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Performance-based design optimization of tall concrete framed structures subject to wind excitations

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ABSTRACT

This paper presents an integrated computational design optimization method for the performance-based design of tall buildings subjected to various levels of wind excitation. A performance-based wind engineering design framework is proposed by defining various performance objectives associated with multiple levels of wind hazards. A nonlinear static pushover analysis is employed to predict the inelastic drift performance of tall buildings subject to very rare extreme wind events. The optimal performance-based design problem considering inelastic deformation is formulated and solved by the augmented optimality criteria method. The effectiveness and practicality of the optimal wind-resistant performance-based design technique are illustrated by a practical 40-story residential building.

1. Introduction

Recent trends towards developing increasingly taller and irregularly-shaped complex buildings have led to structures that are potentially more sensitive to wind excitation. As buildings become taller and more slender, they become more vulnerable to wind than to earthquake effects. In a wind-prone area, high-rise buildings may suffer from wind-induced hazards that cause occupant discomfort due to motion, loss or deterioration of service, failure in non-structural partitions and cladding, damage to structural elements, or even threats to life safety (Foley, 2002). In this study, wind hazards are considered to be threats to humans and to what they value that are caused by extreme wind events.

The approach to address wind excitation that is found in traditional building codes commonly uses a 50-year or 100-year return period wind speed for the evaluations of the prescriptive design criteria related to the static lateral drift and the overall stability of buildings. For the ultimate limit states of strength, the building codes generally use factored Equivalent Static Wind Loads (ESWLs) where the ESWLs are calibrated from the 50-year or 100-year return period wind speeds. The factoring of the ESWLs is normally equivalent to considering a wind speed with a mean recurrence interval (MRI) of around 500 years (Spence and Kareem, 2014). Although those building design codes may provide an acceptable level of life-safety protection, recent research studies indicate that the traditional prescriptive approaches based on a single design level of wind excitation may yield poor reliability for the dynamic serviceability and inadequate protection against wind-induced local damage, e.g., loss of cladding. Although the general consensus is that the complete loss of lateral stability due to wind loading is rare, a tall building may exhibit non-linear behavior when subjected to very rare wind hazards (Tamura, 2009). There is a growing body of evidence that suggests that prescriptively designed tall buildings may not guarantee satisfactory serviceability performance and do not necessarily safeguard against local damage losses from different levels of wind hazards. For tall buildings subjected to moderate wind hazards, their habitability performance is often what controls the design of the structural system (Huang et al., 2011, 2012).

The modern approach of performance-based engineering offers a rational design framework for making design decisions by assessing the appropriate risks and meeting various performance objectives of the engineered facilities that are subjected to natural hazards. Performance-based seismic design and assessment guidelines for new buildings and other structures have been proposed by several FEMA programs (FEMA-350; FEMA-P695; FEMA-P752). With the scale and complexity of modern tall buildings, seismic performance-based design requires extensive computational resources and effort.

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To improve design efficiency, an innovative performance-based design optimization (PBDO) methodology was developed for tall buildings. Performance-based design optimization is the combination of state-of-the-art performance-based engineering and a computational design optimization technique into an automated and synthesized design platform that aims to minimize the structural or life-cycle cost for buildings subject to natural hazards such as severe earthquakes and extreme windstorms (Li and Hu, 2014). The PBDO concept and its application in seismic engineering have been researched extensively in recent years (Ganzerli et al., 2000; Xu et al., 2006; Foley et al., 2007; Zou et al., 2007; Fragiadakis and Lagaros, 2011).

Unlike performance-based seismic engineering, a general consensus of the multi-level wind performance-based design framework has not yet been achieved. Some researchers made an attempt to establish a compatible set of wind design criteria within the framework of performance-based seismic engineering that was “risk-consistent” in terms of the return periods and the probability of occurrence during the lifetime of a building (Chock et al., 1998). Jain et al. (2001) proposed a probability-based methodology for determining site-specific performance-based design wind speeds for building designs. It has been demonstrated that using such site-specific extreme wind loads, which are proportional to the square of the design wind speeds, can often lead to more cost-efficient designs. Foley (2002) presented a preliminary multi-level wind performance-based design framework that considered various design issues such as structural strength, façade damage and occupant discomfort at different levels of wind hazards. Van de Lindt and Dao (2009) presented the concept of performance-based wind engineering for wood-frame buildings through the development and application of fragilities to form different owner/user performance expectations, namely occupant comfort, continued occupancy, life safety, and structural integrity. A probabilistic procedure for the performance-based design of tall buildings subjected to wind excitations was proposed by Petrini and Ciampoli (2012). The central objective of the procedure is the assessment of the adequacy of the structure through the probabilistic description of a structural performance (no collapse, occupant safety, accessibility, full functionality, limited displacements or accelerations, etc.) based on the over-simplified models.

