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Performance-Based Hurricane Engineering (PBHE) framework

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ABSTRACT

This paper presents an innovative fully-probabilistic Performance-Based Hurricane Engineering (PBHE) framework for risk assessment of structural systems located in hurricane-prone regions. The proposed methodology is based on the total probability theorem and disaggregates the risk assessment into elementary components, namely hazard analysis, structural characterization, environment–structure interaction analysis, structural analysis, damage analysis, and loss analysis. This methodology accounts for the multi-hazard nature of hurricane events by considering both the separate effects of and the interaction among hurricane wind, flood, windborne debris, and rainfall hazards. A discussion on the different sources of hazard is provided, and vectors of intensity measures for hazard analyses are proposed. Suggestions on the selection of appropriate parameters describing the interaction between the environmental actions and the structure, the structural response, and the resulting damage are also provided. The proposed PBHE framework is illustrated through an application example consisting of the performance assessment of a residential building subjected to windborne debris and hurricane strong winds. The PBHE framework introduced in this paper represents a step toward a rational methodology for probabilistic risk assessment and design of structures subjected to multi-hazard scenarios.

1. Introduction

Performance-Based Engineering (PBE) is a general methodology that (1) defines the performance objectives for structural systems during their design life, (2) provides criteria and methods for verifying the achievement of the performance objectives, and (3) offers appropriate methodologies to improve the design of structural systems. In the last two decades, significant research efforts have been devoted to the development of PBE in earthquake engineering [1,2], and have led, e.g., to the Performance-Based Earthquake Engineering (PBEE) framework implemented by the Pacific Earthquake Engineering Research (PEER) Center [2,3]. More recently, the civil engineering community has shown significant interest toward the possible development and extension of PBE to other subfields of structural engineering [4]. In particular, Performance-Based Blast Engineering has received considerable attention in the US after the terrorist attacks of September 11, 2001 [5]. Other PBE examples are Performance-Based Fire Engineering [6], Performance-Based Tsunami Engineering [7], and Performance-Based Wind Engineering (PBWE) [8,9]. In earthquake engineering, modern design codes have gradually substituted prescriptive approaches with PBEE procedures for the design of new facilities and the retrofit of existing ones [10,11]. PBEE has been shown to facilitate design and construction of structural systems based on a realistic and reliable assessment of the risk associated with seismic hazard, thus leading to a more efficient use of resources for construction, maintenance, and retrofit of structures [12,13].

The advantages demonstrated by a PBE approach to civil engineering provide a strong motivation to develop a PBE methodology for structures subjected to hurricanes. The need for assessing and improving the resilience of the built environment subjected to hurricane hazard is widely recognized. Some initial interest in PBE has been expressed in hurricane engineering [14–16], but a complete and rigorous framework is still needed.

The development of a Performance-Based Hurricane Engineering (PBHE) methodology presents several additional challenges when compared to other existing PBE methodologies. In fact, while other PBE methodologies focus on single hazards, the landfall of a hurricane involves different hazard sources (wind, windborne debris, flood, and rain) that interact to generate the hazard scenario for a given structure and to determine its global risk. Thus, hurricanes can be viewed, and must be analyzed, as multi-hazard scenarios. In addition, monetary losses due to structural and non-structural damage assume more relevance for hurricane events than for other types of hazard (e.g., earthquakes) for which no (or very short) warning is available. Therefore, for hurricane hazard, performance levels related to limitation of the monetary losses due to damage may be required for a large portion of existing or newly designed structures.

During the last decade, significant attention has been also devoted to multi-hazard scenarios [17–19]. Multi-hazard scenarios raise

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non-trivial issues mainly related to the following three problems: (1) modeling the interaction among concurrent sources of hazard; (2) calibrating design values having comparable occurrence rates for different hazards; and (3) balancing the design in order to attain similar safety levels with regard to multi-hazard scenarios implying hazards that, if taken separately, would drive design solutions in different (and even opposite) directions (e.g., increasing the elevation of the structure as a safe guard against flood may result in increased wind loads).

In this paper, the PBE approach is formally extended to develop a fully-probabilistic PBHE methodology. The interaction among the multiple hazards is discussed, and a scheme for representing the uncertainties from all pertinent sources and their propagation through a probabilistic performance assessment analysis is proposed. Analytical models of the relevant environmental phenomena generated by hurricane events are briefly described. The paper includes suggestions for candidate parameters for the probabilistic characterization of: (1) the interaction between the structure and the hazard sources; (2) the structural response; (3) the resulting structural damage; and (4) the consequences of the structural damage. The proposed approach is illustrated through an application focused on the performance assessment of a residential building subjected to both wind and windborne debris hazard.

2. Proposed PBHE framework

In a PBE approach, the structural risk is conventionally measured by the probability of exceeding (within a given reference period usually taken as one year) a specified value of a decision variable, *DV*, corresponding to a target performance. Each *DV* is a measurable attribute of a specific structural performance and can be defined in terms of cost/benefit for the users and/or the society (e.g., loss of human lives, economic losses, exceedance of safety/serviceability limit states). An assessment based on PBE provides a probabilistic description of the appropriate *DV* for different design choices in order to allow a rational decision among different design options.

A PBE procedure for structures subject to hurricane hazard can be decomposed into elementary phases that must be carried out in sequence. Perhaps the most important expected feature of the procedure is the qualitative independence of each phase from the others (i.e., the choice of the parameters that are characteristic for a given phase is independent from the parameters adopted in the previous phases). The PBHE framework proposed in this paper is based on the total probability theorem, similar to the PEER PBEE and the PBWE frameworks. The structural risk is defined in terms of a given *DV* as follows

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

where $G(\cdot)$ = complementary cumulative distribution function, and $G(\cdot|\cdot)$ = conditional complementary cumulative distribution function; $f(\cdot)$ = probability density function, and $f(\cdot|\cdot)$ = conditional probability density function; *DM* = damage measure (i.e., a parameter describing the physical damage to the structure); *EDP* = engineering demand parameter (i.e., a parameter describing the structural response for the performance evaluation); *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); and *IP* = vector of interaction parameters (i.e., the parameters describing the interaction phenomena between the environment and the structure). In Eq. (1), *IM* and *SP* are assumed as uncorrelated and independent of *IP*, while *IP* is dependent on both *IM* and *SP*. The extension to the case of vectors of *DM* and *EDP* is straightforward.

By means of Eq. (1), the problem of risk assessment is disaggregated into the following tasks (see Fig. 1): (1) hazard analysis, (2) structural characterization, (3) interaction analysis, (4) structural analysis, (5) damage analysis, and (6) loss analysis. Detailed explanation of steps (1), (4), (5), and (6) can be found in the PBEE literature [2], while steps (2) and (3) have been introduced in PBWE to rigorously model the effects on the structural response of the interaction between the structural system and the environment (e.g., the aerodynamic effects, see [20]). In particular, the probabilistic hazard analysis phase (i.e., the probabilistic characterization of *IM*) can be performed by using the (joint) probability density function *f*(*IM*). The *IM* should be chosen as strictly independent on the investigated structure. Thus, the probabilistic information about *IM* should be provided by meteorologists, climatologists, and other experts in atmospheric sciences, while the engineers have the task of clarifying what information is needed.

3. Characterization of uncertainties

The PBHE framework described in the previous section requires the identification of the uncertainties that affect the structural performance and the evaluation of the interaction phenomena occurring among the different hazards and the structure. It is noted here that uncertainties can be classified into two different categories, i.e., aleatoric uncertainties, which are due to natural variability of physical, geometrical, and mechanical properties, and epistemic uncertainties, which are due to lack of knowledge, imprecise modeling, and limited statistical information [21]. Aleatoric uncertainties are inherent in nature and, thus, are virtually irreducible. On the contrary, epistemic uncertainties can and should be reduced as much as possible, e.g., by implementing more accurate and realistic models. While epistemic uncertainties can significantly affect the confidence on the end results of the PBHE framework proposed in this study, their detailed study is beyond the scope of this paper.

This paper focuses on the characterization of the hazard for a single structure located in a hurricane-prone region. Three different zones can be distinguished [20] (see Fig. 2):

1. The *environment*, i.e., the space surrounding the structure but sufficiently far from it, where the parameters describing the wind field and the other hurricane-related environmental actions are not influenced by the presence of the structure itself.
2. The *exchange zone*, i.e., the space immediately surrounding the structure, where the structural configuration and the environmental action are strongly correlated, and the interaction between the structure and the environmental agents, as well as the presence of adjacent structures, cannot be disregarded.
3. The *structural system*, which includes the structure (characterized by a set of uncertain parameters collected in a vector *S*) as well as the non-environmental actions and/or elements that can modify the structural behaviour (characterized by a set of uncertain parameters collected in a vector *A*).

