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Design optimization on high-rise buildings considering occupant comfort reliability and joint distribution of wind speed and direction

Jiyang Fu[a], Qingxing Zheng[a,b], Youqin Huang[a,*], Jiurong Wu[a], Yonglin Pi[a,c], Qiongxiang Liu[b]

[a] Centre for Engineering Structure Disaster Prevention and Control, Guangzhou University, Guangzhou 510006, China
[b] Shenzhen General Institute of Architectural Design and Research Co., Ltd., Shenzhen 518031, China
[c] Centre for Infrastructure Engineering and Safety (CIES), School of Civil and Environmental Engineering, The University of New South Wales Sydney, NSW 2052, Australia

A R T I C L E I N F O

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A B S T R A C T

A new procedure for the wind resistant optimization of high-rise buildings considering the uncertainties of the wind speed, structural natural frequency and damping ratio, and the joint distribution of the wind speed and direction is proposed. The novelty of the procedure includes three aspects. Firstly, the modal acceleration responses of buildings are employed to evaluate the occupant comfort in the building instead of the commonly used total acceleration responses. This enhances the applicability of the proposed method and reduces the computation error by including the effect of the reoccurrence period of wind and avoiding calculation of the peak factor of response. Secondly, because the current method such as the modified Hasofer-Lind-Rackwitz-Fiessler (HLRF) algorithm is not suitable to the optimization design considering multiple wind directions, to overcome this problem, the design point method in generalized random space (DPG method) is used to establish equations of reliability for converting modal acceleration constraints to natural frequency constraints, in which an approach of mapping transformation is used to treat the non-normal variables. Thirdly, by improving the method of determining the limit of the wind speed based on the joint distribution of the wind speed and direction, the failure probabilities of modal accelerations under all wind directions are combined based on the joint probability distribution of the wind speed and direction to obtain the limit of natural frequency constraints. The parameters of the joint probability distribution are determined from the meteorological observation data of the wind speed. In association with the Optimality Criterion (OC) algorithm, the proposed method is applied in the wind resistant optimization of a 60-stories standard model of Commonwealth Advisory Aeronautical Research Council (CAARC). The investigations show that the proposed method can effectively decrease the structural total weight subject to reliability frequency constraints, displacement constraints and inter-story drift constrains. Considering the randomness of parameters and joint distribution of the wind speed and direction in the comfort constraint could enhance the design space for the structural total weight.

1. Introduction

The horizontal displacement and acceleration responses of a high-rise building subject to the horizontal load increase with its height. Excessive responses are detrimental to the normal service of the building and the occupant comfort in the building and even lead to the damage of structural members of the building. The horizontal load is mainly referred to the earthquake action and wind loading. Studies have shown that the wind load is the controlling factor in design of the concrete structures higher than 250 m and steel structures higher than 150 m [1]. Hence, the wind resistant optimal design of high-rise buildings has increasingly attracted attentions from researchers and structural designers [2,3]. The optimization design adjusts the sections of structural members of a high-rise building to reduce its construction cost in premise of assuring its structural safety. For this, Chan et al. studied the wind resistant optimization of high-rise buildings using the equivalent static wind loads (ESWLs), and established a systematic method for the optimal design of high-rise buildings considering wind effects on the building [4–11]. Since the occupant comfort is closely related to the acceleration response of high-rise buildings, Chan defined the acceleration as the main constraint of the optimization, and further converted the acceleration constraint to the frequency constraint to reflect the dynamic essence of the acceleration. The method adopted by Chan considers the total acceleration response calculated by the peak factor and the root-mean-square of modal accelerations. Because the value of the peak factor has to be calculated using load codes and thus

* Corresponding author.
E-mail address: yqhuang@gzhu.edu.cn (Y. Huang).

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varies from country to county, Chan's method is restricted by the variations of the different values of the peak factor and may cause errors in some cases.

Based on Chan's work, Huang et al. carried out the performance-based reliability optimization by including the uncertainties of the wind speed, structural frequency and damping ratio in the explicit expression of accelerations by the modified Hasofer–Lind–Rackwitz–Fiessler (HLRF) algorithm [12–16]. The HLRF algorithm proposed by Hasofer and Lind [17] for the first-order second-moment reliability analysis and later extended by Rackwitz and Fiessler [18] is often used to solve the reliability optimization problem. In HLRF algorithm, the reliability index is defined as the minimum distance from the origin of coordinates in the standard normal space to the limit state surface, which is determined by the limit state equation including random variables. If the random variables don't follow the normal distribution, according to the condition of equivalent normalization, the non-normal random variables are equalized to normal random variables at the design point using the equivalent normalization method proposed by Rackwitz and Fiessler [18]. Finally, the iterative calculation of reliability indices is performed by linearizing the nonlinear limit state equation at the design point and then computing by the Newton's method. The HLRF algorithm is recommended by the Joint Committee of Structural Safety (JCSS), owing to that it has fast convergence for most situations and that it is easy to be accepted by engineers. However, the algorithm may converge slowly or even diverge when the limit state equation is highly non-linear. A modified HLRF algorithm employed by Huang [15] for tackling the non-normal random variables is proposed by Liu and Kiureghian [19] to improve the convergence with a merit function. Although the modified HLRF algorithm performs better than HLRF, it does not always generate a globally convergent sequence, especially for solving the more complicated optimization problem considering effects of multiple wind directions, which is worth investigating and will be studied in this paper.

