of Mexico." *J. Waterway Port Coastal Ocean Eng.*, 10.1061/(ASCE)0733-950X(1997)123:3(113), 113–119.

Chow, C. K., and Liu, C. N. (1968). "Approximating discrete probability distributions with dependence trees." *IEEE Trans. Inform. Theory*, 14(3), 462–467.

Conte, J. P., and Zhang, Y. (2007). "Performance-based earthquake engineering: Application to an actual bridge-foundation-ground system." *Proc., 12th Italian National Conf. on Earthquake Engineering*, Associazione Nazionale Italiana di Ingegneria Sismica (ANIDIS), Rome.

Cornell, C. A., and Krawinkler, H. (2000). "Progress and challenges in seismic performance assessment." *PEER Center News*, 3(2), 1–4.

Datin, P., Prevatt, D., and Pang, W. (2010). "Wind-uplift capacity of residential wood roof-sheathing panels retrofitted with insulating foam adhesive." *J. Archit. Eng.*, 10.1061/(ASCE)AE.1943-5568.0000034, 144–154.

Der Kiureghian, A., and Liu, P. (1986). "Structural reliability under incomplete probability information." *J. Eng. Mech.*, 10.1061/(ASCE)0733-9399(1986)112:1(85), 85–104.

Ellingwood, B., Rosowsky, D., Li, Y., and Kim, J. (2004). "Fragility assessment of light-frame wood construction subjected to wind and earthquake hazards." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2004)130:12(1921), 1921–1930.

FEMA. (2007a). "Multi-hazard estimation methodology—Hurricane model." *Rep. No. HAZUS-MH-MR4 technical manual*, Dept. of Homeland Security, Washington, DC.

FEMA. (2007b). "USACE hurricane debris estimating model." *FEMA-325*, Dept. of Homeland Security, Washington, DC.

FEMA. (2012). "HAZUS-MH 2.1 hurricane model technical manual." Washington, DC.

Frangopol, D., Lin, K., and Estes, A. (1997). "Life-cycle cost design of deteriorating structures." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1997)123:10(1390), 1390–1401 .

Grayson, M., Pang, W., and Schiff, S. (2012). "Three-dimensional probabilistic wind-borne debris trajectory model for building envelope impact risk assessment." *J. Wind Eng. Ind. Aerodyn.*, 102, 22–35.

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

Gurley, K., Pinelli, J. P., Subramanian, C., Cope, A., Zhang, L., and Murphree, J. (2005). "Predicting the vulnerability of typical residential buildings to hurricane damage." *Florida Public Hurricane Loss Projection Model (FPHLPM) Engineering Team Final Rep.*, I.H.R. Center, Florida International Univ., Miami.

Herbin, A. H., and Barbato, M. (2012). "Fragility curves for building envelope components subject to windborne debris impact." *J. Wind Eng. Ind. Aerodyn.*, 107–108, 285–298.

Holmes, J. D. (2004). "Trajectories of spheres in strong winds with application to wind-borne debris." *J. Wind Eng. Ind. Aerodyn.*, 92(1), 9–22.

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

Huang, Z., Rosowsky, D. V., and Sparks, P. R. (2001). "Long-term hurricane risk assessment and expected damage to residential structures." *Reliab. Eng. Syst. Saf.*, 74(3), 239–249.

IEM. (2001). "Iowa environmental mesonet database." ⟨http://www.mesonet.agron.iastate.edu/request/download.phtml?network=FL_ASOS⟩ (Apr. 16, 2014).

Jalayer, F., and Cornell, C. A. (2003). "A technical framework for probability-based demand and capacity factor design (DCFD) seismic formats." *PEER Rep. 2003/08*, Pacific Earthquake Engineering Research Center, Univ. of California, Berkeley, CA.

Leicester, R. H., Bubb, C. T. J., Dormant, C., and Beresford, F. D. (1980). "An assessment of potential cyclone damage to dwellings in Australia." *Wind engineering*, J. E. Cermak, ed., Pergamon, New York, 23–36.

Li, Y. (2010). "Assessment of damage risks to residential buildings and cost-benefit of mitigation strategies considering hurricane and earthquake hazards." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)CF.1943-5509.0000204, 7–16.

Li, Y., and Ellingwood, B. R. (2006). "Hurricane damage to residential construction in the us: Importance of uncertainty modeling in risk assessment." *Eng. Struct.*, 28(7), 1009–1018.

Li, Y., and Ellingwood, B. R. (2009). "Framework for multihazard risk assessment and mitigation for wood-frame residential construction." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2009)135:2(159), 159–168.

Li, Y., and van de Lindt, J. W. (2012). "Loss-based formulation for multiple hazards with application to residential buildings." *Eng. Struct.*, 38, 123–133.

Liel, A. B., and Deierlein, G. G. (2013). "Cost-benefit evaluation of seismic risk mitigation alternatives for older concrete frame buildings." *Earthquake Spectra*, 29(4), 1391–1411.

Lin, N., Holmes, J., and Letchford, C. (2007). "Trajectories of wind-borne debris in horizontal winds and applications to impact testing." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2007)133:2(274), 274–282 .

