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A unified framework for performance-based wind engineering of tall buildings in hurricane-prone regions based on lifetime intervention-cost estimation

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ABSTRACT

Accurate evaluation of structural performance is necessary in modern tall building design. In wind engineering, the current approach employed by researchers is the Monte-Carlo sampling method. Structural failure probability is calculated by combining structural fragility curves with the random variability of wind speed and direction, depending on local wind climate. In the hurricane-prone regions of the USA, wind climate and its effects on building response require accurate assessment of wind-induced structural performance.

This paper proposes a simulation framework for tall buildings that combines fragility analysis with local wind climate information to evaluate structural vulnerability. Hurricane wind climate information directly considers maximum wind speed, wind direction along with their correlation at hurricane landfall. Consequently, structural fragility surfaces will be generated, conditional on these two variables. This result will be used to examine lifetime intervention cost accumulation, associated with nonstructural damage on the building façade, and to determine an "optimal" wind-direction-dependent building orientation.

1. Introduction

1.1. General context, literature review and statement of purpose

Tall buildings are the land-mark and center of human activities. They greatly influence local culture, economy and society. Therefore, accurate evaluation of structural performance under extreme winds is necessary. The designation performance-based design (PBD) has been originally coined and employed in seismic engineering over the past several years, as an alternative to the prescriptive design methods, based on the correspondence between earthquake recurrence intervals and performance levels [1]. The basic concept of PBD is to ensure that the structure satisfies a set of pre-defined performance requirements [2], when subjected to different hazard levels. Implementation of similar PBD-inspired methods has been recently considered in wind engineering and for various structures sensitive to wind-induced loads. The PBD is also attractive since it enables cost-effective design by assisting with the planning of maintenance in the aftermath of a catastrophic event.

Currently, the Monte-Carlo sampling method is used to calculate the probability of "structural failure" in a tall building at various wind speeds and to generate structural fragility curves, needed by PBD. The probability of structural failure, i.e., exceedance of a pre-selected limit-state threshold level, can be efficiently computed by repeating the random analysis $\mathcal{N}$ times (sample population size), since algorithmic complexity is not influenced by the number of uncertain or random quantities. Numerous studies have appeared in recent years to more rationally extend the PDB methodology to wind-load-sensitive structures (e.g., [3–10]). Literature review on PBD in the wind engineering field has also revealed the interest in the study of load effects on low-rise buildings [11–15], since damage and collapse are possible. Among the various contributions, the research groups from Notre Dame University and the University of Michigan have made notable advancements in the field of structural optimization, inspired by PBD concepts, applied to tall buildings under wind loads [16,17].

1.2. Performance-based wind engineering of tall buildings: Research opportunities and motivation

The research group from Northeastern University has examined several issues related to performance-based wind engineering (PBWE) for vibration-sensitive structures, such as long-span

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bridges [18,19] and tall buildings [20–24]. Principal emphasis has been given to the simulation and analysis of lifetime intervention costs. The research has been inspired by seminal studies applying monetary loss analysis to study wind loads and performance of other structures (e.g., [25,26]) and, more generally, seismic engineering models [27]. Study activities have also been recently expanded through collaboration with another research unit from the University of Perugia, Italy (e.g., [28,29]).

However, the wind climate in hurricane-prone regions and its relationship with the building response still call for more accurate assessment of wind-induced structural response and more precise performance evaluation over the structural lifetime. The state-of-the-art structural performance analysis method against wind hazards, proposed in recent years by this group, is composed of three steps aiming to: (1) identify the most unfavorable wind direction, which predominantly contributes to the extreme wind load, either by wind tunnel test or through computational fluid dynamics; (2) construct the structural fragility curves at various wind speeds through numerical simulation; (3) incorporate the building's local wind climate data into the structural fragility analysis to evaluate structural failure probability. One of the main simplifications, partially ignored in previous studies, is the possibility of multi-directional winds with variable (or predominant) mean wind direction, which may positively or negatively affect the structural vulnerability and, consequently, the lifetime cost estimation. The important role of wind direction in relation to the PBD of buildings has in fact been noted in the engineering practice [30] and recently examined in more detail (e.g., [29]).

