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Simulation and analysis of intervention costs due to wind-induced damage on tall buildings

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ABSTRACT

A numerical algorithm is developed for estimating the life-cycle monetary losses (maintenance and repair costs) due to wind-induced damage on tall buildings. The wind loading on tall buildings is evaluated by combining the effect of buffeting forces and vortex shedding forces. The translation process theory is subsequently used to estimate the peak value of the resultant response, which is a non-Gaussian stochastic process. "Fragility curves", accounting for random aerodynamic coefficients due to experimental errors, are used to estimate vulnerability and wind-induced damage probability. These curves represent the probability of exceeding a given structural damage state (or performance threshold), conditional on the mean wind speed. The thresholds are based on top-floor resultant acceleration, for occupant comfort, and resultant peak displacements, for structural damage. The results of the fragility analysis and wind speed probability are subsequently used to analyze monetary losses. The cost analysis model is adapted from an existing life-cycle simulation algorithm for earthquake hazards.

The pilot study employs a 183 m tall building (CAARC model). Fragility and life-time cost analysis simulate the behavior of a building located in a "mixed" wind climate, typical of Southern Florida in the United States. Effects of various limit state criteria, meteorological environment and measurement accuracy of the structural parameters are discussed.

1. Introduction

1.1. Context and methods: performance-based engineering

Over the past several years, performance-based engineering (PBE) has been developed and applied by structural engineers and researchers in seismic engineering. For instance, the Structural Engineers Association of California has set about a framework for the design of structures, based on the correspondence between earthquake recurrence intervals and performance levels [1], in which performance levels are combined with earthquake excitation levels to determine appropriate design criteria. The basic concept is to ensure the structure to satisfy the selected performance requirement, when subjected to different levels of the hazard, in order to achieve performance-based design [2]. The next important and logical step is to apply this advanced procedure to the wind engineering field and to evaluate the performance of either new or existing structures under wind load [3].

The derivation of more rational performance-based design methods has received the attention of the research community, as indicated by the numerous studies in recent years on this subject [4–10]. The fundamental idea behind PBE is to "expand" the flexibility of the design procedure [11]. It is to ensure that a building, for example, subjected to different levels of a hazard (as opposed to the largest foreseeable event), is capable of achieving a selected performance objective level [12]. Current PBE methodologies go beyond the prescriptive specifications of a design standard by ensuring that life safety is preserved under "severe" events. They also establish criteria for the structure not to collapse under "extreme" events, and to preserve immediate occupancy under "moderate" events. Interestingly, the exact definitions of "severe", "extreme", and "moderate" are still under development [12]. The overall concept of PBE provides an attractive alternative for owners, since it can enable cost-effective design and can reduce planning in the aftermath of a catastrophic event.

A brief literature review of PBE in the wind engineering field has revealed that most attention has been given to the study of the load effects on low-rise buildings [12–16], where damage and

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Nomenclature

B	building width
B_w	spectral bandwidth
$C(t)$	total cost at time t
C_0	initial cost of the structure
C_D	drag coefficient
C_L	lift coefficient
C_j	repair cost for exceeding the limit state j at present monetary value
C_{zi}	decay coefficient of the co-coherence function for turbulence in direction i
$\tilde{C}_L$	RMS lift coefficient
D	building depth
$F()$	cumulative distribution function
F_{T_j}	fragility curve for limit state j
$f()$	probability distribution function
g	peak effect factor
h	building height
I_u	turbulence intensity
k	total number of limit states considered
L_s	vortex shedding correlation length
$M_{g,i}$	generalized mass for fundamental mode along direction i
$N(t)$	total number of wind hazards at time t
n	frequency
n_s	frequency of vortex shedding
$n_{0,i}$	fundamental natural frequency for direction i
$P[]$	probability operator
P_j	annual probability of exceeding the limit state j
S_{ii}	power spectral density of random variable i
t	time (in years, for cost analysis)
$\bar{U}(z)$	mean wind speed at height z
u	wind turbulence in along-wind direction
u^*	shear flow velocity
v	wind turbulence in crosswind direction
$\bar{X}$	mean static displacement
z_0	roughness length of boundary layer
$\zeta_{a,i}$	aerodynamic damping for direction i
$\zeta_{s,i}$	structural damping for direction i
κ	average occurrence parameter of Poisson process $N(t)$
λ	discount rate per year
μ_i	expectation of variable i
ν	up-crossing rate
ρ	air density
σ_i	standard deviation (RMS) of variable i
$\Phi_i(z)$	shape function along direction i