In addition, since the database of the wind load is not sufficient for fully understanding the complexity and uncertainty of the wind load, the load codes in most countries adopt the most unfavorable rule in computing wind effects on structures [20,21]. However, the most unfavorable model corresponding to the most unfavorable wind direction is conservative in determining the wind load acting on buildings in the real wind environment because the distribution and occurrence probability of wind speeds are quite different in various wind directions. Previous studies have shown that the effect of wind directions needs to be considered and the most reasonable way to describe the wind loading is to construct the joint distribution function for the wind speed and direction [22–28]. Spence et al. [29–32] considered the joint distribution of the wind speed and direction in wind resistant optimization, in which constraints on the failure probability of structural responses are constructed under the ultimate wind speed based on the joint distribution model proposed by Davenport [23,33]. However, constraints on wind-induced structural accelerations were not considered in [29–32], and the joint distribution of the wind speed and direction is considered only in determining the ultimate wind speed, but not for the structural acceleration. Additionally, Ciampoli and Petrini [34] assessed the occupant comfort requirement with a joint probability density function of the mean wind velocity and dominant direction, but the assessment has not been applied to the wind resistant optimization of high-rise buildings hitherto.

In this work, the modal acceleration is directly used to reflect the occupant comfort in high-rise buildings, which avoids the error caused by approximately computing the total acceleration, and also increases the applicability of the optimization design in many different cases. The design point method in the generalized random space (DPG method) is considered as a reliability-based method and can be applied for more complicated reliability optimization problems [35,36]. The principle of the DPG method is similar to the HLRF algorithm, and the difference between the two methods is the treatments of non-normal random variables. The mapping transformation method is employed in the DPG method while the modified HLRF algorithm uses the equivalent normalization method [18,35–38]. When the mapping transformation method is used, original non-normal random variables are replaced by standard normal random variables in the generalized random space based on the principle of isoprobabilistic transformation prior to the structural reliability analysis [35,36]. The DPG method, therefore, is mathematically more rigorous and suitable for the derivation and analysis of complex structural reliability problems, such as the present wind resistant optimization problem with high nonlinearity and continuous types of random variables.

In addition, the theory of joint distributions of wind speeds and directions is further introduced to obtain the mean natural frequency, which is the probabilistic constraint limit of the natural frequency corresponding to the horizontal acceleration of high-rise buildings. The constraint conditions of the natural frequency in association with the algorithm of Optimality Criterion (OC) are finally applied in the wind resistant optimization on a standard model of high-rise buildings to achieve an optimum balance between the structural safety and the construction cost.

2. Reliability analysis on acceleration response in single wind direction

It is usually considered that motion-induced loss of occupant comfort is usually related with peak (or RMS) values of the floor accelerations of the building, and does not depend on the reoccurrence period of wind speed [39–43]. However, because the horizontal acceleration criteria for the worst 10 consecutive minutes in a 5 year reoccurrence period for buildings as a function of frequency are specified in ISO 6897 [44], Melbourne and Palmer [45] proposed a new acceleration criteria for occupant comfort by including the reoccurrence period of the wind speed and showed that there are different acceleration criteria corresponding to the different reoccurrence periods. Based on the new criteria proposed by Melbourne and Palmer [45], a new procedure accounting for the largest allowable modal horizontal acceleration is herein presented to deal with the acceleration constraint in the wind resistant optimization of high-rise buildings from a viewpoint of reliability analysis.

2.1. The reliability equation for modal acceleration

For a high-rise building, the j-th modal acceleration can be approximately calculated by [9]

$$\sigma_{\ddot{q}_j}^2 \approx S_{F_jF_j}(f_j)\frac{\pi f_j}{4m_j^2\zeta_j} \tag{1}$$

where $\ddot{q}_j$ and $\sigma_{\ddot{q}_j}$ denote the j-th modal acceleration response and its root-mean-square, respectively; $S_{F_jF_j}(f_j)$ represents the auto-spectrum of the j-th modal force; f_j, m_j and ζ_j denote the j-th natural frequency, modal mass and damping ratio of the building, respectively.

Non-dimensioning the auto-spectrum of modal force and fitting its descending segment leads to

$$\frac{fS_{F_jF_j}(f)}{(0.5\rho V^2BH)^2} = \beta_j\left(\frac{fB}{V}\right)^{\alpha_j} \tag{2}$$

where ρ and V denote the density and speed of the wind, B and H are the width of the windward side and height of the building, and α_j and β_j are the fitting coefficients.

Substituting Eq. (2) into Eq. (1) yields the explicit expression of the modal acceleration related to the natural frequency, damping ratio and wind speed as

$$\sigma_{\ddot{q}_j}^2 = (0.5\rho V^2BH)^2\pi\beta_j\left(\frac{f_jB}{V}\right)^{\alpha_j}/4m_j^2\zeta_j \tag{3}$$

Meanwhile, if first 3 modes are considered, the peak acceleration of