Hereinafter, the uncertain basic parameters of interest describing the environmental actions in the environment are collected in the vector *IM*; the uncertain basic parameters describing the structural system and non-environmental actions or devices applied to the structure are collected in the vector *SP*; and the uncertain (usually derived) parameters of interest in the exchange zone are collected in the vector *IP* (Fig. 2). Examples of *IP* are the aerodynamic and hydrodynamic coefficients, as well as the parameters defining the impact energy of windborne debris. The uncertain parameters *IP* describing the exchange zone can be chosen so that they do not affect directly the uncertain parameters characterizing both the environment (*IM*) and the structural system (*SP*). Instead, uncertainty propagation from the structural system and the environment to the exchange zone is

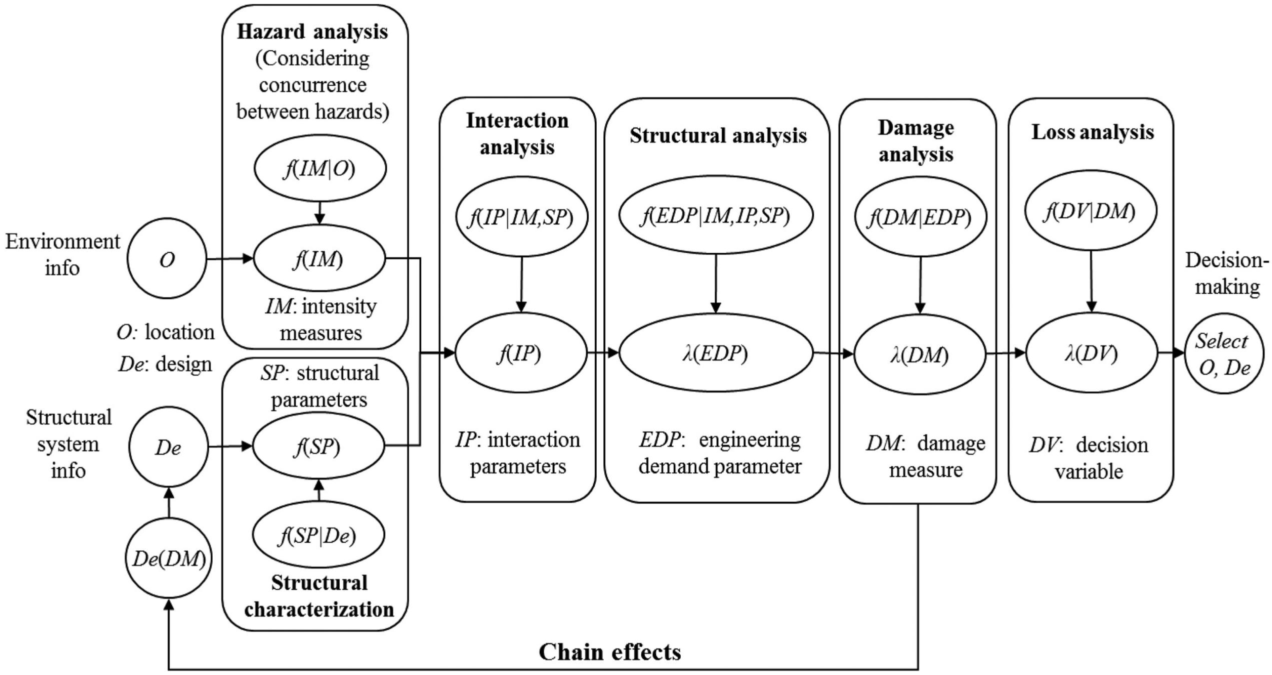

Fig. 1. Probabilistic analysis components in the proposed PBHE framework.

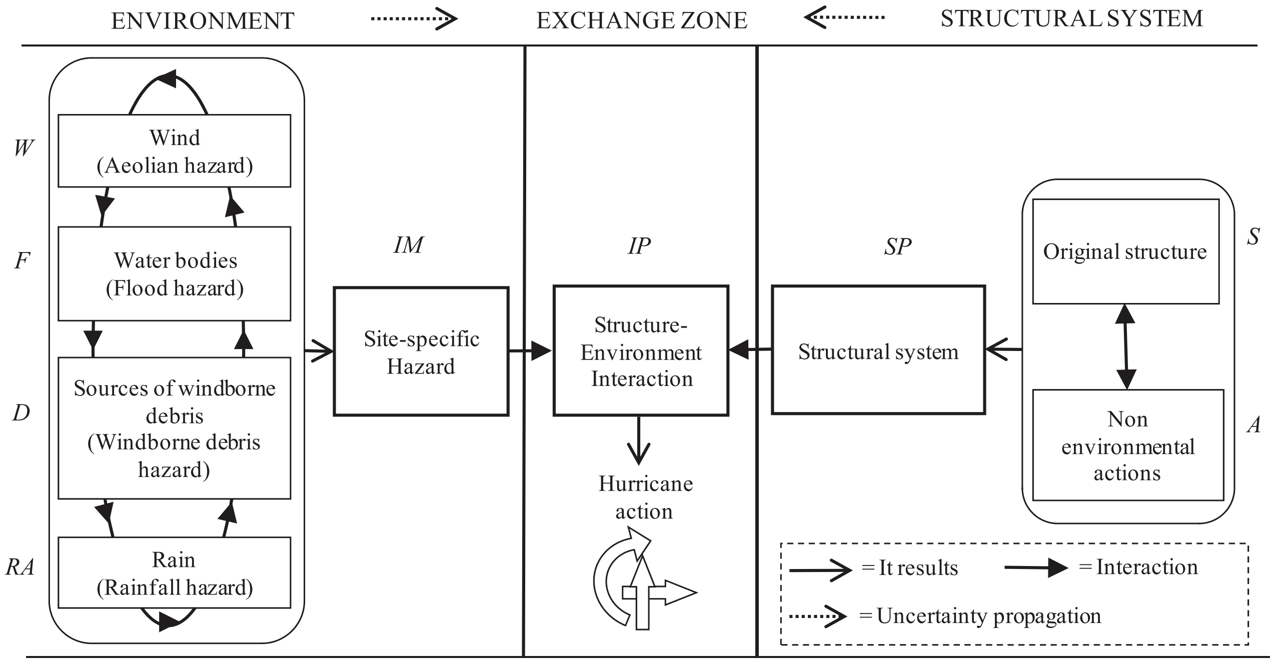

Fig. 2. Identification of the uncertain parameters needed to describe the interaction between environment and structure in PBHE.

likely (e.g., the integrity of the building envelope affects the values of the wind pressure acting on the building surfaces).

In Fig. 2, the different sources of uncertainties corresponding to the environment, the structural system, and the exchange zone are shown, and the different hazard sources and their interaction identified. The environmental hazard due to a hurricane event in a specified geographic region is generated by the following four main sources of hazard:

1. Hurricane strong winds (described by the uncertain vector W), which can produce wind damage (*wind hazard*).
2. Water bodies (described by the uncertain vector F), which can produce flood damage (*flood hazard*).
3. Sources of windborne debris (described by the uncertain vector D), which can produce windborne debris damage (*windborne debris hazard*).
4. Rainfall rates (described by the uncertain parameter vector RA), which can induce flash flooding and direct damage to the interiors of building when the building envelope has been breached (*rainfall hazard*).

These various sources of hazard usually interact to produce the actual hurricane hazard for a given structure. Typical examples are the interaction between wind and waves in offshore sites, or the interaction between storm surge and wind in coastal regions. A set of uncertain parameters included in vectors *W*, *F*, *D*, and *RA* must be selected in order to describe the multiple hazards using *IM*. This set must accurately describe all pertinent hazard sources and must be as small as possible in order to be both "sufficient" and "efficient" [22]. An analogous selection operation (for vectors *A* and *S*) is needed to describe the structural behavior by *SP*. To derive the probabilistic characterization of the hurricane actions on a structural system, the proposed PBHE methodology also requires the identification of the vector *IP* of the stochastic parameters describing the interaction between the environment and the structural system in the exchange zone.

4. Multi-hazard characterization of hurricane events

Unlike other existing PBE engineering methodologies, in which only a single hazard source is considered (e.g., PBEE and PBWE, which consider earthquake and wind hazard only, respectively), the proposed PBHE framework innovatively accounts for concurrent and interacting hazard sources, i.e., storm surge and water bodies that can cause flooding, windborne debris, rainfall, and strong winds. It also accounts for the possible sequential effects of these distinct hazards. The multi-hazard nature of the phenomena related to hurricanes and their effects on the built environment can manifest in the following three different modalities [23]:

1. *Independent hazards*, when different hazards affect the structure independently. For example, windborne debris and flood hazard can be considered as independent of each other because no mutual interaction between the two hazards has the effect of modifying the intensity of the corresponding actions. These hazards can occur individually or simultaneously.
2. *Interacting hazards*, when the actions produced on a structure by different hazards are interdependent (e.g., wind and windborne debris hazards).
3. *Hazard chains*, when the effects of some hazards modify sequentially the effects of other hazards. For example, the actions on a structure due to windborne debris can damage the structural envelope and increases the vulnerability of the structure to strong winds.

In the proposed framework, the first two cases (i.e., independent and interacting hazards) are treated within the hazard analysis, by assuming proper interaction models between the hazards (e.g., by using a proper joint probability distribution function to describe the variability of the *IM* for different hazards [24,25]). The study of hazard chains requires modeling the structural system configuration and properties as a function of the level of structural damage caused by the different hazards. In particular, the presence of a hazard chain implies that the *SP* can change as a consequence of *DM* exceeding certain thresholds. Thus, structural characterization, interaction analysis, and structural analysis cannot be carried out without any information or assumption on the values of *DM*. It is noteworthy that the proposed probabilistic approach is consistent with the state-of-the-art in hurricane hazard and loss modeling, which can be identified with the HAZUS® methodology [26].

