Probabilistic Performance Evaluation of Buildings: An Occupant Comfort Perspective

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ABSTRACT: Modern tall buildings are expected to meet certain wind-induced drift (serviceability) and acceleration (occupant comfort) criteria to preserve the integrity of building cladding system, interior finishes, and operation of elevator system and to ensure occupant comfort due to building motion. Despite their significance, checking procedures for occupant comfort limit states have not been as strictly developed as those for strength design. The problem is further complicated by the uncertainty associated with the parameters in the occupant comfort checking procedure which are based on the level of acceleration and its relationship to human perception and reaction to motion. An effective checking procedure may be derived on the basis of the propagation of uncertainty in the parameters of the wind load-response-performance chain. In light of the significance of occupant comfort requirements of a building, this paper presents a probabilistic framework to evaluate a building's occupant comfort performance at different recurrence interval winds including parametric uncertainties, e.g., damping and wind speed, among others. To illustrate the effectiveness of this framework, several examples are presented. Finally, an occupant comfort performance checking procedure is introduced that has the promise of becoming a practical probabilistic design procedure for evaluating the habitability of tall buildings.

KEYWORDS: Uncertainty Analysis, Monte Carlo Simulation, Occupant Comfort Assessment, Reliability Analysis, Dynamics, Damping, Wind, Tall Buildings

1 INTRODUCTION

Modern tall buildings are expected to meet certain wind-induced drift (serviceability) and acceleration (occupant comfort) criteria to preserve the integrity of building cladding system, interior finishes, and operation of elevator system and to ensure occupant comfort due to building motion. In order to limit the response of tall buildings under the action of wind and satisfy occupant comfort criteria, the structural system needs to be modified leading to added stiffness. However, increasing stiffness alone may not be sufficient to ensure that the structure satisfies occupant comfort criteria, which often governs tall building design. In fact, these buildings may completely satisfy strength and serviceability requirements, yet undergo accelerations that may cause occupant discomfort, triggering emotional and physical reactions that include concern, anxiety, fear, dizziness, headaches, and nausea [1, 2]. Despite their significance, checking procedures for occupant comfort limit states have not been as strictly developed as those for strength design. The problem is further complicated by the uncertainty associated with the parameters in the occupant comfort checking procedure, including damping, wind speed, and the occupant comfort criteria, which are based on the level of acceleration and its relationship to human perception and reaction to motion.

By increasing the level of inherent damping, the acceleration response can be decreased, making it a structural property most critical to meeting occupant comfort criteria. Unfortunately, inherent damping cannot be determined with a high degree of certainty in design [3] and cannot be predictably engineered in a structure like mass and stiffness, since its mechanisms are complex

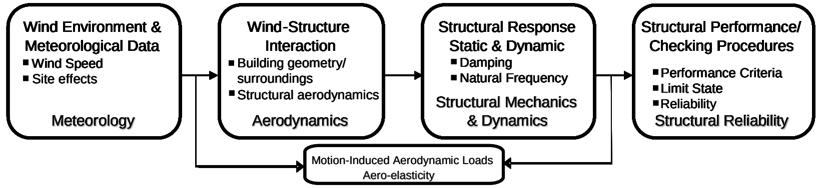

Figure 1 Wind Load-Response-Performance Chain for Propagation of Uncertainty

and, as of yet, not fully understood. As damping and ensuing accelerations are not the only quantities surrounded by uncertainty, this study will also consider the uncertainty inherent in the occupant comfort criterion itself, arising from its subjective nature and a number of physchological and physiological factors that contribute to perception of motion [4]. As will be described in Section 3, habitability criteria are based on both full-sale studies and motion simulator controlled testing. The results from these studies emphasize the importance of uncertainty in modeling human biodynamical response to motion [2].

Finally, a typical checking procedure may be derived on the basis of the propagation of uncertainty in the parameters of the wind load-response-performance chain described in Figure 1. In light of the significance of habitability requirements of a building, this paper presents a probabilistic framework to evaluate a building's habitability performance at different recurrence interval winds including parametric uncertainties in, e.g., damping and wind speed. Examples are presented to illustrate the effectiveness of this framework. An occupant comfort based checking procedure is introduced that may lead to a practical probabilistic design procedure for evaluating habitability of tall buildings.

