

ST5396

Multihazard Interaction Effects on the Performance of Low-Rise Wood-Frame Housing in Hurricane-Prone Regions

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ABSTRACT

Hurricanes represent multihazard events that include wind, windborne debris, storm surge, and rainfall hazards. Conventional risk analysis does not consider the interaction between these multiple hazards, and treats each risk source as statistically independent of other hazards. In this paper, the effects of multihazard interaction on the performance of low-rise wood-frame residential buildings subject to hurricane hazard are investigated using the Performance-Based Hurricane Engineering (PBHE) framework. The use of different hazard modeling techniques and vulnerability analysis approaches is examined. A new consistent terminology to classify different hazard modeling techniques is also proposed. A case study consisting of a realistic building in an actual residential development in Charleston, South Carolina, is presented to investigate the effects of hazard interaction in the different phases of the PBHE framework. Three different hazard modeling techniques (based on different amounts of available statistical information) and two vulnerability analysis approaches (global vulnerability and assembly-based vulnerability) are considered, for a total of six combinations of loss analysis results for each location. It is concluded

that the use of different hazard models and vulnerability approaches can affect significantly the final results of a loss analysis.

KEY-WORDS: Multihazard analysis; performance-based engineering; hurricane engineering; loss analysis; residential buildings; wood-frame housing.

INTRODUCTION

Structures located in coastal regions at tropical and subtropical latitudes are at high risk of suffering severe damages and losses from wind, windborne debris, surge, and rainfall hazards due to tropical storms and hurricanes. 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). Early studies on hurricane hazard assessment and mitigation focused on the damage and loss from individual hazards such as wind alone or storm surge alone. Powell and Houston (1995) proposed a real-time damage assessment model based on a damage function relating various meteorological variables to the percentage of damage to the buildings. Thomalla et al. (2002) built a storm surge and inundation model for the risk assessment of residential buildings. Discrete damage states were identified and assigned on the basis of inundation and component damage of the building. Li and Ellingwood (2006) developed a probabilistic risk assessment methodology to assess the performance and reliability of low-rise light-frame wood residential constructions subject to hurricane wind hazard.

Conventional multihazard risk analyses, such as those used by the Hazards United States Multi-Hazards (HAZUS-MH) software (FEMA, 2012), consider each risk source as statistically independent of other hazards and do not consider the interaction among multiple hazards (Pang et al. 2014). Dao and van de Lindt (2011) presented a methodology, which was based on the

combination of existing wind tunnel data and a rainwater intrusion model, for estimating the probability of rainwater intrusion into each room of typical wood-frame structures subjected to hurricanes. Li et al. (2011) introduced a loss-based approach for design of light-frame wood buildings in areas prone to more than one natural hazard. The correlation between the hazards was not considered in these studies.

Phan et al. (2007) proposed a methodology for creating site-specific joint distributions of combined hurricane wind and surge, by using full track hurricanes to compute the wind speed and the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model to estimate surge heights (Jelesnianski et al., 1992). Lin and Vanmarcke (2010) developed an integrated vulnerability model that explicitly accounts for the correlation between windborne debris damage and wind pressure damage. This integrated vulnerability model was obtained by coupling a pressure-damage model derived from the component-based model of the Florida Public Hurricane Loss Model (Gurley et al., 2005) with the windborne debris risk model developed by Lin and Vanmarcke (2008). Needham and Keim (2013) examined the relationship between storm surge heights and tropical cyclone wind speeds at 3-hour increments preceding landfall and observed that storm surge magnitudes correlate better with pre-landfall wind speeds than with wind speeds at landfall. Pei et al. (2014) developed joint hazard maps of combined hurricane wind and surge for Charleston, South Carolina. The surface wind speeds and surge heights from individual hurricanes were computed using the Georgiou's wind field model (Georgiou, 1985) and the SLOSH model (Jelesnianski et al., 1992), respectively.

Vickery et al. (2006) presented an overview of the damage and loss models used in the HAZUS-MH hurricane model and proposed wind-windborne debris damage states for residential buildings. Womble et al. (2006) developed a joint hurricane wind–surge damage scale based on a loss-

consistent approach using the HAZUS-MH hurricane model's damage and loss functions and the US Army Corps of Engineers flood depth-loss functions (USACE, 2000) for the assessment of damage from combined wind and flood events. van de Lindt and Taggart (2009) proposed a methodology for the performance-based design and loss analysis of wood buildings subjected to flood hazard using an assembly-based vulnerability model. The methodology involved the calculation of the damage suffered by each building component and the corresponding cost of repair or replacement.

Li et al. (2011) conducted a risk assessment analysis for residential buildings by estimating the combined losses from hurricane wind, storm surge, and rainwater intrusion. The correlation between wind and surge was considered in their study by implementing a hurricane-induced surge model through regression analysis of historical data. Pita et al. (2012) presented an approach to assess the interior building damage caused by hurricanes by simulating the co-occurrence of wind, rain, and envelope damage. The vertical free falling rainfall rate was estimated as a function of the radius and maximum wind speed of the storm, and was converted into an unobstructed impinging rain rate using a semi-empirical framework proposed by Straube and Burnett (2000). Barbato et al. (2013) developed a Performance-Based Hurricane Engineering (PBHE) framework and applied it to the risk assessment of residential buildings subjected to wind and windborne debris impact. They also investigated the effect of interaction between the sources of wind and windborne debris impact hazards on the expected annual loss (EAL) assessment. Unnikrishnan and Barbato (2015, 2016b) used the PBHE framework for the risk assessment of non-engineered buildings subject to combined wind, windborne debris, flood, and rainfall hazards. The correlation between the hazards was considered only implicitly, by modeling the rainfall and flood hazards as functions of the hurricane wind speed. A global vulnerability analysis approach was adopted. The annual

probabilities of loss exceedance and the EAL of the target building were computed for different individual hazards and their interaction. They also emphasized the need to consider the multihazard nature of hurricane events for accurate probabilistic loss analysis.