However, the proposed PBHE framework presents the following major differences when compared with the HAZUS methodology:

1. HAZUS is a GIS-based natural hazard assessment software used for the regional risk and loss assessment of structures. Although it is possible to use the HAZUS software for individual buildings, the corresponding results can only estimate the average loss for the class of buildings that are similar to the one under consideration. By contrast, the proposed PBHE framework is specifically developed to account for the characteristics of an individual building. Thus, it has the potential to provide more accurate results.
2. HAZUS is not intended for use as a structural design tool. On the contrary, the proposed PBHE framework is the first step toward a performance-based design methodology, which includes the performance-based assessment procedure described in this paper.
3. HAZUS approximates the multi-hazard nature of the hurricane events as a simple superposition of various effects produced by different sources of hazards, i.e., wind, windborne debris, flood and rainfall. The proposed PBHE framework directly models the multi-hazard nature of hurricanes by taking into account also the effects due to the interaction between different hazard sources.
4. The proposed PBHE framework is significantly more flexible than HAZUS, since it is based on the total probability theorem, which allows for independence of the different analysis components. This property permits to take advantage of the state-of-the-art knowledge in the research subfields involved in the assessment and design of structures located in hurricane prone regions, e.g., in climatology, structural analysis, structural design, material technology, and loss analysis.

5. Performance expectations

In PBE, several performance expectation levels are defined based on the severity of structural and non-structural damage and the corresponding losses (e.g., see [8,14,27]). Commonly, two main performance expectation levels with each level having different performance objectives are identified [8,20], i.e., a high level performance expectation (related to serviceability requirements) and a low level performance expectation (related to structural safety and/or integrity). For the PBHE framework proposed in this paper, additional considerations are needed to account for the fact that early warning of the population is possible in case of hurricane hazard, in contrast with other hazards (like the seismic hazard) for which warning is impossible or very limited. Thus, empty buildings during the hurricane transit are not rare. In this situation, significant losses due to the damage to non-structural components (e.g., building envelope, interiors of the building) can occur without problems for people (because occupants left the building) or for the structural integrity (because the structural parts do not suffer damages). In view of this consideration, an additional intermediate performance level related to non-structural damage is introduced.

The three performance expectation levels can be further subdivided in sub-levels or performance levels, e.g., the high performance expectation level for a building can be related to occupant comfort (higher) and/or continued occupancy (lower). Moreover, different performance expectation levels need to be defined for different structural typologies (e.g., buildings, bridges). A possible list of performance expectations for buildings and their short description are provided in Table 1.

6. Description of the analysis steps

This section presents a brief description of the analysis steps of the PBHE framework. Particular emphasis is given to the differences between the PBHE framework and other existing PBE frameworks.

6.1. Hazard analysis

The hazard analysis provides the probabilistic description of the intensity measures *IM*. A comprehensive vector *IM* is obtained by considering the components of the basic random parameter vectors *W*, *F*, *D*, and *RA* that describe the different sources of hurricane hazard

Table 1
Classification of building performance expectation for PBHE.

Category	Level	Description	Damage level
High: comfort and safety of occupants	Occupant comfort	No or little discomfort to the building occupants	No damage
	Continued occupancy	No threat to safety of building occupants, small economic losses	Minor exterior damage, no interior damage
Intermediate: damage to non-structural elements	Limited damage to envelope/content	No threat to safety of building occupants, some economic losses	Exterior damage, minor interior damage
	Extensive damage to envelope/content	Safety of building occupants is jeopardized, significant economic losses	Significant exterior and interior damage
Low: structural integrity	Structural damage	Structural integrity is jeopardized, reduced safety	Structural components and/or connections are damaged
	Extensive structural damage	Visible signs of structural distress, structure is not safe	Loss of integrity of structural components, significant reduction or loss of bearing load capacity

(Fig. 2). It is noteworthy that, for a specific structure *s* and a specific performance objective *p*, the elements of *IM* that do not represent a relevant hazard for *s* and/or have small influence on *p* can be neglected or treated as deterministic. The reduced vector $IM^{(s,p)}$ (i.e., the vector *IM* specialized for the structure *s* and the performance *p*) can be used more efficiently than the vector *IM* at a negligible loss of sufficiency. For example, the flooding hazard can be neglected in the case of structures that are sufficiently far from water bodies.

The selection of the *IM* components strictly depends on the choice of the (usually deterministic) models used to describe the environmental phenomena related to the various hazards, as illustrated in the available technical literature. In general, the key parameters of these models are treated as stochastic variables. In this paper, the *IM* components are identified by selecting state-of-the-art models for hurricane-related environmental phenomena. While the selected *IM* depend on the specific models, the approach proposed here to identify *IM* is general and can also be applied to different hazard models.

6.1.1. Wind field and wind hazard characterization

A model of the wind field associated with a hurricane is needed to characterize the wind hazard. The following three methodologies (of increasing complexity) can be adopted to define the hurricane wind field and the corresponding hazard [26]:

1. The statistical description of the gust wind velocity, *V*, at the structural location is directly derived from existing data by fitting a proper probability distribution [28].
2. The site specific statistics of some fundamental hurricane parameters are obtained, and a Monte Carlo approach is used to sample these parameters from the statistical information. Using the sampled values, a mathematical representation of the hurricane is obtained, and the statistics of the parameters that describe the hurricane actions are evaluated for the structure of interest at its specific location [29].
3. The full track of the hurricane is modelled, from its initiation over the ocean until final dissipation [30]. Several tracks are simulated. The statistics of the parameters describing the hurricane actions are estimated from the parameter values in each simulated track for the structure of interest at its specific location.

The different methodologies provide different vectors *IM*. In particular, the first methodology gives $W = V$, while the other two methodologies give [15]:

$$W = [RMW \quad V_c \quad \Delta p_c \quad B \quad H^* \quad z_0]^T \tag{2}$$

where RMW = radius of maximum wind (defined as the radial distance between the storm center and the maximum wind location); V_c = translational speed of the center of the storm; Δp_c = hurricane central pressure deficit; B = Holland parameter [31]; H^* = atmospheric boundary layer height; z_0 = terrain roughness length; and the superscript T denotes the matrix transpose operator.

6.1.2. Flood hazard characterization

The flood hazard due to the presence of water bodies surrounding the structure depends on the total water surface elevation with respect to the mean surface, η_{tot}, and on the flooding water velocity, V_{water} (i.e., the value of the component of the water velocity orthogonal to the flooding barriers). These two parameters allow for the computation of the volumetric rate of flow and can be used as synthetic indicators of the flood intensity. The basic parameters characterizing these indicators can be selected as the components of *F*.

Three main natural phenomena cause water level increase and contribute to flood hazard: the astronomical tide (η_{tide}), the waves (η_{wave}), and the storm surge (η_{surge}). The total water surface elevation is the sum of the three contributions at the same instant of time, i.e., $\eta_{tot} = \eta_{tide} + \eta_{wave} + \eta_{surge}$. The flooding water velocity, V_{water}, can be assumed, as a first approximation, equal to the highest velocity for each of the three considered phenomena (V_{tide}, V_{wave}, and V_{surge}, respectively). Specific basic parameters subvectors can be defined for each of the three contribution (i.e., F_{tide}, F_{wave}, F_{surge}), and the vector *F* obtained as the union of the three subvectors.

The flood hazard due to the astronomical tide can be characterized by the two random variables η_{tide} and V_{tide}, i.e., $F_{tide} = [\eta_{tide} V_{tide}]^T$. The individual characterizations of the flood hazard due to waves and storm surge require more detailed considerations. The water level, η_{wave}, and the wave speed, V_{wave}, can be directly related to: the water depth, *d*; the wave height, *H*; the wave length, *L*; and the wave period, *T*. The last three quantities can be obtained by propagating in space and time [32] the waves corresponding to a given wave energy density spectrum (e.g., JONSWAP [33]) valid for the sea waves as determined by the wind field (i.e., RMW, V_c, Δp_c, and B), as well as by other parameters [32]. A storm surge is defined as the water surface response to wind-induced surface shear stress and pressure fields. Storm surges can produce considerable short-term increases in water level. Current storm surge models are based on the depth-averaged momentum and continuity equations for steady long waves under the hypothesis of incompressible water [34].

Based on the existing literature, the following vector *F* is suggested for a suitable flood hazard characterization

$$F = [RMW \quad V_c \quad \Delta p_c \quad B \quad H^* \quad z_0 \quad \eta_{tide} \quad V_{tide} \quad d \quad U_{curr} \quad z_b]^T \tag{3}$$

where U_{curr} = current velocity, and z_b = sea bottom friction roughness.