2 WIND-INDUCED RESPONSE

In order to estimate structural response to wind loads, basic random vibration theory is utilized. The response can be determined analytically in terms of a power spectral density (PSD) function of the wind load which is obtained from a HFBB wind tunnel study. Alternatively, the peak along-wind acceleration at any height of the building can be found using the following expressions recommended in the ASCE 7-05 Commentary (http://aerodata.ce.nd.edu/) [5]:

$$\hat{\ddot{x}}(z) = \frac{\int_0^H \hat{P}_R(z)\phi(z)dz}{\int_0^H m(z)\phi^2(z)dz}\phi(z) \qquad \hat{P}_R(z) = g_R\sigma_{C_M}\overline{M}'\sqrt{\frac{\pi}{4\xi}C_M(f)}\,\frac{m(z)\phi(z)}{\int_0^H m(z)\phi(z)zdz} \qquad (1, 2)$$

where $\hat{P}_R$ is the resonant component of equivalent static wind loading, $\hat{M}_R$ is the resonant base bending moment, $\overline{M}'$ is the reference moment equal to $\frac{1}{2}\rho\overline{U}_H^2BH^2$ in which ρ is the air density, B is the width of the building, H is its height, $\overline{U}_H$ is the gradient wind speed, and the parameters σ_{C_M} and C_M are related to the spectra of the aerodynamic base moments and obtained from the website [5]. It is also possible to estimate response by employing the web-based on-line module [5]. The approach using the Aerodynamic Loads Database will be utilized in the uncertainty analysis discussed in Section 4.

3 UNCERTAIN PARAMETERS AND VARIABLES

3.1 *Wind Speed*

The wind speed used in the determination of wind-induced response has considerable uncertainty. In most cases, models for gradient wind speeds for most urban areas are based on surface level data collected at regional airports often a number of miles from the downtown zone. The extrapolation of this data to gradient or building height introduces additional uncertainty in the response prediction. As such, several uncertainty factors are used to describe the variability of modeling the wind, as outlined in Bashor, et al. [4], Kareem [6], and Minciarelli, et al. [7]. In the following analysis, these factors are defined as e_1 for the aerodynamic uncertainty associated with the use of scaled-models in wind tunnels, e_2 to account for the uncertainty introduced due to using model-scale versus full-scale data, e_3 to allow for transforming aerodynamic loads into structural load effects, e_4 accounts for observational errors in measuring wind speed, e_5 and e_6 assign uncertainty to the terrain exposure constants of ASCE 7, while e_7 and e_8 consider the uncertainty of the Aerodynamic Loads Database parameters [4]. The wind speed is assumed to be represented by a power law expression, using the parameters defined in ASCE 7.

While most of the random variables are modeled as either Gaussian or lognormal, the extreme wind speed must be modeled as an extreme value distribution, either Type I or Type III [7, 8]. The wind speed is customarily defined at a particular return period, assuming Type I distribution, as in Equation (4) in which the assumption in Equation (5) is commonly employed.

$$X_R \cong \lambda + \delta \ln(R) \qquad -\ln\left(-\ln\left(1-\frac{1}{R}\right)\right) \cong \ln(R) \tag{3,4}$$

where X_R is the wind speed, λ, δ are the mean and standard deviation. But as this approximation is only valid for large values of R ($R \geq 10$), it raises the question as to the appropriateness of this approximation to small values of R, such as $R = 1$.

3.2 *Damping*

Although there have been efforts to develop predictive tools for damping estimation based upon measured response in full-scale, there is considerable scatter in the derived values of damping, as well as a lack of information for buildings of significant height for which resonant response components dominate. Thus, rather generic damping values are assumed, resulting in designs with uncertainty regarding the building's ability to satisfy comfort criteria. It is evident that a reduction in the uncertainty of wind-induced loads and attendant response cannot be realized without addressing the uncertainty in structural damping, which is closely tied to the predicted accelerations of a structure and thus greatly affect the ability to meet occupant comfort criteria [3, 4].

3.3 *Human Comfort Threshold*

There is still much debate surrounding the levels of acceleration that are truly acceptable and how to quantify them. In many cases, the habitability design criteria defined with respect to these accelerations becomes the governing limit state of tall buildings. The perception of these motions increases with the frequency of vibration and can be affected by body position [1]. In light of these factors, a number of studies have attempted to quantify the acceptable levels of acceleration using both motion simulators and full-scale studies. Human response to building motion, which differs from person to person, depends on many cues, including the amplitude and direction of motion, visual observations, noise, and co-worker comments [1]. To define the human comfort threshold, there are two distinct categories of human response to motion: perception of motion and level of tolerance. Perception of motion is when an occupant first perceives the building's motion. Level of tolerance is the amount of motion the occupant is willing to tolerate before complaining. Two methods have been employed to identify the acceleration amplitude at which people begin to perceive motion: (1) motion simulator tests and (2) full-scale studies.

