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Inelastic responses of wind-excited tall buildings: Improved estimation and understanding by statistical linearization approaches

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ABSTRACT

Two statistical linearization approaches are used to determine the inelastic response statistics of wind-excited tall buildings with bilinear hysteretic restoring force character. Their accuracy and effectiveness are illustrated though the comparison with the predictions from response time history simulations. The statistical linearization approaches give good estimations of response standard deviation (STD), extreme value distribution and fatigue damage, while discrepancies are observed when the inelastic behaviour is significant that leads to hardening non-Gaussian response distribution. The results demonstrate that the inelastic response with zero mean component is lower than that of corresponding elastic system attributed to the increase in system damping resulted from the hysteretic restoring force. The ductility factor and reduction in response increase with the decrease in yield displacement, especially, for flexible tall buildings. On the other hand, when response has non-zero mean component under static load, the yielding results in displacement drift and the inelastic displacement is featured by stochastic drift and fluctuating components. The time-varying mean response can be calculated from state-space equation of motion, and its steady-state value is determined by the mean load and second stiffness. While the hysteretic damping results in reduction of the fluctuating response, the increase in the mean component can lead to total inelastic response noticeably higher than that of the corresponding elastic system. The results of this study help in developing improved understanding of inelastic building response under ultimate wind loads, contributing to achieve safer and more economical performance-based design of buildings beyond the current linear elastic framework.

1. Introduction

Current tall building design to ultimate wind loads is based on linear elastic design framework. The safety and reliability of tall buildings beyond linear elastic limit is unclear. The development of performance-based wind engineering requires evaluation of building performance under various levels of wind hazards including inelastic response (e.g., [21,16,15,32]. Permitting controlled inelastic responses of some building members under ultimate limit state, while ensuring elastic response under serviceability limit state may bring innovative building design solutions to wind loading with improved performance and economics. Furthermore, some of the damping devices used for response reduction can have nonlinear hysteretic restoring force characteristics (e.g., [23,30,20]. Buildings with base isolation systems also show nonlinear hysteretic behaviour [24]. Performance assessment of these tall buildings against wind loading requires prediction of inelastic response.

The inelastic response of wind-excited structures has been explored in literature [36,13,27,34,33,17,21]; [12]; [4,22,26,18,32]. The alongwind response of elasto-plastic single degree of freedom (SDOF) structures was calculated in Vickery [36] using a simplified equivalent elastic system approach. The inelastic behaviour of low-rise building elements under wind load excitations was examined in Georgiou et al. [13]. Hong [17] examined the damage rate and ductility demand of alongwind response of bilinear SDOF systems through response history analysis (RHA). The results showed that the ductility demand of flexible structures could be much less than that of rigid structures. The alongwind inelastic RHA of bilinear structures was further carried out in Gani and Légeron [12]. The relationship between natural frequency and strength reduction factor for a given constant ductility factor was established, confirmed that flexible structures benefit more from ductility effect than rigid structures. Judd and Charney [22] carried out incremental dynamic analysis to investigate collapse risk of a SDOF building under alongwind and crosswind loadings. The inelastic alongwind response of SDOF structures under nonstationary wind was discussed in Hong [18] through RHA.

The bilinear crosswind response of tall buildings was investigated in Ohkuma et al. [27] based on RHA considering the fundamental building

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mode. An energy-based framework to estimate inelastic response using an equivalent elastic system was proposed with the estimation error within 20%. Tsujita et al. [34] investigated both alongwind and crosswind responses of tall buildings with bilinear restoring force character for the generalized forces, and proposed approximate analysis approaches on the basis of peak response distribution. Tamura et al. [33] used finite element models of two-dimensional (2D) multi-story building frames for examining the inelastic crosswind building response. Beck et al. [4] addressed the optimal stiffness of a hysteretic multi-degree-of-freedom (MDOF) RC building subjected to zero-mean wind load excitation. An exploratory wind tunnel study was carried out by Mooneghi et al. [26] to study the tall building response beyond elastic limit. The elasto-plastic reliability of alongwind-excited structures with uncertainties was evaluated by Tabbuso et al. [32]. The inelastic response of tall buildings with hysteretic dampers and base isolation systems has been studied in Sato et al. [30], Katagiri et al. [24] and Ikegami et al. [20] through wind tunnel testing and RHA.

This study presents a statistical linearization technique for the analysis of statistics of inelastic response of tall buildings. While RHA approach can in general provide more accurate results, the linearization approach is computationally more effective. The generalized restoring modal force is described by bilinear hysteretic restoring force model with building response represented by fundamental mode. Other hysteretic restoring models can also be used. The wind loading is characterized by the power spectrum of base bending moment coefficient that was determined based on wind tunnel measurement or load specifications. The response statistics are quantified through statistical linearization approaches, and their accuracy is illustrated through comparison with response time history simulations. The characteristics of inelastic response and the influence of mean wind load are examined through a comprehensive parametric study for both crosswind and alongwind responses. It should be mentioned that the theory of random inelastic response analysis of hysteretic systems with use of statistical linearization approaches has been extensively addressed in literature (e.g., [2,3,25], where the nonlinear restoring force is often described by Bouc-Wen model [37,38]. However, their applications to wind-induced response of tall buildings have not yet been well explored. New insights are provided toward improved understanding of inelastic building response under ultimate wind loads based on an extensive parametric study.