To make PBDO of tall buildings subject to wind excitation feasible, an integrated wind load analysis and stiffness optimization method has been developed for the serviceability design of tall buildings subject to wind-induced drift or acceleration design constraints (Chan et al., 2009, 2010). Recently, Huang et al. (2012) developed a reliability performance-based optimization method for the wind-induced drift and occupant comfort performance design of tall buildings. Spence and Kareem (2014) proposed an efficient probabilistic performance based design and optimization strategy for uncertain linear systems driven by experimentally determined stochastic wind loads. However, such developed stiffness optimization techniques are only applicable to the elastic design of tall buildings subject to wind loads. The inelastic wind-induced damage of buildings occurred during Hurricane Katrina (van de Lindt and Dao, 2009), and various occurrences of wind-induced damage in buildings and the corresponding wind speeds have been reported by Tamura (2009). On the other hand, the ever increasing strength of tropic cyclone intensity calls for the consideration of very destructive wind hazards (Balentine, 2014). For example, Super Typhoon Haiyan made landfall near Tacloban City in the Philippines on November 8, 2013, and left widespread destruction in its path. The sustained very strong wind of 195 miles per hour (87.1 m/s) has been reported (www.wunderground.com/tropical/tracking/wp201331.html) during the attack of Haiyan. An effort was made to develop an optimization framework in order to find the optimal stiffness of a nonlinear/hysteretic RC structure subject to stationary wind excitation (Beck et al., 2014). The simplified Bouc–Wen hysteretic model was employed to capture nonlinear behavior of a building structure and simple story stiffness was used as design variables through the optimization process. It is necessary to further develop a computer-based structural sizing optimization technique for the performance-based, wind-resistant design of tall buildings that will take into account both elastic and inelastic behavior at various intensity levels of wind conditions.

In this paper, an integrated computational design optimization technique for the wind engineering performance design of tall buildings is developed. The performance-based design wind speed, a measure of the wind hazard intensity, can be statistically determined using the probabilistic analysis of extreme wind speed data recorded at meteorological observatories. A performance-based wind engineering design framework is presented by defining various performance objectives associated with multiple levels of wind hazards. A nonlinear static pushover analysis is proposed to evaluate the possible inelastic behavior of tall building structures during very rare wind events, e.g., wind hazards with a return period of 475 years. Then, the optimal design problem of a tall building subject to a set of comprehensive performance-based design criteria is explicitly formulated in terms of element sizing design variables. An augmented Optimality Criteria algorithm, which combines the Lagrangian multiplier method with an exact penalty function, is developed to solve the multi-level performance-based design optimization problem. Finally, a practical 40-story building example with three-dimensional (3D) mode shapes is used to demonstrate the applicability and effectiveness of the optimal multi-level wind performance-based design technique.

2. Performance-based wind engineering design framework

The performance-based approach provides a means to design a building with a predictable and acceptable performance at multiple levels of hazards during the lifetime of the building. In the wind performance design framework, performance objectives can be described as the combination of expected performance levels with their corresponding wind excitation/hazard intensities, which are defined by the magnitudes of the wind speed of a wind hazard.

A four-level, wind engineering performance design framework for tall buildings is presented in Fig. 1. The basic performance objectives can be considered as the minimum requirements. The motion perception performance objective is defined by occupants possibly perceiving the slight motion of a building but not feeling discomfort due to the small magnitude of the motion during yearly wind events. The operational performance objective considers degradations in normal building serviceability function up to moderate levels, but with no threats to safety or injury during occasional wind events. The immediate occupancy performance objective is strictly required for tall buildings under rare wind hazards to ensure structural integrity with slight damage to nonstructural components. Life safety, the fourth level of the performance objectives, takes into account the potential

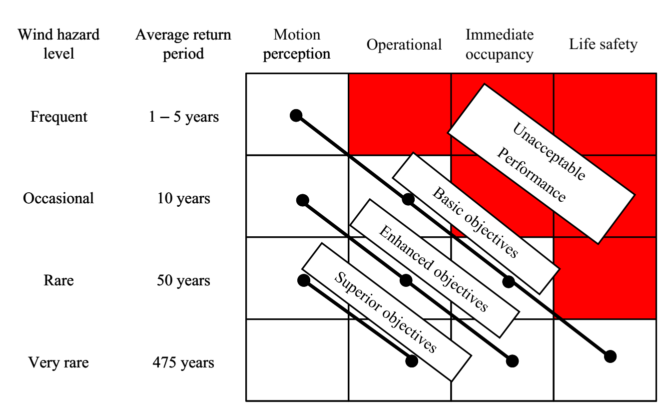

Fig. 1. Performance-based design objectives against wind hazards.