6.1.3. Windborne debris hazard characterization

The vector *D* of intensity measures for windborne debris hazard describes the intensity of the wind field (needed to determine the impact wind speed), and the characteristics of the windborne debris that could affect the structure. The additional parameters needed to describe the debris are: the density of upwind buildings with respect to the investigated structure, $n_{\mathrm{buildings}}$; the properties of the different (potential) debris types, e.g., M_{d} = mass per unit area of the debris, $C_{\mathrm{D,d}}$ = drag coefficient of the debris (and/or other parameters describing the debris flight characteristics), and A_{d} = reference area of the debris; and the resistance model for the missile sources (which contributes to determine the number of windborne debris). The following vector *D* is suggested in this study:

$$D = [RMW \quad V_{\mathrm{c}} \quad \Delta p_{\mathrm{c}} \quad B \quad H^{*} \quad z_{0} \quad n_{\mathrm{buildings}} \quad M_{\mathrm{d}} \quad C_{\mathrm{D,d}} \quad A_{\mathrm{d}}]^{\mathrm{T}} \tag{4}$$

6.1.4. Rainfall hazard characterization

The high rainfall rate associated with hurricane events can induce significant damage to the interior of buildings when the building envelope has been breached [35]. To the best of the authors' knowledge, no analytical rainfall hazard model is available in the technical literature. However, several models based on the interpolation of statistical data define the correlation between the rainfall rate and other fundamental hurricane parameters. One of the more widely accepted and used models is the one implemented in HAZUS® [26,36], which is valid for tropical cyclones. The estimates of rainfall rates resulting from this model are employed in HAZUS® to evaluate the amount of water that enters the buildings through broken windows and glass doors, while they are not used to assess the risk associated with inland flash flooding. Consistently with HAZUS®, this study does not consider inland flash flooding hazard. The proposed vector *RA* of basic random parameters is given by

$$RA = [RMW \quad V_{\mathrm{c}} \quad \Delta p_{\mathrm{c}} \quad B \quad H^{*} \quad z_{0} \quad \dot{p}_{\mathrm{c}}]^{\mathrm{T}} \tag{5}$$

where $\dot{p}$c is the first time derivative of the hurricane central pressure.

6.2. Structural characterization

The step of structural characterization in the PBHE framework provides the probabilistic description of the components of *SP*, which define the geometrical and/or mechanical properties of the structure that characterize its response to environmental and man-made loading. Uncertainties affecting *SP* are well-known and have been extensively investigated in the past decades for ordinary buildings [37,38]. They are usually identified as the parameters determining the structural resistance and stiffness [39]. However, parameters describing shape, size, and orientation of structural components can also be considered, since they can affect the load acting on the structure. In addition to the above parameters, robustness, connectivity, and redundancy are also critical in the analysis of wind-induced effects on structures. Robustness implies the property of a structure not to respond disproportionately to either abnormal events or initial local failure [40]. A general framework, based on the total probability theorem, was proposed in the literature to assess probabilistically the robustness of systems subject to structural damage [41,42]. This framework is consistent with the proposed PBHE framework, e.g., by using as *DV* the robustness index [41]. However, the computation of the robustness index for structures subjected to hurricane hazard requires significant research and implementation work, and is outside the scope of this paper.

Particular attention is needed when a hazard chain is possible or likely. The probabilistic description of *SP* (e.g., the first- and second-order statistics, as well as the distribution type) needs to be expressed as a function of the damage parameter *DM*. A typical example of this situation occurs when the behavior of buildings subjected to windborne debris hazard is considered [43]. If windows or doors break due to windborne debris impact, the characteristics of the building envelope (described by *SP*) vary, causing a change in the internal pressure coefficients and in the loads acting on the structure [44].

6.3. Interaction analysis

The interaction parameters *IP* describe the physical interaction between structure and environment, which influences the structural response and performance, as well as the intensity and distributions of the environmental actions as a result of the interaction between the structure and the environment. Typical examples of *IP* are the aerodynamic pressure coefficients and the aerodynamic derivatives for dynamic wind actions, the rate of water flow impacting the structure for flooding actions, the kinetic energy and linear momentum of the impacting missile for windborne debris, the wind pressure on the internal and external building surfaces for wind actions on a building envelope, and the rate of water intrusion in a building under strong rain for rainfall action [45].

In other words, the *IP* are parameters that influence the intensity of the environmental actions on the structure, and that depend simultaneously on *IM* and *SP*, as well as on their variability (e.g., the aerodynamic derivatives of a bridge depend both on wind direction and velocity, which are components of *IM*, and on structural damping, which is a component of *SP*). In deterministic terms, this dependency is described by a mechanistic model of the *IP* as functions of the *IM* and *SP* (e.g., see Fig. 3(a)).

In a probabilistic analysis, the uncertainty of both *IM* and *SP* must be taken into account in order to obtain the probability distributions of *IP*, which can be derived by using probability distributions conditional to *IM* and *SP*. The propagation of uncertainties from *IM* and *SP* to *IP* can be performed, e.g., by characterizing the *IP* via parametric probabilistic distributions whose parameters are deterministic functions of *IM* and *SP* (see [9]). The conceptual separation of the interaction analysis from others analysis steps carried out in PBE approaches is an aspect of novelty of the proposed PBHE framework with respect to the original PEER approach. This clear separation between independent parameters (IM and *SP*) and derived parameters (*IP*) has also the merit of highlighting the correct direction of uncertainty propagation.

Examples of interaction analysis in structural engineering subfields other than hurricane engineering are: soil–structure interaction analysis in earthquake engineering, fluid–structure interaction analysis in offshore engineering and wind engineering, and heat-transfer analysis in fire engineering.

6.4. Structural analysis and damage analysis

The structural analysis phase provides the probabilistic description of a proper *EDP*, which concisely represents the essential aspects of the structural response for damage and performance evaluation. Examples of *EDP* are: axial force, shear force, bending moment, and stress state in structural and non-structural elements; response quantities describing the structural motion (deflections, velocities, and accelerations of selected points); structural deformation indices (e.g., interstory or global drift ratio and beam chord rotation).

The damage analysis provides the probabilistic description of *DM* conditional to the values of *EDP*. The results of a probabilistic damage analysis are commonly expressed in terms of fragility curves as shown in many recent applications in hurricane engineering [28,46–48]. For example, for low-rise wood residential construction, the damage states of interest relate to those components that are essential to maintain the integrity of the building envelope, i.e., roofs, windows, and doors, since the building envelope is the residential construction component that is most vulnerable to hurricane-induced damage [46].

In some applications, it is convenient to assume *DM* = *EDP*, e.g., in the case of low rise gable roof structures, in which the number

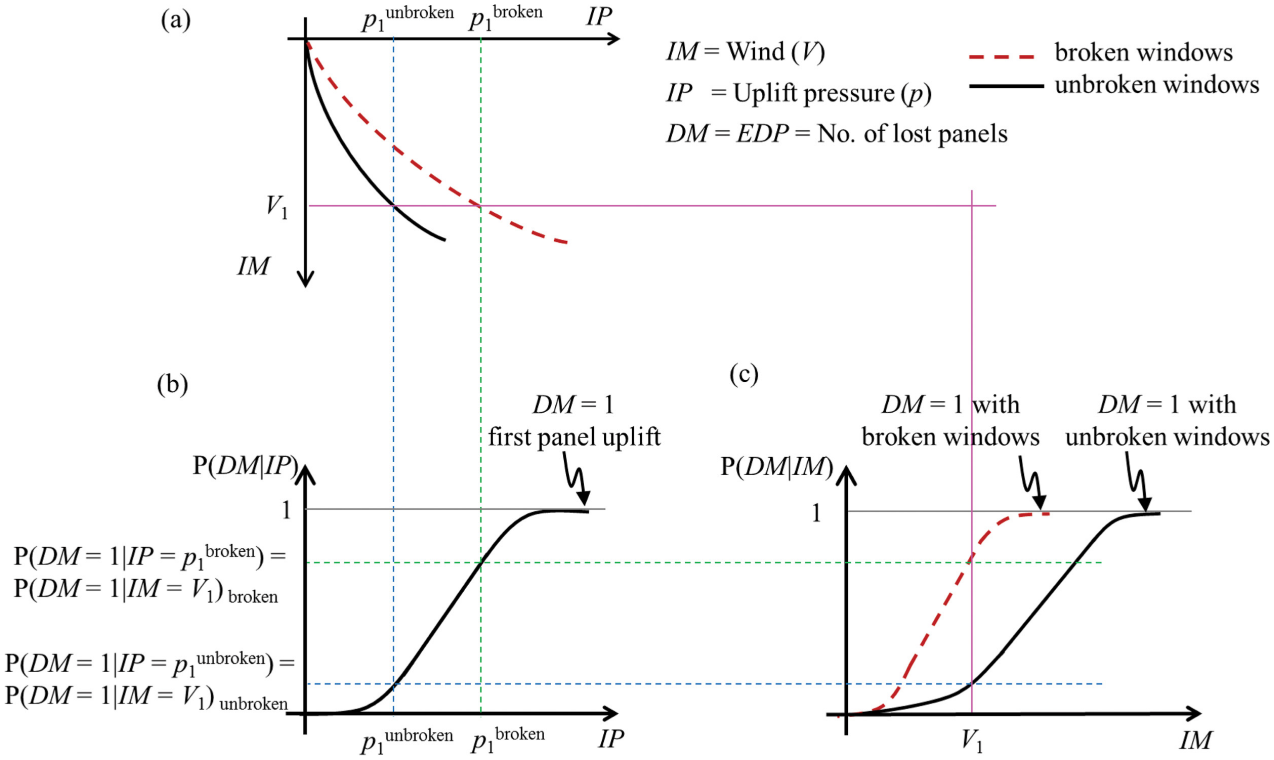

Fig. 3. Different representations of fragility curves in case of interaction between two hazards: (a) relation between *IP* and *IM*, (b) fragility curve as a function of *IP*, and (c) fragility curves as functions of *IM*.

of lost roof panels due to the uplift pressure generated by hurricane winds can be chosen as both *DM* and *EDP*. The hurricane wind fragility is then expressed as the cumulative probability distribution conditional to the uplift pressure (*IP*) or to the wind gust velocity (*IM*). In case of hazard chains (e.g., if wind and windborne debris hazards are considered), the representation of the fragility as the probability of *DM* conditional to *IM*, namely P(*DM*|*IM*), can be used to assess the effects of the interaction, e.g., based on the differences between the functions P(*DM*|*IM*) obtained by considering undamaged or broken windows (e.g., after a missile impact).