This paper investigates the effects of the interaction among multiple hazards sources and the modeling approaches that can be employed within different phases of the PBHE framework to incorporate these interaction effects. To the authors' knowledge, the present study is the first of its kind to explicitly quantify the effects of multihazard interaction and different modeling approaches within the PBHE framework. Different typologies of hazard models available in the literature are identified and investigated based on their level of complexity and amount of information required to use them. Similarly, different vulnerability modeling techniques that are used in performance-based risk assessment are also identified and described within the PBHE framework. A consistent terminology is also proposed to classify the different hazard models and vulnerability analysis approaches available in the literature. A realistic case study is presented to illustrate these interaction effects on the risk assessment for a typical house of an actual residential development located in Charleston, SC. The EALs computed using different hazard models and vulnerability modeling approaches are compared for three different neighborhoods in Charleston, SC. These three locations correspond to different multiple hazard scenarios and are selected to investigate the effects of different hazard and vulnerability models on the loss analysis under different hazard scenarios.

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:

$$G(DV) = \int \int \int \int \int G(DV|DM) \cdot f(DM|EDP) \cdot f(EDP|IM, IP, SP) \cdot f(IP|IM, SP) \cdot f(IM) \cdot f(SP) \cdot dDM \cdot dEDP \cdot dIP \cdot dIM \cdot dSP \quad (1)$$

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). By means of Eq. (1), the performance 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. Additional details on the general PBHE framework and its specialization to non-engineered structures can be found elsewhere (Barbato et al., 2013; Unnikrishnan, 2015; Unnikrishnan and Barbato, 2016a, 2016b).

MULTIHAZARD CHARACTERIZATION OF HURRICANE EVENTS

Multihazard interactions can occur at two levels (Zaghi et al. 2016): (1) through the nature of the hazards (also called Level-I interactions), when the interactions among multiple hazards are independent of the presence of physical components; and (2) through the effects of the hazards

(also called Level-II interactions), when the interactions among multiple hazards take place through “site effects, impacts on physical components, network and system disruptions, and social and economic consequences” (Zaghi et al. 2016). The Level-I multihazard interactions among different natural and man-made hazards can be classified into the following three different modalities (Barbato et al., 2013; Gill and Malamud, 2014): (1) independent hazards, i.e., hazards that are not correlated in nature and/or derive from different sources/extreme events, which can be acting at different times or at the same time; (2) interacting hazards, i.e., hazards that increase or decrease the probability of occurrence and/or the intensity of other hazards; and (3) hazard chains or cascading hazards, i.e., when one hazardous event (primary hazard) triggers one or more different hazards (secondary hazards). In the case of hurricane events, four different hazards are acting at the same time: (1) strong winds, (2) windborne debris, (3) storm surge, and (4) heavy rain. It is noted here that the wind hazard is always interacting with all other hazards by increasing their intensity for increasing wind speed, whereas windborne debris and storm surge are practically independent one from the other. It is noted here that, according to the definition provided above, the four co-occurring hazards considered in this study are not cascading hazards by themselves, but could be the triggering effects for other hazards (e.g., heavy rain triggering landslides), thus, possibly producing chain hazards. The investigation of potential chain hazards triggered by hurricane events is outside the scope of this paper.

Consideration of Level-II hazard interactions is also crucial for the performance assessment of structures subject to hurricane hazards. One of the most important aspects to be accounted for is the fact that the effects of some hazards can modify (usually amplify) the effects of other hazards on a given structure. In this paper, the terms “chain hazard effects” or “cascading hazard effects” are used to distinguish this situation from that of hazards triggering other hazards (i.e., hazard

chains or cascading hazards). For hurricane events, cascading hazard effects can be significant, e.g., windborne debris and storm surge can produce hazard chain effects (by producing breaches in the building envelope) with the wind and rainfall hazard (Unnikrishnan and Barbato, 2016a).

In this section, the multihazard interaction modalities and available modeling approaches within each of the different analysis phases of the PBHE framework are discussed in detail. A consistent terminology is also proposed to identify different approaches used in the literature to model the interaction among the different hazards characterizing a hurricane event. Particular attention is given to the different interaction modeling at the hazard and loss analysis phases, since the range of modeling options available for these two analysis phases is wider than for other analysis phases and, thus, the selection of different hazard or vulnerability models can most affect the performance assessment of low-rise residential buildings subject to hurricane hazard.

Interaction at hazard analysis phase

The hazard analysis phase of the PBHE framework is used to model the Level-I interactions for the cases of independent hazards and interacting hazards. For independent hazards, independent models are adopted to statistically describe the corresponding intensity measures. For interacting hazards, different models can be adopted to describe the correlation between the intensity measures of different hazards. These models can be classified in terms of modeling complexity and required statistical information.

In terms of modeling complexity, three approaches of increasing complexity and computational cost can be used to determine the statistical description of the intensity measures of interest. In the lowest complexity approach, the statistics of the different intensity measures (e.g., 3-second gust wind velocity, V , and/or of the storm surge height, ζ) are directly obtained from existing records at the building site (Boon et al., 1978; Batts et al., 1980; Li and Ellingwood, 2006). This approach

is referred to as “direct statistics approach” hereinafter. In the intermediate complexity approach, the statistics of the different intensity measures are obtained indirectly based on the site-specific statistics of fundamental hurricane parameters such as storm maximum wind speed, V_{\max} , storm radius of maximum wind, R_{\max} , and storm central pressure deficit, Δp (Batts et al., 1980; Vickery and Twisdale, 1995). This approach is referred to as “indirect statistics approach” hereinafter. Finally, the highest level of complexity directly models the possible full tracks of hurricanes from initiation over the ocean until final dissipation and uses these tracks to obtain the statistics of the intensity measures of interest at the building site (Vickery et al., 2000). This approach is referred to as “full track approach” hereinafter.