Subscripts

H	hurricane climate
j	j-th limit state
m	mixed climates
NH	non-hurricane climate
r	resultant response
$\ddot{x}$	along-wind motion acceleration
$\dot{x}$	along-wind motion velocity
x	along-wind direction
$\ddot{y}$	crosswind motion acceleration
$\dot{y}$	crosswind motion velocity
y	crosswind direction

collapse can be related to localized loss of capacity in key members or connections. Few studies are available on high-rise buildings, in which either a framework for the analysis of uncertainty is developed [17], or in which a methodology for the design of buildings is proposed [18,19]. Some attention has been recently paid to wind loads on long-span bridges [20,21].

1.2. Motivation of the study in the context of wind load analysis on tall buildings

From the early stages of the research activities on tall buildings in wind engineering, the frequency domain analysis method has been employed due to the presence of random turbulent wind and consequent structural random vibration [22,23]. The evaluation of the dynamic response of tall buildings accounts for two main phenomena: buffeting and vortex shedding. Buffeting is an aerodynamic phenomenon, caused by the interaction between wind turbulence and the structure in motion. The dynamic motion caused by buffeting loads can be adequately predicted under quasi-static loading assumption, in which all aerodynamic load parameters are assumed as constant and measured by a number of static force coefficients averaged over time. In general, buffeting force will increase with the mean wind speed. Vortex shedding is a periodic loading mechanism at a predominant frequency that occurs when wind flows around a bluff body at given speed. For flexible structures, such as very tall and flexible buildings of the new generation, it is conceivable that the frequency of vortex shedding, which depends on the size and shape of the structure, may approach the fundamental frequency of the structure, possibly causing large-amplitude vibration at certain wind speeds [24].

In PBE fragility curves are often used to evaluate the probability of a system reaching or exceeding a limit state as a function of the hazard intensity (engineering demand), such as the peak ground acceleration or the mean wind speed at a predefined height from the ground in high winds. Originally developed in earthquake engineering, they have become a very useful tool to evaluate structural integrity for performance-based design. In the case of wind engineering the method can account for various sources of uncertainty including error-contaminated aerodynamic parameters. Recently, in parallel with the development of computer technology, Monte-Carlo simulation has become an important numerical approach for generating fragility curves [18] on computer clusters as well as on general purpose graphic processing unit (GPGPU) [25]. As a result, fragility analysis, based on Monte Carlo simulation, has been recently investigated in wind engineering and successfully applied to tall buildings [2] and long-span bridges [21].

This study will focus on the uncertainty associated with unavoidable experimental errors in a wind tunnel test, used to determine the loads on the full-scale structure; it has been shown that this can be a relevant uncertainty source for structural reliability [2,21,26]. For instance, experiments conducted on the same building model in different laboratories can lead to different results due to different geometric scales in the models or variations in the properties of the boundary layer replicated in the wind tunnel [27]. These aspects lead to an inherent variability in the aerodynamic load coefficients, confirming the stochastic nature of the aerodynamic parameters. This study aims at specifically examining the relevance of this uncertainty type on the predicted response of a tall building. It is clear that other relevant uncertainty sources should be considered in future studies. Other uncertainty sources may include: test facilities, human errors, test procedures, wind