Motion simulators have been used to determine the threshold of perception in many studies (e.g., Chen and Robertson [9]). The results of these tests are often the basis for current standards; however, many of these early tests show discrepancies with actual building performance [10]. These discrepancies can be attributed to the uni-axial, sinusoidal motion used in the many motion simulator tests that do not represent the multi-directional, random motions created by wind [2, 10]. In addition to the differences in the motion itself, test subjects isolated in the small rooms used in motion simulators may lack the visual and audio clues contributing to motion perception in actual buildings [10]. There has been some effort to remedy these shortcomings.

While motion simulators provide a controlled environment for quantifying the levels of perceivable motion, full-scale studies can provide a far more realistic assessment of the levels of motion being perceived or those causing distress and discomfort, establishing a level of tolerance. The first study to evaluate human tolerance at a full-scale level was performed by Hansen, et al. [11] in which two buildings were studied after wind storms and a tentative criterion was established based on occupant surveys [11]. Follow up studies led to the development of the ISO 6897 (International Organization for Standardization) Standard which established guidelines for habitability in buildings [12]. In a further attempt to relate a building's motion to occupant comfort, a survey concerning Wind-Induced Accelerations of Tall Buildings was conducted by ASCE and CTBUH [13]. Currently, there are also online surveys being conducted by different research groups including ones available at http://www.nd.edu/~tallbldg/survey.html [14] and at http://www.wwtf.ust.hk/NewPage/MotionSimulator/Home.htm [1] which have the promise of adding to the understanding of occupant level of tolerance to building motions. The perception thresholds determined from the motion simulator and full-scale studies discussed previously, along with new criteria [15, 16], are summarized in Figure 2. These criteria typically focus only on lateral motions, even though it has been well-established that the presence of torsional motion can significantly increase perception of motion, even at low amplitudes [2, 13].

Since the issue of human comfort in tall buildings was introduced, there has been a debate over whether rms or peak acceleration is a more accurate descriptor. Until recently, North America used peak accelerations to establish the maximum allowable acceleration whereas most of the rest of the world used rms values. However, more recently, both AIJ and ISO have adopted frequency-based peak acceleration criteria [15, 16]. Advocates of the rms measure generally feel it better represents the sensations experienced by occupants in sustained events, as the duration and number of cycles of motion that occur above a threshold value may be more significant for occupants than an occasional high peak [2]. Advocates for the use of peak values contend that occupants are more dramatically affected by large events or peaks in the response [10]. Further-

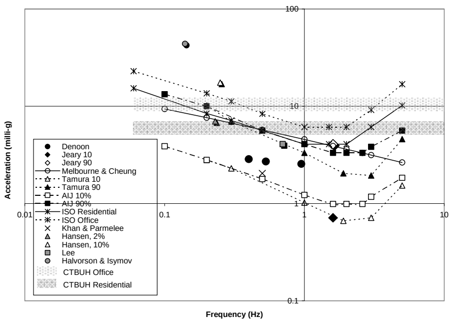

Figure 2 Comparison of Occupant Comfort: Perception Criteria for 1-Year Return Period.

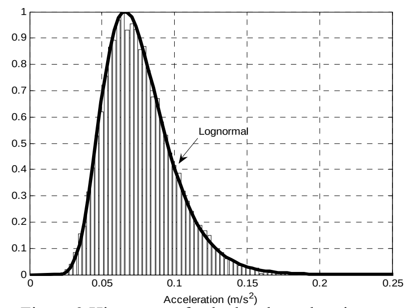

Figure 3 Histogram of calculated acceleration.

more, while the combination rules for rms response components are more straightforward than the peak values, rms criteria ignore the probability distribution of the peak accelerations, which may vary significantly.

This study also considers the uncertainty inherent in the habitability criterion itself, arising from its subjective nature and a number of additional factors that contribute to perception of motion [8]. In nearly all the perception studies, the probability density function (pdf) of the perception threshold was determined to be log-normal [4]. In addition, the average COV of the perception was found to be approximately 0.50. Another source of uncertainty is the modeling of the probability distribution of acceleration. Typically, acceleration is assumed to be Gaussian, leading to occupant comfort criteria based on peak accelerations that use Gaussian peak factors which may be different for other distributions [17].