Lin, N., and Vanmarcke, E. (2008). "Windborne debris risk assessment." *Probab. Eng. Mech.*, 23(4), 523–530.

Lungu, D., and Rackwitz, R. (2001). "Joint committee on structural safety–probabilistic model code. Part 2: Loads." ⟨~http://www.jcss.byg.dtu.dk/~/media/Subsites/jcss/english/publications/probabilistic_model_code/part_ii⟩ (Oct. 5, 2013).

Masters, F. J., Gurley, K. R., Shah, N., and Fernandez, G. (2010). "The vulnerability of residential window glass to lightweight windborne debris." *Eng. Struct.*, 32(4), 911–921.

Myers, V. A., and Ho, F. P. (1975). "Joint probability method of tide frequency analysis applied to apalachicola bay and St. George sound, florida." *NOAA technical Rep. NWS 18*, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, MD.

NAHB. (2000). "A state-of-the-art review and application of engineering information for light-frame homes, apartments, and townhouses." U.S. Dept. of Housing and Urban Development Office of Policy Development and Research, Washington, DC.

Nelsen, R. B. (2007). *An introduction to copulas*, Springer, New York.

NIST. (2005). "Extreme wind speed data sets: Hurricane wind speeds." ⟨http://www.itl.nist.gov/div898/winds/hurricane.htm⟩ (Mar. 10, 2011).

Petrini, F. (2009). "A probabilistic approach to performance-based wind engineering (PBWE)." Ph.D. dissertation, Univ. of Rome "La Sapienza," Rome.

Pielke, R., Gratz, J., Landsea, C., Collins, D., Saunders, M., and Musulin, R. (2008). "Normalized hurricane damage in the United States: 1900–2005." *Nat. Hazards Rev.*, 10.1061/(ASCE)1527-6988(2008)9:1(29), 29–42.

Pinelli, J., et al. (2004). "Hurricane damage prediction model for residential structures." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2004)130:11(1685), 1685–1691 .

Pinelli, J. P., Torkian, B. B., Gurley, K., Subramanian, C., and Hamid, S. (2009). "Cost effectiveness of hurricane mitigation measures for residential buildings." *Proc., 11th American Conf. on Wind Engineering (ACWE)*, International Association of Wind Engineering (IAWE). San Juan, Puerto Rico.

Porter, K. A. (2003). "An overview of peer's performance-based earthquake engineering methodology." *Proc., 9th Int. Conf. on Applications of Statistics and Probability in Civil Engineering (ICASP9)*, Millpress, Rotterdam, Netherlands, 973–980.

Porter, K. A., Kiremidjian, A. S., and LeGrue, J. S. (2001). "Assembly-based vulnerability of buildings and its use in performance evaluation." *Earthquake Spectra*, 17(2), 291–312.

Russel, L. R. (1971). "Probability distributions of hurricane effects." *J. Waterways Harbors Coastal Eng. Div.*, 97(1), 139–154.

Sklar, A. (1959). "Fonctions de répartition à n dimensions et leurs marges." Publications de l'Institut de Statistique de L'Université de Paris, Paris, 229–231.

Stewart, M., Rosowsky, D., and Huang, Z. (2003). "Hurricane risks and economic viability of strengthened construction." *Nat. Hazards Rev.*, 10.1061/(ASCE)1527-6988(2003)4:1(12), 12–19.

Stubbs, N., and Perry, D. (1996). "Damage simulation model for buildings and contents in a hurricane environment." *Proc., Building an*

International Community of Structural Engineers-14th ASCE Structures Congress, ASCE, Chicago, 989–996.

Tang, X.-S., Li, D.-Q., Zhou, C.-B., Phoon, K.-K., and Zhang, L.-M. (2013). "Impact of copulas for modeling bivariate distributions on system reliability." *Struct. Saf.*, 44, 80–90.

Twisdale, L. A., Vickery, P. J., and Steckley, A. C. (1996). "Analysis of hurricane wind-borne debris impact risk for residential structures." *Rep. No. 5303*, Applied Research Associates, Raleigh, NC.

Unnikrishnan, V. U. (2015). "Probabilistic performance-based hurricane engineering (PBHE) framework." Ph.D. dissertation, Louisiana State Univ. and Agricultural and Mechanical College, Baton Rouge, LA.

Unnikrishnan, V. U., and Barbato, M. (2015). "Performance-based comparison of different design alternatives and retrofit techniques for residential buildings subjected to hurricane hazard." *Structures Congress 2015*, ASCE, Reston, VA, 1596–1607.

van de Lindt, J., and Dao, T. (2009). "Performance-based wind engineering for wood-frame buildings." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2009)135:2(169), 169–177.

Vickery, P., Skerlj, P., and Twisdale, L. (2000). "Simulation of hurricane risk in the U.S. Using empirical track model." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2000)126:10(1222), 1222–1237.

Vickery, P., and Twisdale, L. (1995). "Prediction of hurricane wind speeds in the United States." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1995)121:11(1691), 1691–1699 .

Wills, J. A. B., Lee, B. E., and Wyatt, T. A. (2002). "A model of wind-borne debris damage." *J. Wind Eng. Ind. Aerodyn.*, 90(4–5), 555–565.