Fig. 3 shows two alternative representations of the fragility curve for the roof panel uplift limit state, i.e., P(*DM*|*IP*) and P(*DM*|*IM*), in the case of low-rise gable-roof buildings under the chain-effect of wind and windborne debris hazards. In this example, the wind velocity *V* is assumed as *IM*, the uplift pressure *p* is assumed as *IP*, and the number of roof panels that are lost due to wind is assumed as *DM*. The damage scenario corresponding to the loss of the first roof panel ($DM = 1$) is considered. The relation between uplift pressure and wind velocity (i.e., $IP = IP(IM)$) is different for the cases "broken" and "unbroken" windows (see, e.g., ASCE standard as shown in Fig. 3(a)). In fact, this relation must take into account the internal pressurization of the building caused, e.g., by the failure of a door/window due to windborne debris impact (i.e., the chain effect). The fragility curves obtained from the technical literature in the form P(*DM*|*IP*) are the same for the two case of "broken" or "unbroken" windows, since they depend only on the properties of the roof panels (see Fig. 3(b)). Two different *IP* values (identified in Fig. 3(a) and (b) as p_1^{broken} and p_1^{unbroken}) correspond to a given *IM* value (V_1 in Fig. 3(a) and (c)). Thus, two different fragility curves P(*DM*|*IM*) can be built for the two cases of "broken" or "unbroken" windows, which highlight the effects of considering the interaction between wind and windborne debris hazard. In the case of vector *IM* and *IP*, the fragility can be represented through appropriate fragility surfaces [49].

6.5. Loss analysis

The loss analysis step gives the estimate of the annual probability of exceedance of *DV*, *G*(*DV*), where *DV* can be used as an indicator for structural risk. Hurricanes are among the most costly natural hazards to impact residential construction in the southeast coastal area of the United States [46]; thus, *DV* is usually expressed in monetary terms. It is noteworthy that, from a loss-based design perspective, non-structural and structural damage are both losses; moreover, in addition to direct losses, hurricanes can lead to social disruption for extended periods of time, including the need to relocate building inhabitants [25].

DV can be chosen as the repair cost related to the hurricane induced damage, or a percentage of the insured value, or the lifetime cost of the structural system, evaluated by taking into account the construction and maintenance costs, the repair costs after an event, the economic losses due to damage (also to building contents), and the loss of functionality [50]. Even in the simplest cases, repair costs are highly uncertain, and updated data from insurance companies are needed to obtain an appropriate probabilistic description of repair costs.

In addition, both ethic and technical problems arise when the *DV* is related to the loss of human life and/or to a life quality index for the structure subjected to the hurricane. Further research is needed to overcome the technical challenges related to the inclusion of these aspects in evaluating the losses associated with the structural damages and failures due to the hurricanes. In addition, a constructive dialogue is needed among different stakeholders to determine a consensus on when and how to consider life quality indices and costs associated with loss of life into hurricane risk assessment.

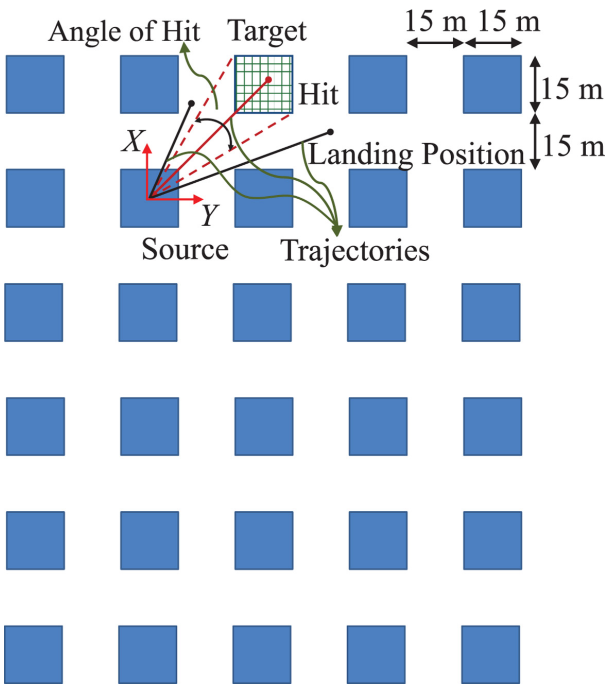

Fig. 4. Plan view of the benchmarck residential development.

7. Application example

The proposed PBHE framework is illustrated through the risk analysis for a building belonging to a hypothetical residential development, located near the coast in South Florida and composed by 30 identical concrete block gable roof structures (see Fig. 4). This application example seems sufficiently advanced to display some of the specific critical issues of the PBHE framework, and highlights the importance of the interaction between different hazards in a hurricane risk analysis. However, it is also simple enough to avoid the complexities of more realistic applications, thereby maintaining the focus of this paper on the illustration of the PBHE framework.

The risk analysis is performed for the building identified as “Target” in Fig. 4. The interaction of wind and windborne debris hazards is taken into account. Roof covers are considered as debris sources, whereas the windows and glass doors are considered as debris impact vulnerable components [51].

7.1. Hazard analysis and structural characterization

In the present study, the 3-second hurricane wind speed V recorded at 10 m above the ground is used as the only component of W for characterizing the wind hazard. For the sake of simplicity, the wind direction variability has been neglected by assuming that the maximum local winds generated by hurricanes act only in the most unfavorable direction for windborne debris hazard (i.e., in the X direction in Fig. 4).

For windborne debris hazard, the considered intensity measures (IM) are: the wind speed, V; the debris area, A_d; and the mass per unit area of debris, M_d. It is assumed that the buildings in the benchmark residential development are the only windborne debris source affecting the target structure. Thus, the parameter $n_{buildings}$ (i.e., the density of upwind buildings with respect to the investigated structure) can be excluded from the D vector. All windborne debris are assumed of sheet type with flight characteristics described by deterministic parameters. The choice of IM is based on damage analysis results available in the literature, which show a strong correlation between the selected parameters and the structural damage produced by wind and windborne debris hazard. A study of sufficiency and efficiency of different potential IM [22], albeit important, is out of the scope of this study.

Table 2
Probabilistic characterization of external and internal pressure coefficients.

Location/ condition	Mean	COV	Distribution
GC_p			
Roof (near ridge)	−0.855	0.12	Normal
Roof (away from ridge)	−1.615	0.12	Normal
Windward wall	0.95	0.12	Normal
Leeward wall	−0.76	0.12	Normal
Side wall	−1.045	0.12	Normal
GC_{pi}			
Enclosed	0.15	0.33	Normal
Breached	0.46	0.33	Normal

Among the wind occurrence models available in the literature [46,52], the Weibull distribution is adopted here to describe the hurricane wind speed variability [28]. The two-parameter Weibull cumulative distribution function, $F(V)$, is given by:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{a}\right)^{b}\right] \tag{6}$$

The two shape parameters a and b are site specific and are determined by fitting the hurricane wind speed records provided by the National Institute of Standards and Technology (NIST) to a Weibull distribution. The NIST wind speed records contain data sets of simulated 1-minute hurricane wind speeds at 10 m above the ground in an open terrain near the coastline for locations ranging from milepost 150 (near Port Isabel, TX) to milepost 2850 (near Portland, ME), spaced at 50 nautical mile intervals (92,600 m). Considering South Florida as the location for the case study, the dataset corresponding to milepost 1400 is used for fitting the distribution. The 1-minute hurricane wind speed ($\overline{V}$) dataset is converted into 3-second wind speed as $V = 1.77\overline{V}$ [37,44]. The two parameter Weibull distribution function is fitted using the converted wind speeds, and the parameters are $a = 25.2447$ m/s and $b = 1.6688$, respectively. The area and mass per unit area of debris are assumed to follow a uniform distribution in the range [0.108, 0.184] m^2 and [10.97, 23.35] kg/m^2, respectively [27].

The considered structural parameters (SP) are: the wind pressure exposure factor (evaluated at the height h of the roof of the target building), K_h; the external pressure coefficient, GC_p; and the internal pressure coefficient, GC_{pi}. The pressure coefficients include the effects of the gust factor G. The topographic factor, K_{zt}, the wind directionality factor, K_d, are modeled as deterministic and assumed equal to one; whereas the total vulnerable area on each side of each building is assumed equal to 20% of the total wall area. 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 [39]. The characterization of the external and internal pressure coefficients is given in Table 2 [46,52].