4 UNCERTAINTY ANALYSIS FRAMEWORK

In a given problem, there are many variables with varying degrees of uncertainty. These uncertainties enhance the risk of failure in any of the design limit states, which is expressed in terms of probability of failure [8, 18]:

$$P_f = P(Z<0) = \int \dots \int_{g()<0} f_X(x_1, x_2, \dots, x_n)\, dx_1 dx_2 \dots dx_n \qquad (5)$$

where Z, the limit state, can be described as $Z = g(X_1, X_2, \dots, X_n)$. Several options exist to solve Equation (5), including a full distribution approach, analytical approximations to the integral, or simulation techniques [8]. Analytical approximations are often used and can vary in their level of computational effort e.g., First-Order Reliability Method (FORM) methods. Alternatively, Monte Carlo simulation can be utilized. In this framework, both of these approaches are used to determine the probability of failure.

To understand the extent to which the uncertainty in assumed levels of damping and other parameters affect the ability of a given design to satisfy any of the occupant comfort criteria, the probability of failure will be calculated with respect to the occupant comfort limit state. To do this, the limit state will be defined such that $Z = R - S$ where R will represent the occupant comfort criterion (capacity), expressed as an acceleration value, and S will represent the acceleration of a building at the top floors (demand). This framework is used so that uncertainty in damping and human sensitivity to motion, as well as other variables contributing to wind-induced response, can be propagated in the wind load-response-performance chain. The probabilistic parameters outlined in the previous sections and identified in Table 1 are used in the simulation of structural response. Although many of the pdfs and coefficient of variation (CoV) values can be ascertained from the literature [8], these parameters still need critical reassessment and refinement. In the case of damping and frequency, CoVs were determined by the analysis of data from the Chicago Full-Scale Monitoring Project. The CoV of the acceleration criteria was determined using the perception thresholds discussed in Bashor, et al. [4].

Examples are presented in the following for a building having the following features: H = 180 m, D = 30 m, B = 30 m, f_n = 0.2, ζ = 1%, ρ_{bldg} =180 kg/m^3. The building performance is assessed primarily in winds of return periods associated with serviceability/habitability. The building was assumed to be in Chicago and Tokyo to assess its performance under different conditions and criteria. In Chicago, the criterion for a 10-year wind was used leading to a corresponding 3-second wind speed at reference height of 34 m/s. For Tokyo a one-year return period acceleration criteria given by AIJ were used and the corresponding wind speed at reference height averaged over 3-seconds is 26 m/s [16].

Table 1 List of Variables for FORM Analysis and Monte Carlo Simulation with PDFs

Building Inputs				Calculated Variables Based on Inputs			
Name	Unit	Description	PDF	Name	Unit	Description	PDF
H	m	Building height	–	μ_U, σ_U	m/s	Wind speed parameters	Normal
B	m	Building width	–	EC	–	Exposure category	–
D	m	Building depth	–	α,b	–	Terrain exposure constants	–
m	kg/m	Mass per unit height	Normal	U	m/s	Wind speed	Gumbel
k	–	Mode shape exponent	Normal	H_{ref}	m/s	Reference height of wind	–
ζ	%	Damping ratio	Lognormal	T	s	Averaging time of wind speed	–
f	Hz	Natural frequency of building	Lognormal	ρ	kg/m^3	Air density	Normal
N	year	Return period	–	$\ddot{y}$	milli-g	Peak acceleration criteria	Lognormal
Variables Defining Uncertainty							
e_1	–	Errors associated with using scaled-models in wind tunnels	Normal	e_2	–	Use of model-scale versus full-scale	Normal
e_3	–	Transforming aerodynamic effects to structural load effects	Normal	e_4	–	Observation errors of wind speed	Normal
e_5	–	Uncertainty of b	Normal	e_7	–	Uncertainty of C_M	Normal
e_6	–	Uncertainty of α	Normal	e_8	–	Uncertainty of σ_M	Normal

4.1 *First-Order Reliability Method (FORM)*

The distribution of the calculated acceleration from a Monte Carlo simulation study was determined to be lognormal, as shown in Figure 3. Literature review suggests that the human comfort acceleration criteria have considerable uncertainty which has a lognormal distribution. Thus, the limit state may be approximately solved using FORM. In this case, the probability of failure is defined as:

$$p_f = \Phi(-\beta) \qquad \beta = \frac{\lambda_R - \lambda_S}{\sqrt{\varsigma_R^2 + \varsigma_S^2}} \qquad (6)$$

where $\Phi(x)$ is the cumulative distribution function of the standard normal distribution and λ, ς are lognormal distribution parameters that are functions of the mean and CoV. For the example buildings considered, the FORM probability of failures are tabulated in Table 2.