In terms of amount of statistical information required to fully describe the statistical models for the intensity measures, three different modeling approaches for use in the PBHE framework can be identified: (1) models based on a limited set of primary intensity measures described through their marginal probability distributions, referred to as “primary distributions models” (PDMs) hereinafter; (2) models based on a complete set of intensity measures, each described by their marginal probability distributions, referred to as “multiple distributions models” (MDMs); and (3) models based on the joint probability distributions of the complete set of intensity measures, referred to as “joint distributions models” (JDMs) hereinafter. It is noteworthy that any of the three different complexity approaches can be used in conjunction with any of the three statistical information levels; however, higher complexity models are often paired with higher levels of statistical information (Vickery et al., 2000).

Primary distributions models (PDMs)

The PDMs consider the statistical distribution of one or a few intensity measures, usually used to describe a single hazard (referred to as primary intensity measures hereinafter), and describe all

other derived intensity measures (for the same or other hazards) as functions of the primary intensity measures. These functions are usually developed using regression analysis of historical data (in the form of explicit functions, e.g., Conner et al., 1957) and/or simulations (in which case the relations between primary and derived intensity measures are implicit, e.g., Tuleya et al., 2007; Irish et al., 2008). The earlier PDMs used a direct statistics approach and, for example, predicted surge height as a function of storm central pressure deficit as $\zeta = A \cdot \Delta p^B$, where A and B denote regression coefficients and Δp represent the primary intensity measure (Conner et al., 1957). With the advent of efficient computers, numerical hydrodynamic models (based on more advanced indirect statistics or full track approaches) were developed to forecast the hurricane surge heights based on hurricane parameters, storm track, and local topographic and bathymetric data. Some of these models include SLOSH (Jelesnianski et al., 1992), Advanced Circulation Model (Luettich et al., 1992), Coastal Marine Environment Prediction System (Pietrafesa et al., 2002), and Finite Volume Coastal Ocean Model (Chen et al., 2003). A common characteristic of PDMs is that derived intensity measures are usually highly correlated with primary intensity measures, thus, often overestimating the actual correlation between different intensity measures.

Multiple distributions models (MDMs)

MDMs use marginal distributions of all pertinent intensity measures obtained from historical data and/or simulations. The correlations between different intensity measures are neglected. The direct statistics approach can be used to obtain the statistical characteristics of hurricane wind speed by fitting hurricane wind speed records, e.g., those provided by the National Institute of Standards and Technology, to appropriate probability distribution functions (Barbato et al., 2013). The wind speed records provided by the National Institute of Standards and Technology contain datasets 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 mile post 2850 (near Portland, ME), spaced at 50 nautical mile (92,600 m) intervals. Similarly, the statistical characteristics of surge and rainfall can be directly derived, e.g., from the National Weather Service Cooperative Observer Program (NWS, 2016) and National Oceanic and Atmospheric Administration National Centers for Environmental Information database (NOAA, 2016), respectively. The indirect statistics or full track approach can also be employed using appropriate models and neglecting the correlation between different intensity measures.

Joint distributions models (JDMs)

JDMs can be developed from historical records and/or numerical simulations, e.g., joint wind-surge models (Phan et al., 2007; Pei et al., 2014) and joint wind-rain models (Rosowsky et al., 2016). Also in this case, the direct statistics, indirect statistics, or full track approaches can be used to obtain the marginal distribution and the correlation between the intensity measures. For the direct statistics approach, in addition to the records for each intensity measure, information is needed regarding the contemporaneity of the data relative to different quantities. For the indirect statistics approach, site specific statistics of the basic hurricane parameters can be used in conjunction with appropriate numerical models to obtain the wind, surge, and rainfall at any location. Similarly, for the full track approach, the joint statistics of the intensity measures can be obtained by modeling the full track of hurricanes and combining that with surge (SLOSH, Advanced Circulation Model, etc.) and rainfall (Tuleya et al., 2007; FEMA, 2012) numerical models. Once the marginal distributions of the pertinent intensity measures and their correlations are obtained, different techniques are available in the literature to generate the joint probability distribution of the intensity measures, e.g., the Chow-Liu tree (Chow and Liu, 1968), the Nataf transformation (Der Kiureghian and Liu, 1986), and the copula-based approach (Nelsen, 2007).

Interaction due to cascading hazard effects

The Level-II interaction of hazards may occur in the form of cascading hazard effects, when the effects of some hazards modify sequentially the effects of other hazards on the structure. For example, the actions on a structure due to windborne debris can damage the building envelope, e.g., by damaging brittle components such as glass windows and doors. This damage to the building envelope can increase the vulnerability of the subject structure to strong winds, i.e., by transforming the structure from an enclosed building to a partially enclosed one, for which the internal pressure coefficients are significantly higher than those for an enclosed building (Li and Ellingwood, 2006; ASCE, 2010). The increase of the internal pressure coefficients can further amplify the damage to the building envelope and initiate a chain reaction until the building collapses. The study of hazard chain effects requires modeling the structural system configuration and properties as functions of the level of structural damage caused by the different hazards. In particular, the presence of hazard chain effects implies that the structural parameters can change as a consequence of damage measures exceeding specified thresholds. Barbato et al. (2013) and Unnikrishnan and Barbato (2016a) investigated the hazard chain effects due to the interaction between windborne debris and wind hazards on the loss analysis of residential buildings. Those studies highlighted the importance of considering cascading hazard effects for accurate hurricane risk assessment of low-rise residential buildings.

Interaction at loss analysis phase

Level-II multihazard interactions can occur at the loss analysis phase, and their effects on risk assessment and design depend on the type of vulnerability analysis being performed. In fact, losses are produced by different hazards, which tend to affect simultaneously different components of the structural system of interest. Two different kinds of vulnerability analyses are commonly

considered in the existing literature and will be illustrated here: (1) global vulnerability analysis, and (2) assembly-based vulnerability analysis.