2. Theoretical framework

2.1. Equation of building motion

The equation of wind-induced building motion in terms of first modal response is expressed as:

$$M_s\ddot{x} + 2M_s\omega_s\xi_s\dot{x} + f(x,\dot{x}) = Q(t) \tag{1}$$

$$M_s = \int_0^H m(y)\phi^2(y)dy; \quad Q(t) = 1/2\rho U_H^2 BH^2\eta C_M(t)/H \tag{2}$$

where x is generalized (modal) displacement; M_s and ξ_s are generalized mass and damping ratio; $\omega_s = 2\pi f_s = \sqrt{k/M_s}$ is modal frequency calculated by using the initial generalized stiffness k; $f(x,\dot{x})$ is generalized restoring force; $Q(t)$ is generalized force estimated from base bending moment; $m(y)$ is building mass per unit height; $\phi(y)$ is mode shape function; η is mode shape correction factor and is unit for linear mode shape; ρ is air density; U_H is wind speed at building top; B and H are building width and height; and $C_M(t)$ is base bending moment coefficient.

The restoring force $f(x,\dot{x})$ shown in Fig. 1 is described by the following bilinear hysteretic force model (e.g., [25]:

$$f(x,\dot{x}) = \alpha kx + (1-\alpha)kz \tag{3}$$

$$\dot{z} = \dot{x}\{1-u(z-x_y)u(\dot{x})-u(-z-x_y)u(-\dot{x})\} \tag{4}$$

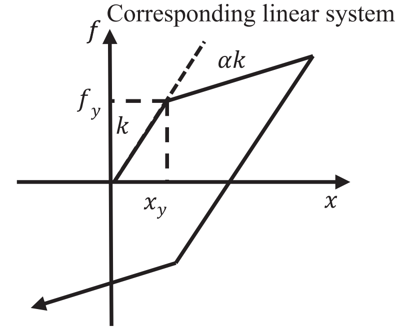

Fig. 1. Bilinear hysteretic restoring force model.

where x_y is yield displacement; α is second stiffness ratio to the initial stiffness; z is hysteretic displacement; and $u(\cdot)$ is unit step function. In the case of linear elastic system, $z = x$.

Eqs. (1)–(4) can be written in a state-space format as

$$\dot{\boldsymbol{q}} = \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}Q \tag{5}$$

$$\boldsymbol{q} = \begin{bmatrix} x \\ \dot{x} \\ z \end{bmatrix}; \quad \boldsymbol{g}(\boldsymbol{q}) = \begin{bmatrix} \dot{x} \\ -\alpha\omega_s^2 x-2\omega_s\xi_s\dot{x}-(1-\alpha)\omega_s^2 z \\ \{1-u(z-x_y)u(\dot{x})-u(-z-x_y)u(-\dot{x})\}\dot{x} \end{bmatrix}; \quad \boldsymbol{D} = \begin{bmatrix} 0 \\ 1/M_s \\ 0 \end{bmatrix}$$

Introducing the non-dimensional parameters and variables:

$$t^* = \omega_s t; \quad x^*(t^*) = \frac{x(t)}{x_y}; \quad z^*(t^*) = \frac{z(t)}{x_y}; \quad x^{*'}(t^*) = \frac{dx^*(t^*)}{dt^*} = \frac{\dot{x}(t)}{\omega_s x_y}; \quad x^{*''}(t^*) = \frac{d^2x^*(t^*)}{dt^{*2}} = \frac{\dot{x}(t)}{\omega_s^2 x_y}; \quad z^{*'}(t^*) = \frac{dz^*(t^*)}{dt^*} = \frac{\dot{z}(t)}{\omega_s x_y}; \quad Q^*(t^*) = \frac{Q(t)}{kx_y} \tag{6}$$

the equation of motion is then expressed in the non-dimensional equation as:

$$x^{*''} + 2\xi_s x^{*\prime} + \alpha x^* + (1-\alpha)z^* = Q^*(t^*) \tag{7}$$

$$z^{*'} = x^{*'}\{1-u(z^*-1)u(x^{*'})-u(-z^*-1)u(-x^{*'})\} \tag{8}$$

It is evident that the non-dimensional inelastic response is determined by three non-dimensional parameters: damping ratio ξ_s; stiffness ratio α and normalized generalized force Q^*. The response time history can be computed using a step-by-step integration method, or Runge-Kutta method. In the following, the statistical linearization technique is used to define an equivalent linear system for which the response statistics can be directly calculated.

For the inelastic wind-induced response of tall buildings addressed in this study, the reduction of building frequency due to inelastic behaviour is negligibly small. While the traditional modal analysis is theoretically no longer valid for inelastic system, the inelastic response can still be decomposed into modal responses of linear elastic system. It is reasonable to assume that the inelastic response is dominated by the fundamental modal response similar to the elastic response. The new interpretation of modal analysis for inelastic system has led to the development of modal pushover analysis of buildings to seismic excitations [8]. In this study, the uncoupled inelastic crosswind and alongwind responses of tall buildings are addressed. Similar to elastic response, the alongwind and crosswind responses can be considered to be uncorrelated and discussed separately. The resultant response is then estimated by combining the contributions of alongwind and crosswind responses using square-root-of-sum-of-squares (SRSS) rule.