7.2. Interaction analysis

The choice of the interaction parameters (IP) is crucially dependent on the performance levels of interest and the corresponding monitored responses of the structural and non-structural elements. The main parameters controlling the effects of windborne debris impact are the impact linear momentum, L_d, the impact kinetic energy, E_d, and the number of impacting debris, n_d. It is known from the literature that the impact linear momentum is well correlated with damage for envelope components with a brittle behavior (e.g., doors, windows, see [53,54]), whereas the impact kinetic energy is better correlated

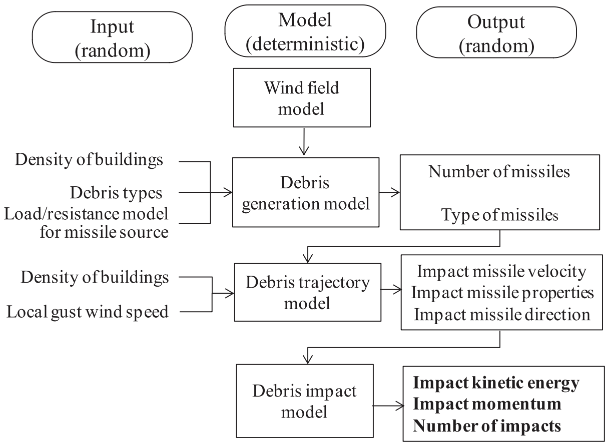

Fig. 5. Interaction analysis for windborne debris hazard.

with damage to envelope components with a ductile behavior (e.g., aluminum storm panels, see [48]). Hereinafter, it is assumed that the glass windows and doors are unprotected and have a brittle behavior. Based on this assumption, the *IP* selected in this study are: (1) the linear momentum of the debris at impact, L_d, for the windborne debris hazard; and (2) the wind pressure acting on the walls and roof, p_w, for the wind hazard.

The procedure proposed here for the interaction analysis corresponding to windborne debris hazard is summarized in the flowchart shown in Fig. 5. The input of the interaction analysis for windborne debris hazard is obtained from the hazard analysis and the structural characterization steps. A debris generation model provides the number and type of windborne debris that can affect the structure under consideration. The debris generation model used in this study is that employed by the Florida Public Hurricane Loss Model (FPHLM), in which the mean percentage of damage to roof covers is based on the simulation results from a component-based pressure induced damage model, and is expressed as a function of the wind speed [27]. The number of debris generated from each source house is calculated considering the percentage of roof cover damage at a given wind speed and the geometry of the house [27,51].

The results of the debris generation model, derived according to the geometry of the considered example case (i.e., density and relative position of debris sources with respect to the target structure), are taken as input for the debris trajectory model [55–57]. The debris trajectory model is used to assess if and at which impact velocity a given windborne debris hits the building. In this study, the debris trajectory model provides the landing position of the debris, which is identified by the random variables X = along-wind flight distance and Y = across-wind flight distance. The random variables are modeled using a two-dimensional Gaussian distribution described by the following parameters: μ_X = mean along-wind flight distance; μ_Y = mean across-wind flight distance = 0 m; $\sigma_X = \sigma_Y = 0.35\mu_X$ = standard deviation of the along-wind and across-wind flight distances, respectively [52]. The parameter μ_X is computed as:

$$\mu_X = \frac{2M_d}{\rho_a} \cdot \left[\frac{1}{2}C \cdot (K \cdot \tilde{T})^2 + c_1 \cdot (K \cdot \tilde{T})^3 + c_2 \cdot (K \cdot \tilde{T})^4 + c_3 \cdot (K \cdot \tilde{T})^5\right] \tag{7}$$

where $\rho_a = 1.225\ \mathrm{kg/m^3}$ = air density; $K = \frac{\rho_a \cdot V^2}{2M_d \cdot g}$ = Tachikawa number; $\tilde{T} = \frac{g \cdot T}{V}$ = normalized time; g = gravity constant; T = flight time in seconds; and C, c_1, c_2, and c_3 = non-dimensional coefficients that depend on the shape of the debris.

The flight time is assumed to follow a uniform distribution in the interval [1, 2.5] s. For the sheet-type debris considered in this study, $C = 0.91$, $c_1 = -0.148$, $c_2 = 0.024$, and $c_3 = -0.0014$. The debris horizontal velocity at impact, u_d, is a function of the wind velocity and the distance travelled by the debris (determined by its landing position), and is given by [51]

$$u_d = V \cdot \left[1 - \exp\left(-\sqrt{2 \cdot C \cdot K \cdot x}\right)\right] \tag{8}$$

where $x = \frac{g \cdot X}{V^2}$ = dimensionless horizontal flight distance of the debris. The debris is assumed to hit the target building if the debris flight distance is larger than the distance between the source and the target building and, at the same time, the landing position falls within the angle of hit (see Fig. 4).

Finally, the debris impact model uses the horizontal component of the missile velocity (obtained from the debris trajectory model) and data related to the missile size and mass (obtained from the debris generation model) to compute the impact linear momentum of the missile (i.e., the linear momentum corresponding to the windborne debris velocity component orthogonal to the impacted surface, conditional to the event of at least one impact on windows). In this study, the debris impact model gives the impact linear momentum as

$$L_d = M_d \cdot A_d \cdot u_d \tag{9}$$

The interaction analysis for the wind hazard provides the statistical characterization of the wind pressure, p_w. For the sake of simplicity, in this study, the wind pressure is computed as

$$p_w = q_h \cdot (GC_p - GC_{pi}) \tag{10}$$

where the wind velocity pressure at a quote h, q_h , is given by

$$q_h = 0.613 \cdot K_h \cdot K_{zt} \cdot K_d \cdot V^2 \cdot I \tag{11}$$

I = importance factor (assumed here equal to 1). In Eq. (11), V is measured in m/s and q_h is measured in $\mathrm{N/m^2}$. It is noted here that the simplified approach used in this study to perform the interaction analysis for the wind hazard is appropriate for the simple and small structures considered in the example application. However, larger and more complex structures may require a more rigorous approach based on the use of stochastic processes, random fields, and computational fluid dynamics to evaluate the wind effects on the structure.

7.3. *Structural analysis and damage analysis*

In this example application, the structural analysis step is not needed explicitly because the engineering demand parameters (*EDP*) can be assumed to coincide with the *IP*. The strengths of glass windows, glass doors, and roof (which are assumed to be the only components that can be damaged) are obtained from empirical relations available in the literature and directly compared to the corresponding *IP*. Following a procedure commonly used in PBEE, the physical damage conditions are represented using a limit state function g for each damage limit state, i.e.,

$$g = DM - IP \tag{12}$$

where the demand measure (*DM*) corresponds to the limit state capacity for the given damage limit state. The damage limit states considered here are (1) the breaking of annealed glass windows/doors, and (2) the uplift of the roof sheathings. The statistics of the damage limit state capacities for different components and limit states are provided in Table 3 [52,54].

7.4. *Loss analysis*

In this study, the decision variable (*DV*) is taken as the repair cost of the building, *RC*, expressed as a percentage of the total cost of the building. The complementary cumulative distribution of *DV* can be used for informed risk-management decision [58] and is computed as the convolution integral of the conditional probability of *DV* given *DM* and the derivative of the complementary cumulative density function of *DM* [4,59]. Since the repair costs associated with the different component limit states are not independent, the computation of $G(DV)$

Table 3
Statistics of limit state capacities.

Component	Limit state	Parameter	Mean (unit)	COV	Distribution
Roof	Uplift	R_{roof}	2762.7 ($\mathrm{N/m^2}$)	0.20	Normal
Windows	Pressure	R_{M}	4998.7 ($\mathrm{N/m^2}$)	0.20	Normal
Windows	Impact	R_{window}	4.72 (kg m/s)	0.23	Lognormal

Table 4
Summary of parameters used in the risk assessment analysis.

Analysis step	Parameters	Symbol	Definition
Hazard analysis	*IM*	V	3-Second gust wind speed
		A_{d}	Area of debris
		M_{d}	Mass of debris per unit area
Structural characterization	*SP*	K_h	Wind pressure exposure factor
		GC_{p}	External pressure coefficient
		GC_{pi}	Internal pressure coefficient
Interaction analysis	*IP*	L_{d}	Impact linear momentum
		p_{w}	Wind pressure on the surface
Damage analysis	*DM*	R_{window}	Strength for pressure (window)
		R_{roof}	Strength for uplift (roof)
		R_{M}	Strength for impact (window)
Loss analysis	*DV*	RC	Repair cost (% of total cost)

requires the joint probability density function of the repair costs of all component limit states, which is very difficult to obtain. To overcome this difficulty, a very efficient multilayered Monte Carlo simulation (MCS) approach is used in this study to estimate the loss hazard curve [60]. The multilayered MCS approach is able to account for the uncertainty in the various parameters involved in the risk assessment methodology (i.e., *IM*, *IP*, *DM*, and *DV*), which are summarized in Table 4.

The probabilistic hurricane loss analysis is performed for three different scenarios: (1) considering only the losses due to windborne debris hazard (the debris-only scenario); (2) considering only the losses due to wind hazard (the wind-only scenario); and (3) considering the losses due to windborne debris and wind hazards, and the effects of their interaction (the interaction scenario). In the debris-only scenario, the repair cost is associated to the failure of a glass door or a window due to the windborne debris impact (i.e., $L_{\mathrm{d}} \geq R_{\mathrm{M}}$). No chain reaction is considered, because the failure of a door or a window does not affect the impact linear momentum of the other missiles. In the wind-only scenario, the repair cost is associated to the failure of a glass door and/or a window, as well as to the uplift of the roof due to the wind pressure (i.e., $p_{\mathrm{w}} \geq R_{\mathrm{window}}$ and/or $p_{\mathrm{w}} \geq R_{\mathrm{roof}}$). In this case, a chain reaction is possible because the failure of a glass door or a window produces an internal pressurization of the building and modifies the wind pressure acting on the other doors and windows and on the roof (through the modification of the GC_{pi} parameter from enclosed to breached building, see Table 2). The interaction scenario considers the failure of glass doors and windows due to both debris impact and wind pressure, as well as the roof uplift due to the wind pressure. In this case, two types of hazard chains are possible, corresponding to the internal pressurization of the building caused by the failure of a door/window due to the windborne debris impact or to the wind pressure. Thus, the two scenarios considering wind-only and debris-only can be obtained as particular cases of the interaction case by neglecting the wind pressure damage on the doors/windows and roof for the debris-only scenario, and the damage on the doors/windows due to windborne debris impact for the wind-only scenario.