Global vulnerability analysis

Global vulnerability analysis is a widely used methodology in seismic risk assessment of structures (FEMA, 2007; Nielson and DesRoches, 2007). In this approach, the buildings are classified into different (discrete) damage states based on the damages to the individual components and the global response of the structure. Unnikrishnan and Barbato (2015) used the global damage state model proposed by Womble et al. (2006) for the performance-based hurricane risk assessment of residential structures subject to multiple hazards. The use of a global vulnerability analysis approach for hurricane loss analysis requires the knowledge of loss statistics associated with each global damage state, which can be obtained from insurance claims, when available, and/or numerical simulations (e.g., based on assembly-based vulnerability analysis). This approach is computationally very efficient since the total loss is estimated based only on the global damage state of the building. However, the accuracy of the procedure can be significantly affected by imprecision in the damage state classification and scarcity of information in determining the loss statistics for each damage state.

Assembly-based vulnerability analysis

The assembly-based vulnerability approach was originally proposed by Porter et al. (2001) to calculate the building loss due to seismic hazard. It involves dividing the entire building into components based on specific details of the building. The building-specific damage and loss estimation procedures are developed at the component level. Component response and fragility curves are used to evaluate the damage level for each individual component. It is assumed that the total loss in a building is equal to the sum of repair and/or replacement costs of the individual

components damaged during the damaging event. The assembly-based vulnerability approach was later adopted in the risk assessment of residential buildings subjected to hurricanes (Gurley et al., 2006; Li et al., 2011; FEMA, 2012; Unnikrishnan and Barbato, 2016a). One of the main features of the assembly-based vulnerability approach is that the loss due to each component produced by each hazard can be easily identified and accounted for in the risk assessment procedure. Hence, this approach allows to estimate the effect of each component damage on the total loss and simplifies the choice of appropriate risk mitigation techniques for a building. However, obtaining a complete inventory of all components and their repair/replacement costs is a complex task. In addition, the higher computational effort associated with the assembly-based vulnerability approach makes its application cumbersome when compared with the global vulnerability analysis.

Interaction at other intermediate analysis phases

In addition to the interactions at the hazard and loss analysis phases, which have predominant effects in the risk analysis for low-rise wood-frame residential buildings, hazard interactions can be identified at any intermediate analysis phase of the PBHE framework. This section briefly illustrates some non-exhaustive examples of these possible interactions, which could be important for other applications of the PBHE framework.

Structural characterization phase

The structural parameters of a system can affect the Level-II interactions among different hazards. For example, internal and external pressure coefficients are correlated (Beste and Cermak, 1997), and this correlation can affect wind-windborne debris cascading hazard effects. Building elevation is another structural parameter that influences hazard interaction, since increasing the building elevation can reduce the risk associated with flooding due to storm surge, but may also increase the wind pressure acting on the building.

Interaction analysis phase

In the interaction analysis phase, hazard interaction mainly depends on the models used to obtain the interaction parameters and on the correlation between different parameters used in these models. For example, the correlations between debris flight time and debris flight distance or between the debris flight distances in the along wind and across wind direction can significantly affect the Level-I interaction between wind and windborne debris hazards (Barbato et al., 2013; Unnikrishnan and Barbato, 2016a). Similarly, the correlation between the wind pressures acting on different components of the building can also affect the breaching of the building envelope and, thus, the Level-II interaction between wind and windborne debris hazards.

Structural analysis phase

In the structural analysis phase, the Level-II hazard interactions can depend on the correlation between the material constitutive parameters used to model the structural system, which affect the structural response under the actions of different hazards. However, since the structural analysis phase is not performed explicitly for non/pre-engineered buildings such as those considered here (Unnikrishnan and Barbato, 2016a), the interaction in the structural analysis phase is not considered in this study.

Damage analysis phase

The resistance of both structural and non-structural components in a building sometimes can be positively correlated because of common construction materials, fabrication, and construction practices (Mori, 2005). For example, if a house is well built, often all elements are of good quality, and vice versa. However, there can be instances where the quality of construction can significantly vary between different components and even between different parts of the same component, resulting in negligible or negative correlation between the strength of different portions of the same

structure. The actual correlation between different structural and non-structural components is usually difficult to quantify due to the lack of data.

This correlation, or lack thereof, can also affect the hazard interaction and the results of a vulnerability analysis. Thus, when using the PBHE framework, the capacity correlation between different components should be included in the vulnerability analysis whenever reliable data is available to estimate this correlation. However, when the data is insufficient, a more prudent approach is to assume that the capacities of different components are uncorrelated, as assumed hereinafter.

APPLICATION EXAMPLE

This study presents as application example the hurricane risk analysis for a single-family one-story wood-frame house subject to wind, windborne debris, surge, and rainfall hazard. This risk analysis is performed using the multi-layer Monte Carlo simulation implementation of the PBHE framework (Barbato et al., 2013; Unnikrishnan and Barbato, 2016a, 2016b). The effects of hazard interaction at the hazard and loss analysis levels on the risk analysis performed using the PBHE framework are investigated. An actual residential development located in South of Broad, Charleston, SC, is considered in this study (Fig. 1). To compare the effects of the interaction in the hazard analysis phase, three different locations were selected in Charleston, SC, i.e., Roper Hospital, South of Broad, and French Quarter (Fig. 2). These three location were selected because they correspond to three different hazard scenarios, i.e., scenarios with predominant wind losses, predominant surge losses, and comparable losses from wind and surge, respectively. The elevation above mean sea level of the base of the building at the three location is 2.99 m, 1.95 m, and 2.11 m, respectively.