Table 2 Probability of Failure for examples using both FORM and Monte Carlo simulations

		Example in Japan with different % of people objecting		
	Example in Chicago	10%	50%	90%
Criteria	0.2 milli-g	0.028 milli-g	0.049 milli-g	0.098 milli-g
FORM	0.378	0.972	0.821	0.390
Monte Carlo	0.374	0.971	0.821	0.387

4.2 *Monte Carlo Simulation*

In the probabilistic framework, a Monte Carlo simulation is performed to determine the probability of failure different return periods. The probabilistic parameters outlined in the previous sections are used in the simulation of accelerations. The probability that the acceleration at the top of the building will exceed the criteria is calculated, providing an assessment of the performance of the building under the prescribed occupant comfort limit state. Analyzing the building under different conditions and different distributions provides further insight into the role of these uncertainties in the wind load-response-performance chain. Results of the example building are shown in Table 2. From the table, it is evident that the probabilities of failure calculated using

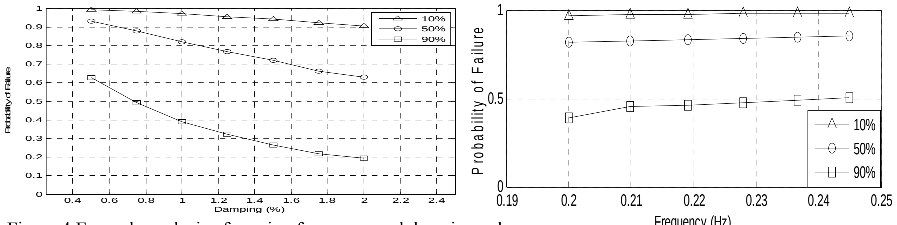

Figure 4 Example analysis of varying frequency and damping values.

FORM are very close to the probability of failure calculated with Monte Carlo simulations which validates approximate analysis for this example.

This framework allows the design to quickly check the habitability of the proposed building as well as investigate the habitability performance if parameters were modified. As an example, the buildings described previously are further investigated by modifying damping and frequency values. In Figure 4, the probability of failure with varying damping ratios and frequencies provides an indication of the impact of these parameters. It is interesting to note that the probability of failure actually slightly increases as frequency is increased due to the frequency-dependence of the AIJ criteria.

5 PROPOSED OCCUPANT COMFORT ASSESSMENT SCHEME

For the proposed occupant comfort assessment, a FORM-based analysis is used to account for the uncertainty in both the estimation of acceleration and the occupant comfort criteria. Equation (6) can be rewritten in the form:

$$A = \frac{\mu_R}{\mu_S} \qquad A = e^{\left[\beta\sqrt{\delta_R+\delta_S}+\frac{1}{2}(\delta_R-\delta_S)\right]} \qquad (7, 8)$$

where A represents the perception index, μ_R is the peak acceleration criterion and μ_S is the calculated acceleration, and δ_R, δ_S are the COVs of the acceleration criteria and calculated acceleration, respectively. From literature review, δ_R is taken as 0.5. When using the method described in Section 2, δ_S can be taken as 0.34. Assuming these COVs and following the perception indices suggested by Tamura et al. [16], the perception index or probability of failure for this assessment can be related to the occupants' reactions and consequences as defined in Table 3. Minor consequences are related to a small probability of failure and negligible economic consequences. Moderate consequences are related to a medium probability of failure and considerable economic consequences. Major consequences are related to a high probability of failure and significant economic consequences. The percentage of people objecting can be related qualitatively to the resulting probability of failure (accelerations exceeding criteria) in that as the acceleration criteria level increases, more people object to the motion, therefore, the probability of failure decreases. For example, for a given buildings' response, the probability of failure will decrease as more people must perceive the motion for failure to occur.

Table 3 Possible Occupants' Reactions and Consequences

Perception Index A	Probability of Failure	Possible Occupants' Reactions	Consequences
A < 1	pf > 0.54	Complaints will occur	Major
1 < A < 2	0.54 > pf > 0.136	Complaints may occur	Moderate
2 < A < 3	0.136 > pf > 0.035	Perceptible motion, but few complaints	Minor
3 < A	0.035 > pf	Not perceptible in majority	None

6 CONCLUDING REMARKS

To evaluate the performance of tall buildings for occupant comfort in light of uncertainties, a probabilistic framework is developed. This framework allows the user to determine the probability of a given building exceeding the habitability criterion. Due to the uncertainty associated with the wind load-response-performance chain, and the occupant comfort criterion itself, both FORM based analysis and Monte Carlo simulation are used to assess the probability of failure. A building under various environments and assumed parameters is analyzed to gain a better understanding of the roles these uncertainties have on occupant comfort. Finally, an occupant comfort based performance checking procedure is introduced that may lead to a practical probabilistic design procedure for evaluating habitability of tall buildings.

7 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the National Science Foundation through grant CMS 00-85109 and CMMI 06-01143.

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