Fig. 6 shows the flowchart of the multilayered MCS approach [60] used for considering the interaction between wind and windborne debris hazards. The number of hurricanes in each year is simulated according to a Poisson random occurrence model with annual occurrence rate obtained from the NIST database. For each generated hurricane, a peak wind speed, V, is generated according to the Weibull distribution. For each value of V, the value of the wind pressure on the doors/windows and the roof is simulated using the pressure coefficients corresponding to the condition of enclosed buildings. The linear momentum is also computed for each debris impact. If the impact linear momentum and/or the wind pressure assume values larger than the corresponding limit state capacity of the glass on any of the four walls, the building envelope is considered to be breached and the internal pressure is modified. The undamaged building components (doors/windows and roof) are checked for further damage due to the modified pressure. A repair cost is then generated for each damaged component according to an appropriate probability distribution. For the sake of simplicity, it is assumed that the repair cost for the breakage of the windows on any side of the building or the uplift of the roof can be represented by a lognormal random variable with mean equal to 20% of the total cost of the building and COV equal to 20%. The total repair cost for the single hurricane simulation is equal to the sum of all the simulated component repair costs, with a maximum value of 100% (total failure of the building). It is also assumed that the building is fully repaired after each hurricane event. The single-year simulation is repeated a large number of times (in the example, 10,000 samples are used) to estimate the annual probability of exceedance (which coincides with the complementary cumulative distribution function of *DV*) of the total repair cost.

The annual probabilities of exceedance of the repair cost for the target building for the three different scenarios are shown in Fig. 7, using a semi-logarithmic scale. A strong interaction is observed between the wind and the windborne debris hazards. This observation suggests that the multi-hazard nature of hurricane must be taken into account for accurate probabilistic loss analyses.

8. Conclusions

In this paper, a Performance-Based Hurricane Engineering (PBHE) framework is proposed and illustrated. The methodology, that can be used to evaluate the structural risk associated with facilities located in hurricane-prone regions, is based on the total probability theorem and builds on techniques already developed and used in other civil engineering subfields. 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. Each of the analysis steps is briefly discussed in this paper. Particular emphasis is given to the differences between PBHE and other existing performance-based engineering frameworks, e.g., the multi-hazard nature of hurricane events, the presence of interacting hazard, and the focus on high, intermediate, and low performance levels.

The feasibility of the proposed framework is demonstrated through an application example consisting in the risk assessment

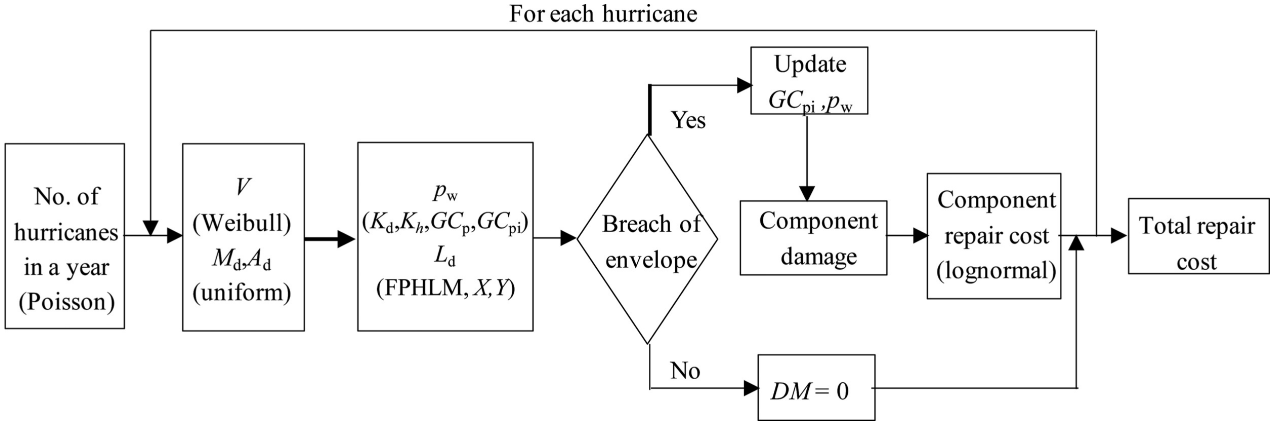

Fig. 6. Multilayered MCS approach for probabilistic hurricane loss estimation.

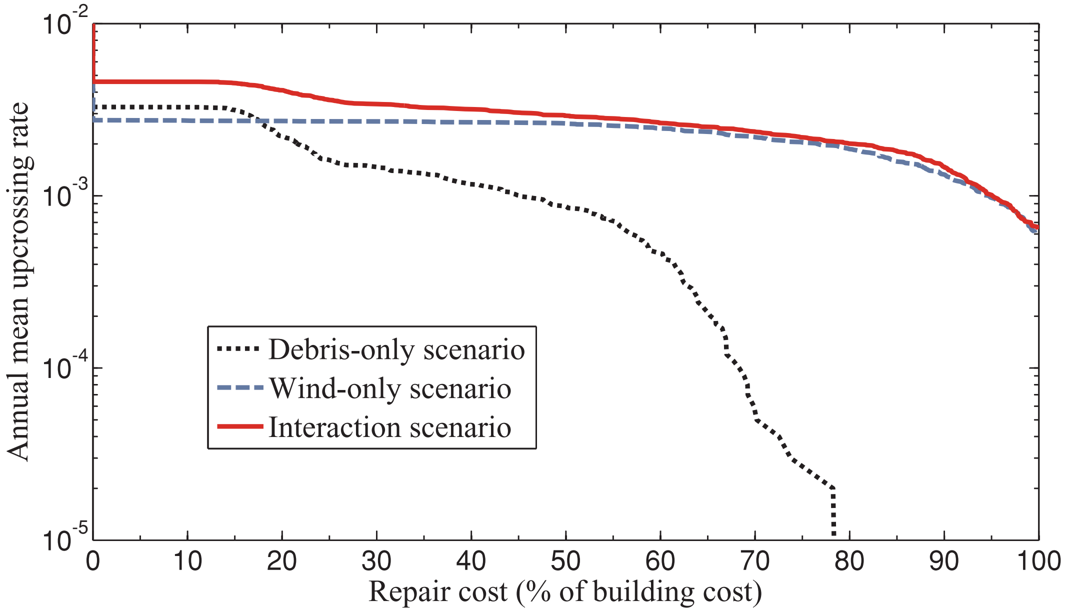

Fig. 7. Annual probability of exceedance of repair cost for different hazard scenarios.

for a target building in a hypothetical residential development under three different hazard scenarios. It is observed that the interaction between wind and windborne debris hazard can affect significantly the value of the annual probability of exceedance of repair cost. This observation suggests the need to consider the multi-hazard nature of hurricane events for accurate probabilistic loss analysis.

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References

[1] Ellingwood BR. Earthquake risk assessment of building structures. Reliab Eng Syst Saf 2001;74:251–62.
[2] Porter KA. An overview of PEER's performance-based earthquake engineering methodology. In: Proceedings of the ninth international conference on applications of statistics and probability in civil engineering (ICASP9), 2003 July 6–9, San Francisco, USA. Rotterdam: Millpress; 2003, pp. 973–80.
[3] Cornell CA, Krawinkler H. Progress and challenges in seismic performance assessment. PEER Center News 2000;3(2).
[4] Augusti G, Ciampoli M. Performance-based design in risk assessment and reduction. Probab Eng Mech 2008;23:496–508.
[5] Hamburger RO, Whittaker AS. Considerations in performance-based blast resistant design of steel structures. In: Proceedings of AISC-SINY symposium on resisting blast and progressive collapse. Dec. 4–5, 2003, New York, USA. 2003.
[6] Lamont S, Rini D. Performance-based structural fire engineering for modern building design. Struct Congr 2008:1–12.
[7] Riggs HR, Robertson IN, Cheung KF, Pawlak G, Young YL, Yim SCS. Experimental simulation of tsunami hazards to buildings and bridges. In: Proceedings of the 2008 NSF engineering research and innovation conference. 2008 Jan 7–10, Knoxville, USA. 2008.
[8] Petrini F. A probabilistic approach to Performance-Based Wind Engineering (PBWE). [Ph.D. dissertation]. Rome, Italy: University of Rome "La Sapienza"; 2009.
[9] Ciampoli M, Petrini F. Performance-based aeolian risk assessment and reduction for tall buildings. Probab Eng Mech 2012;28:75–84.
[10] Applied Technology Council (ATC). NEHRP guidelines for the seismic rehabilitation of buildings. Final report. Report no.: FEMA 273. Washington, DC: Federal Emergency Management Agency (US); 1997

[11] Applied Technology Council (ATC). Development of next-generation performance-based seismic design procedures for new and existing buildings. Report no.: ATC-58. Redwood City, CA: Applied Technology Council; 2005.