In order to accurately estimate the loss annual probability of exceedance (APE), 100,000 samples

were used for all results presented in this study. Six sets of results are presented here for each of the three locations: (1) PDM used in conjunction with global vulnerability analysis, (2) PDM used in conjunction with assembly-based vulnerability analysis, (3) MDM used in conjunction with global vulnerability analysis, (4) MDM used in conjunction with assembly-based vulnerability analysis, (5) JDM used in conjunction with global vulnerability analysis, and (6) JDM used in conjunction with assembly-based vulnerability analysis. It is assumed that the building is fully repaired after each hurricane event.

Description of benchmark structure and structural characterization

The simple residential building used by van de Lindt and Taggart (2009) is considered here as benchmark structure (the location of which within the residential development is identified by a red circle in Fig. 2). The value of the target structure is taken as \$180,000 and the content value is assumed equal to \$90,000. Fig. 3 provides the plan view of the target residential building, including its (deterministic) geometric parameters. Detailed building dimensional information can be found in Taggart (2009).

The base structure is characterized by: (1) roof cover made of asphalt shingles, (2) nailing pattern 8d C6/12 for the roof sheathing, i.e., 8 mm diameter smooth shank nails, with a spacing of 6 inches (15.2 cm) at the center and 12 inches (30.5 cm) at the edge, (3) unprotected windows and doors, and (4) wooden walls. Walls and windows are considered as debris impact vulnerable components. The wind pressure exposure factor K_h is assumed as normally distributed with a mean value of 0.71 and a coefficient of variation (COV) of 0.19. The topographic factor is modeled as a deterministic quantity with value $K_{zt} = 1$. The statistical characterization of the external and internal pressure coefficients can be found in Unnikrishnan and Barbato (2016a).

Hazard analysis

Three different hazard models are considered hereinafter: (1) PDM, (2) MDM, and (3) JDM. In this study, a direct statistics approach is used to obtain the statistics of the different intensity measures. However, most of the data used to obtain these statistics was taken from Pei et al. (2014), in which a full track approach was used to derive the data on wind speed and storm surge height. In all models, the number of hurricanes per year is simulated using a Poisson occurrence model, with an annual hurricane occurrence rate $\nu_{\text{hurricane}} = 0.42$, which was also obtained from the data provided by Pei et al. (2014). The roof covers of all houses in the residential development are considered as potential windborne debris sources. The debris generation model employed by the Florida Public Hurricane Loss Model (Gurley et al. 2005) is adopted here for all three hazard models. Thus, the number of generated debris, n_{debris} , is not discussed further since it is always treated as a derived intensity measure that depends on the 3-second wind speed and the position of the buildings in the residential development relative to the benchmark building.

Hazard analysis based on PDM

The following quantities are selected as primary intensity measures: 3-second wind speed at 10 m above the ground, V , maximum hurricane wind speed, V_{max} , radius of maximum wind, R_{max} , and central pressure deficit, Δp . The derived intensity measures are: surge height, ζ , and impinging rainfall rate, IRR . The hurricane wind speed variability is described by using a Weibull distribution (Unnikrishnan and Barbato, 2016a), the parameters of which are fitted through maximum likelihood estimation of the hurricane wind speed records obtained from Pei et al. (2014) for the three locations. The radius of maximum wind is assumed to follow a lognormal distribution with mean equal to 24 km and COV equal to 0.28, and the central pressure deficit is assumed to follow a Weibull distribution with mean equal to 44.38 mbar and COV equal to 0.46 (Huang et al., 2001).

In this study, the distribution of the storm surge height is obtained using a hurricane-induced surge model proposed by Irish et al. (2008). This model was based on the regression analysis of numerically simulated storm surge data obtained from a coupled hurricane vortex–planetary boundary layer model (Thompson and Cardone, 1996) to estimate sustained near-surface winds throughout the storm. The surge height is computed as:

$$\sqrt{\hat{\zeta}} = \begin{bmatrix} \sqrt{\hat{R}_{\max}} & 1 \end{bmatrix} \cdot C(S_0) \cdot \begin{bmatrix} \Delta\hat{p}^2 \\ \Delta\hat{p} \\ 1 \end{bmatrix} \quad (2)$$

where $\hat{\zeta} = \frac{\zeta \cdot g}{V'^2}$, $\hat{R}_{\max} = \frac{R_{\max} \cdot g}{V'^2}$, $\Delta\hat{p} = \frac{\Delta p}{p_{\text{atm}}}$, $V' = 1\text{-minute wind speed} = 0.79V$, $g = 9.81 \text{ m/s}^2$

$=$ gravity constant, $p_{\text{atm}} =$ atmospheric pressure, $S_0 =$ ocean slope (assumed to be constant and

equal to 1:5000), and $C(S_0) = \begin{pmatrix} -1.078 \times 10^{-1} & 3.996 \times 10^{-2} & 4.444 \times 10^{-4} \\ 3.974 \times 10^0 & -1.093 \times 10^0 & -1.653 \times 10^{-1} \end{pmatrix} = 2 \times 3$ curve fitting

coefficient matrix. This surge hazard model does not capture the effects of local topography and provides the same surge height for any given wind speed at all three locations considered in this study. The correlation coefficient between wind speed and surge height obtained through direct simulation using this model varies between 0.93 and 0.95.

The impinging rainfall rate, IRR , is calculated using the rainfall hazard model proposed in the Florida Public Hurricane Loss Model (Pita et al., 2012) as a linear function of the 3-second gust speed and is given by:

$$IRR = a \cdot V - b \quad (3)$$

where a and b are dimensional regression coefficients, which assume the values 0.128 cm-s/m and 0.65 cm, respectively, for Charleston, SC, based on historical hurricane data obtained from the Iowa Environment Mesonet database (IEM, 2001).