1.3. Main objectives and anticipated outcomes of the study

This study proposes a unified formulation and simulation framework for tall buildings that combines comprehensive fragility analysis and accounts for both variable wind speed and direction when evaluating structural vulnerability. Furthermore, hurricane wind climate information directly considers maximum wind speed, wind direction along with their correlation at hurricane landfall. On one side, wind climate information will consider the correlation between reference wind speed and wind direction to construct the joint probability density function between these two variables and to quantify hazard intensity. On the other hand, structural fragility surfaces, conditional on these two variables, will be generated. This result will be used to investigate structural performance, to examine lifetime intervention costs accumulation due to nonstructural damage on the façade of a reference tall building and to determine an optimal wind-direction-dependent building orientation.

2. Background theory

2.1. Davenport's wind loading chain and its relationship to performance-based wind engineering (PBWE)

In 1961, Professor Alan G. Davenport established the theoretical fundamentals of structural analysis for wind engineering [31]. According to this approach, the wind-induced structural response of a tall building can be determined in the frequency domain through the combination of local wind climatology, local wind exposure and topography, structural aerodynamic characteristics, governed by building shape, and structural dynamic properties. This theory leads to the determination of the power spectral density (PSD) of the generalized turbulence-induced dynamic forces and the structural response [33,34]. Currently, this approach is referred to as the "Davenport Chain" [32].

One of the key steps of the PBWE is the evaluation of the probability that either a system or one of its sub-components reaches or exceeds a given limit state or "failure" probability conditional on the hazard intensity, such as the mean wind speed at a reference elevation. For serviceability limit states, which are usually predominant in the wind-resistant design of a tall building, a linear elastic structural model is adequate [35] and the standard frequency domain random vibration analysis of the Davenport Chain can be used [35–38]. On the basis of this concept, designers or owners can make a decision through appropriate decision variables (DVs) [3]. For example, Ciampoli and Pertini [3] presented a general framework to evaluate the structural risk as the probability of exceeding a prescribed threshold level of the relevant DV, described as:

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

A more detailed description of the variables can be found in [3] (IM: intensity measures, SP: Structural Parameters, IP: interaction parameters, EDP: engineering demand parameter, DM: damage measure). In most current PBWE evaluation methods, especially those for tall buildings, the measure of the wind hazard intensity only includes the extreme value of the wind speed. Wind direction is partially ignored in the PBWE analysis process, even though it is important [30] since aerodynamic forces and vortex shedding effects can drastically change with wind direction. Moreover, the prevailing wind direction at a specific location is not "uniformly" distributed, especially in the presence of tropical winds [39]. Therefore, it is necessary to correctly include the wind direction into PBWE analysis (e.g., [29]).

3. Framework description

3.1. Fundamentals, assumptions and description of the framework "modules"

The general procedure for PBD is schematically presented in Eq. (1). However, some steps are not directly applicable to wind engineering. For example, the damage analysis [$f(DM|EDP)$] is associated with individual structural components, such as columns, beams, etc. Characterization of these components requires analysis of materials and mechanics. This task has not been considered but can be readily included in future work, e.g., following work carried out for reinforced-concrete buildings [40]. Furthermore, damage-induced monetary loss analysis [$f(DV|DM)$] at the structural element level after the occurrence of the hazard is related to engineering economics and is not discussed herein.

Aiming to build a unified performance-based wind engineering formulation, this study will focus on the first four parts described in Eq. (1): the hazard analysis $f(IM)$, the structural parameter analysis $f(SP)$, the aerodynamic analysis $f(IP|SP, IM)$ and the structural response analysis $f(EDP|SP, IM, IP)$. Monetary loss analysis is considered at the cumulative structural level only (e.g., [24]). Damage produced by structural vibration on the building façade is predominantly considered, as it is often observed on the façade of tall buildings. Other damage categories are not included but may be considered in future investigations. Supplementary discussion on the limit state selection is presented in a later section (Section 4.3). Moreover, the assumption $f(DM|EDP) = 1$ is used in this paper; it should be noted that this assumption may cause non-conservative estimation of damage probability in the case of hurricane winds, since the damage is examined only for the worst-case scenario and does not consider the possibility of additional