[12] Krishnan S, Ji C, Komatitsch D, Tromp J. Performance of two 18-Story steel moment-frame buildings in Southern California during two large simulated San Andreas earthquakes. Earthquake Spectra 2006;22:1035–61.

[13] Stojadinovic B, Mackie KR, Wong J-M. Seismic risk evaluation for the baseline PEER bridge testbed. TCLEE 2009:1–12.

[14] Van de Lindt J, Dao T. Performance-based wind engineering for wood-frame buildings. J Struct Eng 2009;135:169–77.

[15] Barbato M, Ciampoli M, Petrini F. A preliminary proposal for a probabilistic performance-based hurricane engineering framework. Struct Congr 2011:1618–29.

[16] Kareem A, McCullough MC. A framework for performance-based engineering in multi-hazard coastal environments. Struct Congr 2011:1961–72.

[17] Wen YK. Minimum lifecycle cost design under multiple hazards. Reliab Eng Syst Saf 2001;73:223–31.

[18] Whittaker AS, Hamburger RO, Mahoney M. Performance-based engineering of buildings and infrastructure for extreme loadings. In: Proceedings of the AISC-SINY symposium on resisting blast and progressive collapse, 2003 Dec 4–5, New York, USA.

[19] Li Y, Ellingwood B. Framework for multihazard risk assessment and mitigation for wood-frame residential construction. J Struct Eng 2009;135:159–68.

[20] Ciampoli M, Petrini F, Augusti G. Performance-based wind engineering: towards a general procedure. Struct Saf 2011;33:367–78.

[21] Melchers RE. Structural reliability analysis and prediction. 2nd ed. John Wiley and Sons; 2002.

[22] Luco N, Cornell CA. Structure-specific scalar intensity measures for near-source and ordinary earthquake ground motions. Earthquake Spectra 2007;23:357–92.

[23] Petrini F, Palmeri A. Performance-based design of bridge structures subjected to multiple hazards: a review. Bridge Maintenance, Safety, Management, Resilience and Sustainability. In: Proceedings of the sixth international conference on bridge maintenance, safety and management (IABMAS2012). 2012, pp. 2040–7.

[24] Toro GR, Resio DT, Divoky D, Niedoroda AW, Reed C. Efficient joint-probability methods for hurricane surge frequency analysis. Ocean Eng 2010;37:125–34.

[25] Li Y, Van de Lindt J, Dao T, Bjarnadottir S, Ahuja A. Loss analysis for combined wind and surge in hurricanes. Nat Hazard Rev 2012;13:1–10.

[26] Federal Emergency Management Administration (FEMA). Multi-hazard estimation methodology – hurricane model. Report No.: HAZUS-MH-MR4 technical manual. Washington, DC: Federal Emergency Management Agency (US), Department of Homeland Security; 2007.

[27] Gurley K, Pinelli JP, Subramanian C, Cope A, Zhang L, Murphree J, et al. Florida Public Hurricane Loss Projection Model (FPHLPM) engineering team final report, volume II: predicting the vulnerability of typical residential buildings to hurricane damage. Miami, FL: Florida International University, International Hurricane Research Center; 2005.

[28] Li Y. Fragility methodology for Performance-Based Engineering of wood-frame residential construction. [Ph.D. dissertation]. Atlanta, GA: Georgia Institute of Technology; 2005.

[29] Vickery P, Twisdale L. Wind-field and filling models for hurricane wind-speed predictions. J Struct Eng 1995;121:1700–9.

[30] Jakobsen F, Madsen H. Comparison and further development of parametric tropical cyclone models for storm surge modelling. J Wind Eng Ind Aerodyn 2004;92:375–91.

[31] Vickery PJ, Masters FJ, Powell MD, Wadhera D. Hurricane hazard modeling: the past, present, and future. J Wind Eng Ind Aerodyn 2009;97:392–405.

[32] Dean RG, Dalrymple RA. Water wave mechanics for engineers and scientists: advanced series on ocean engineering, vol. 2. New Jersey: World Scientific; 2004.

[33] Hasselmann K. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Hamburg: Deutsches Hydrographisches Institut; 1973.

[34] Bode Hardy. Progress and recent developments in storm surge modeling. J Hydraul Eng 1997;123:315–31.

[35] Huang Z, Rosowsky DV, Sparks PR. Hurricane simulation techniques for the evaluation of wind-speeds and expected insurance losses. J Wind Eng Ind Aerodyn 2001;89:605–17.

[36] Vickery P, Lin J, Skerlj P, Twisdale L, Huang K. HAZUS-MH hurricane model methodology. I: hurricane hazard, terrain, and wind load modeling. Nat Hazard Rev 2006;7:82–93.

[37] Lungu D, Rackwitz R. Joint committee on structural safety – probabilistic model code, part 2: loads. Available from: <http://www.jcss.byg.dtu.dk/upload/subsites/jcss/publications/pmc/part_ii.pdf >; 2001.

[38] Koh C, See L. Identification and uncertainty estimation of structural parameters. J Eng Mech 1994;120:1219–36.

[39] Lee KH, Rosowsky DV. Fragility assessment for roof sheathing failure in high wind regions. Eng Struct 2005;27:857–68.

[40] Arangio S. Reliability based approach for structural design and assessment: performance criteria and indicators in current European codes and guidelines. Int J Life Cycle Perform Eng 2012;1(1):64–91.

[41] Baker JW, Schubert M, Faber MH. On the assessment of robustness. Struct Saf 2008;30(3):253–67.

[42] Izzuddin BA, Pereira M, Kuhlmann U, Rölle L, Vrouwenvelder T, Leira BJ. Application of probabilistic robustness framework: risk assessment of multi-storey buildings under extreme loading. Struct Eng Int 2012;22(1):79–85.

[43] Pinelli JP, Gurley KR, Subramanian CS, Hamid SS, Pita GL. Validation of a probabilistic model for hurricane insurance loss projections in Florida. Reliab Eng Syst Saf 2008;93:1896–905.

[44] American Society of Civil Engineers (ASCE). ASCE 7-10: minimum design loads for buildings and other structures. Reston, VA: American Society of Civil Engineers; 2010.

[45] Dao T, Van de Lindt J. Loss analysis for wood frame buildings during hurricanes. I: structure and hazard modeling. J Perform Constr Facil 2012;26(6):729–38.

[46] Li Y, Ellingwood BR. Hurricane damage to residential construction in the US: importance of uncertainty modeling in risk assessment. Eng Struct 2006;28:1009–18.

[47] Shanmugam B. Probabilistic assessment of roof uplift capacities in low-rise residential construction. [Ph.D. dissertation]. Clemson, SC: Clemson University; 2011.

[48] Herbin AH, Barbato M. Fragility curves for building envelope components subject to windborne debris impact. J Wind Eng Ind Aerodyn 2012;107–108:285–98.

[49] Seyedi DM, Gehl P, Douglas J, Davenne L, Mezher N, Ghavamian S. Development of seismic fragility surfaces for reinforced concrete buildings by means of nonlinear time–history analysis. Earthquake Eng Struct Dyn 2010;39:91–108.

[50] Bjarnadottir S, Li Y, Stewart MG. A probabilistic-based framework for impact and adaptation assessment of climate change on hurricane damage risks and costs. Struct Saf 2011;33:173–85.

[51] Lin N, Vanmarcke E. Windborne debris risk assessment. Probab Eng Mech 2008;23:523–30.

[52] Yau SC. Wind hazard risk assessment and management for structures. [Ph.D. dissertation]. Princeton, NJ: Princeton University; 2011.

[53] National Association of Home Builders (NAHB) Research Center. Wind-borne debris impact resistance of residential glazing. Final report: cooperative agreement H-21172CA. Washington, DC: US Department of Housing and Urban Development, Office of Policy Development and Research; 2002.

[54] Masters FJ, Gurley KR, Shah N, Fernandez G. The vulnerability of residential window glass to lightweight windborne debris. Eng Struct 2010;32:911–21.

[55] Holmes JD. Trajectories of spheres in strong winds with application to wind-borne debris. J Wind Eng Ind Aerodyn 2004;92:9–22.

[56] Baker CJ. The debris flight equations. J Wind Eng Ind Aerodyn 2007;95:329–53.

[57] Lin N, Holmes J, Letchford C. Trajectories of wind-borne debris in horizontal winds and applications to impact testing. J Struct Eng 2007;133:274–82.

[58] Mitrani-Reiser J, Haselton C, Goulet C, Porter K, Beck J, Deierlein G. Evaluation of the seismic performance of a code-conforming reinforced-concrete frame building – part II: loss estimation. In: Proceedings of the 8th U.S. national conference on earthquake engineering (NCEE), 2006 Apr 18–22, San Francisco, USA.

[59] Yang TY, Moehle JP, Stojadinovic B. Performance evaluation of innovative steel braced frames: report No.: PEER 2009/103. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley; 2009.

[60] Conte JP, Zhang Y. Performance based earthquake engineering: Application to an actual bridge-foundation-ground system. In: Proceedings of the 12th Italian national conference on earthquake engineering, Pisa, Italy, 2007.