Hazard analysis based on MDM

The following quantities are selected as intensity measures: 3-second wind speed at 10 m above the ground, V , surge height, ζ , and the impinging rainfall rate, IRR . The marginal distribution of V is obtained as for the PDM by fitting a Weibull distribution to the data provided by Pei et al. (2014). The marginal distributions of ζ and IRR are obtained by fitting the empirical cumulative density function of surge data provided by Pei et al. (2014) and the historical rainfall data from the Iowa Environment Mesonet database (IEM, 2001), respectively. Fig. 4 shows the hazard curves in terms of APE for each intensity measure based on the MDM (i.e., assuming no correlation between the different intensity measures).

Hazard analysis based on JDM

The following quantities are selected as intensity measures: 3-second wind speed at 10 m above the ground, V , surge height, ζ , and the impinging rainfall rate, IRR . The intensity measures are described by the same marginal distributions obtained for the MDM. In this study, a copula-based approach with a Gaussian copula is used to generate the joint probability distribution of the intensity measures. 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. A Gaussian copula function is generated for V , ζ , and IRR , based on the marginal distributions and the correlation coefficients obtained (1) from Pei et al. (2014) for V and ζ (see Fig. 5), (2) from the Iowa Environment Mesonet database for V and IRR (IEM, 2001), and (3) from Wahl et al. (2015) for ζ and IRR . The details for the generation of this copula function can be found in Unnikrishnan (2015) and Unnikrishnan and Barbato (2016a). The intensity measures are directly sampled from the joint probability distribution function that is obtained using this copula function. The hazard surfaces of wind and surge hazards at the three different locations as well as for wind and rainfall

hazards are shown in Fig. 6.

Interaction and damage analysis

The following quantities are adopted as interaction parameters to describe the effects of the different hazards: (1) wind pressure, p_w , for wind effects; (2) number of impacting debris, n_d , impact linear momentum, L_d , and impact kinetic energy, K_d , for windborne debris impact effects; (3) height of flood due to surge, h_f , for storm surge effects; and (4) rainfall intrusion height, h_r , for rainfall effects. The detailed procedure to calculate the interaction parameters for wind and windborne impact effects can be found in Unnikrishnan and Barbato (2016a). The flood height is given by:

$$h_f = \zeta - h_b \quad (4)$$

in which h_b denotes the building base elevation. The rainfall intrusion height is computed as (Pita et al., 2012):

$$h_r = \frac{IRR \cdot RAF}{A_b} \cdot \left[\sum_j (d_j \cdot a_j) + a_0 \right] \quad (5)$$

where RAF = rainfall admittance factor, d_j = percentage of damaged area for component j , a_j = area of component j , a_0 = area of pre-existing openings in the building, and A_b = base area of the house. The rainfall admittance factor is assumed to follow a uniform distribution ranging from 0.2 to 0.5 (Straube and Burnett, 2000).

The structural analysis phase is not performed explicitly for the type of structures considered here and the capacity of vulnerable components is directly compared to the corresponding interaction parameter (Unnikrishnan and Barbato, 2016a). Table 1 shows the capacity statistics for the different components of the target building and their corresponding limit states as found in the literature (Stuckley and Carter, 2001; Gurley et al., 2005; Datin et al., 2010; Masters et al., 2010).

Loss analysis results for different locations

In this study, the loss analysis is performed using both global vulnerability and assembly-based vulnerability approaches for all three hazard models, providing a total of six sets of loss analysis results for each of the three locations considered. The global vulnerability approach used in Unnikrishnan and Barbato (2015, 2016b) is adopted also here. The damage states of the benchmark building are mainly governed by the performance of the building envelope (damage state of the components) and are divided into five discrete damage states, varying between 0 (no damage) and 4 (destruction). The different damage states for each of the components are described in Table 2 (Vickery et al., 2006; Womble et al., 2006; Li et al., 2011). The repair cost is then generated for the corresponding damage state according to the probability distributions given in Table 3 in terms of percentage of the building value and of the total content cost. It is noteworthy that the damage states for rainfall intrusion are used to calculate the losses only for the building's content.

The assembly-based vulnerability approach for wind and windborne debris losses is adopted from Unnikrishnan and Barbato (2016a). The assembly-based vulnerability approach for the flood loss is adopted from Taggart (2009), in which the damage and the subsequent loss to each component and to building's content are calculated based on the flood height (h_f). The assembly-based vulnerability approach for the rainfall loss is based on 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 (Unnikrishnan and Barbato, 2016a). The results of the loss analysis are presented in terms of loss annual probabilities of exceedance (APEs), expected annual losses (EALs), and standard deviations of annual losses (SDLs).

Loss analysis results for Roper Hospital

Fig. 7 plots in semi-logarithmic scale the loss APEs relative to the target building at the Roper Hospital location for wind-related (i.e., wind, windborne debris, and rainfall hazards) and storm surge hazards taken independently and for all hazards considered at the same time. These results are obtained using the JDM in conjunction with the assembly-based vulnerability approach (which are considered as the reference results). From Fig. 7, it is observed that the losses due to the combination of wind-related hazards are predominant when compared to the losses due to storm surge hazard. This behavior can be explained by examining the joint hazard curves for storm surge and wind hazard shown in Fig. 6(a). In particular, it is observed that wind speed values that can cause even significant damage to the structure have an APE that is similar to storm surge values for which it is unlikely to have significant structural damage. It is also observed that the EAL due to the interaction of all hazards is 18.3% lower than the sum of the EALs due to the hazards taken separately, indicating a significant (negative) interaction among these hazards.

Fig. 8 plots in semi-logarithmic scale the loss APEs for the target building analyzed using different combinations of vulnerability approaches and hazard models. In this case, the results obtained using the global vulnerability and the assembly-based vulnerability approaches are very close, with a difference in EAL for the same hazard model which ranges approximately between 0.5% and 4.5%. The EALs obtained using the global vulnerability approach are always smaller than the corresponding ones (i.e., calculated using the same hazard model) obtained using the assembly-based vulnerability approach. It is also observed that, for the same hazard model, the loss APE curves obtained using the global vulnerability approach are very close but lower than those obtained using the assembly-based vulnerability approach up to losses of about \$110,000, after which the global vulnerability curves become higher than the corresponding assembly-based

vulnerability curves. The loss APE curves obtained using the PDM, MDM, and JDM are very close one each other when the same vulnerability approach is used. However, the small differences for loss levels lower than about \$110,000, which correspond to relatively high probabilities, produce differences in terms of EAL as high as 16.9% for the global vulnerability approach and 16.8% for the assembly-based vulnerability approach.

Loss analysis results for South of Broad

Fig. 9 plots the loss APEs (obtained using JDM in conjunction with the assembly-based vulnerability approach) relative to the target building at the South of Broad location for wind-related and storm surge hazards taken independently and for all hazards considered at the same time. These results indicate that, for this location, the losses due to surge hazard are predominant when compared to the losses due to wind-related hazards. This behavior can also be explained by examining the joint hazard curves for storm surge and wind hazard shown in Fig. 6(b), from which it is observed that storm surge values that can cause even significant damage to the structure have an APE that is similar to wind speed values for which it is unlikely to have significant structural damage. The EAL due to the interaction of all hazards is 3.7% lower than the sum of the EALs for the hazards taken separately, indicating a small (negative) interaction among these hazards.

Fig. 10 plots in semi-logarithmic scale the loss APEs for the target building analyzed using different combinations of vulnerability approaches and hazard models. For this location, the EAL results obtained using the global vulnerability and the assembly-based vulnerability approaches present significant differences (i.e., 25.3% for PDM, 17.9% for MDM, and 25.1% for JDM), with the global vulnerability EALs that are always lower than the corresponding assembly-based vulnerability EALs. In particular, the assembly-based vulnerability loss APE curves are higher than the corresponding global vulnerability APE curves for losses that are lower than about

\$120,000, after which the two sets of curves become very similar. When using the global vulnerability approach, the loss APE curve obtained using the PDM is significantly lower than those obtained using JDM (intermediate curve) and MDM (highest curve). Similarly, when using the assembly-based vulnerability approach, the loss APE curve obtained using the PDM is significantly lower than those obtained using MDM and JDM. However, in this case, the MDM-based curve is higher than the JDM-based curve for losses lower than about \$70,000, and becomes lower for losses higher than about \$220,000. These differences result in very large variations of the estimated EALs (as large as 72.6% when using the global vulnerability approach and 61.7% when using the assembly-based vulnerability approach), with the PDM that severely underestimate the EALs when compared to both MDM and JDM. These large differences can be explained by noting that the effects on the losses due to storm surge hazard are predominant when compared to the effects due to the other hazards combined. However, the PDM is not able to capture correctly this relative importance, since it underestimates the storm surge height, which is modeled as a function of the wind speed.

Loss analysis results for French Quarter

Fig. 11 plots the loss APEs (obtained using JDM in conjunction with the assembly-based vulnerability approach) relative to the target building at the French Quarter location for wind-related and storm surge hazards taken independently and for all hazards considered at the same time. At this location, the losses due to storm surge and wind-related hazards are very close, and the EAL due to the interaction of all hazards is only 2.0% lower than the sum of the EALs due to the hazards taken separately, indicating a very small (negative) interaction among these hazards. The loss APEs for the target building obtained using different combinations of vulnerability approaches and hazard models are shown in Fig. 12. For this location, the differences in terms of

EAL estimates obtained using the global vulnerability and the assembly-based vulnerability approaches are 11.3% for PDM, 8.6% for MDM, and 8.5% for JDM. Also in this case, the global vulnerability EALs are always lower than the corresponding assembly-based vulnerability EALs. The assembly-based vulnerability loss APE curves are higher than the corresponding global vulnerability loss APE curves for losses that are lower than about \$110,000, after which they become lower. In this case, for both global vulnerability and assembly-based vulnerability approaches, the PDM is the lowest curve, the JDM is the intermediate curve, and the MDM is the highest curve. The variations of the estimated EALs due to the use of different hazard models are significant (as large as 38.1% when using the global vulnerability approach and 42.1% when using the assembly-based vulnerability approach). Also in this case, these significant differences are due to the fact that the PDM is not able to estimate correctly the storm surge height and the corresponding losses.

CONCLUSIONS

The study presented in this paper investigates the effects of multihazard interaction on the performance of low-rise wood-frame residential buildings subject to hurricane hazard. The multiple hazards examined here are: (1) wind, (2) windborne debris, (3) storm surge, and (4) rainfall hazards, which interact during a hurricane event. The use of different hazard modeling techniques and vulnerability analysis approaches are compared within a general Performance-Based Hurricane Engineering (PBHE) framework. To the best of the authors' knowledge, this type of investigation has not been previously attempted. Thus, a new consistent terminology to classify different hazard modeling techniques is also proposed in this paper.

A realistic case study consisting of an actual residential development in Charleston, South Carolina, is presented to establish the effects of hazard interaction in the different phases of the

PBHE framework. The loss annual probabilities of exceedance, expected annual losses, and standard deviations of annual losses for a benchmark building are calculated for three selected locations (Roper Hospital, South of Broad, and French Quarter), using different combinations of hazard models and vulnerability techniques. Three different hazard modeling techniques (primary distributions model or PDM, multiple distributions model or MDM, and joint distributions model or JDM) and two vulnerability analysis approaches (global vulnerability and assembly-based vulnerability) are considered, for a total of six combinations of loss analysis results for each location. For the case study considered in this paper, it is found that, when using the same hazard model and when compared to the more accurate assembly-based vulnerability approach, the global vulnerability approach underestimates: (1) the loss annual probability of exceedance for low loss values and (2) the overall expected annual losses. It is also found that the PDM can significantly underestimate the expected annual losses, particularly if the losses due to storm surge are significant when compared to the losses due to the other hazards combined.

It is noteworthy that the consistency of the loss analysis results obtained by using different hazard modeling techniques and vulnerability analysis approaches strongly depends on both the structural system under investigation and its location. It is evident from the results reported in this paper that the appropriate selection of both hazard model and vulnerability analysis approach has a significant effect on the final results of a loss analysis. Thus, whenever enough information is available, the use of the JDM for the hazard analysis and of the assembly-based vulnerability approach for the vulnerability analysis is recommended. It is also noted here that deriving general conclusions on the appropriate use of the different hazard and vulnerability models (particularly of the simplified ones) considered in this study is a difficult task that will require a future extensive study of many structural systems and locations. This consideration should not be regarded as a limitation of the

results presented in this paper, but as an incentive to extend and continue the seminal work initiated in the present study, similar to the research work that has been and is still being performed in other Performance-Based Engineering frameworks that are more mature than PBHE, such as Performance-Based Earthquake Engineering.

ACKNOWLEDGMENTS

Partial support of this research by: (1) the Longwell's Family Foundation through the Fund for Innovation in Engineering Research (FIER) Program, (2) the Louisiana Board of Regents through the Economic Development Assistantship Program, (3) the Louisiana Department of Wildlife and Fisheries through award #724534, and (4) the National Science Foundation through award CMMI #1537078 is gratefully acknowledged. The authors would also like to thank Dr. Pang from Clemson University for providing them with the data for joint hurricane wind and storm surge hazards for Charleston County, South Carolina. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the sponsors.

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Table 1. Statistics of the limit state capacity for different components of the benchmark structure

Component	Limit state	Mean	COV	Distribution
Roof cover (Shingles)	Separation or pull off (R_{cover})	3.35 kN/m ²	0.19	Normal
Roof sheathing (Nailing pattern 8d C6/12)	Separation or pull off (R_{sh})	6.20 kN/m ²	0.12	Lognormal
Doors	Pressure failure (R_{door})	4.79 kN/m ²	0.20	Normal
Garage door	Pressure failure (R_{g_door})	3.49 kN/m ²	0.20	Normal
Windows	Pressure failure ($R_{w, pressure}$)	3.33 kN/m ²	0.20	Normal
	Impact failure ($R_{w, impact}$)	4.72 kg m/s	0.23	Lognormal
	Pressure failure ($R_{wsh, pressure}$)	6.13 kN/m ²	0.40	Normal
Wall sheathing	Impact failure ($R_{wsh, impact}$)	642.00 kg m ² /s ²	0.07	Lognormal
	Tensile failure ($R_{wcon, wood}$)	16.28 kN/panel	0.20	Lognormal
Wall (Wood)	Lateral failure ($R_{wall, wl}$)	10.80 kN/panel* 7.06 kN/panel**	0.25	Normal
	Uplift failure ($R_{wall, wu}$)	9.00 kN/m* 5.80 kN/m**	0.25	Normal

Note: * Toe nail connection ** Sheathing nail connection

Table 2. Description of damage states for residential buildings

Damage state	Qualitative damage description	Roof cover loss	Roof deck loss	Roof failure	Wall failure	Flood height (m)	Rainfall intrusion (cm)
0	Very minor damage	$\leq 2\%$	No	No	No	None	$0 < h_r \leq 0.02$
1	Minor damage	$> 2\%$ & $\leq 15\%$	No	No	No	$h_f \leq 0.003$	$0.02 < h_r \leq 0.25$
2	Moderate damage	$> 15\%$ & $\leq 50\%$	1-3 panels	No	No	$0.003 < h_f \leq 0.61$	$0.25 < h_r \leq 1.00$
3	Severe damage	$> 50\%$	> 3 panels & $\leq 25\%$	No	No	$0.61 < h_f \leq 2.49$	$1.00 < h_r \leq 2.50$
4	Destruction	-	$> 25\%$	Yes	Yes	$h_f > 2.49$	$h_r > 2.50$

Table 3. Statistics of repair cost (in terms of % of building cost/total content cost) for different damage states (Adapted from Unnikrishnan and Barbato 2015, © ASCE)

Damage state	Mean	COV	Distribution
0	0.2%	0.2	Lognormal
1	2%	0.2	Lognormal
2	10%	0.2	Lognormal
3	30%	0.2	Lognormal
4	70%	0.2	Lognormal

Fig. 1. Plan view of the residential development (map data © 2016 Google).

Fig. 2. Selected locations in Charleston, SC (map data © 2016 Google).

Fig. 3. Plan view of the benchmark building (1 ft = 0.305 m).

Fig. 4. Hazard curves for MDM: (a) wind hazard, (b) surge hazard, (c) rainfall hazard, and (d) windborne debris hazard.

Fig. 5. Actual correlation between storm surge and wind hazard for different locations: (a) Roper Hospital, (b) South of Broad, and (c) French Quarter.

Fig. 6. Hazard surfaces obtained using the JDM: (a) surge-wind hazard surface for Roper Hospital, (b) surge-wind hazard surface for South of Broad, (c) surge-wind hazard surface for French Quarter, and (d) rainfall-wind hazard surface.

Fig. 7. Loss APEs for different hazards relative to the target building located in Roper Hospital (calculated using JDM and assembly-based vulnerability).

Fig. 8. Loss APEs for different hazard models and vulnerability approaches for the target building located in Roper Hospital (GV: global vulnerability, ABV: assembly-based vulnerability).

Fig. 9. Loss APEs for different hazards relative to the target building located in South of Broad (calculated using JDM and assembly-based vulnerability).

Fig. 10. Loss APEs for different hazard models and vulnerability approaches for the target building located in South of Broad (GV: global vulnerability, ABV: assembly-based vulnerability).

Fig. 11. Loss APEs for different hazards relative to the target building located in French Quarter (calculated using JDM and assembly-based vulnerability).

Fig. 12. Loss APEs for different hazard models and vulnerability approaches for the target building located in French Quarter (GV: global vulnerability, ABV: assembly-based vulnerability).