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Extended spectrum-based pushover analysis for predicting earthquake-induced forces in tall buildings

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ABSTRACT

Achievements have been made in the development of effective and accurate simplified methods for predicting the seismic demand of tall buildings. However, most of these methods are primarily focused on the estimation of seismic deformation of buildings, while no analysis and calculation of earthquake-induced forces in the structures have been presented. Based on the spectrum-based pushover analysis (SPA) for estimating the seismic demand of tall buildings, where the complicated vibration mode coupling in the nonlinear vibration of structures is simplified, an extended spectrum-based pushover analysis (ESPA) is developed for the fast prediction of earthquake-induced forces of tall buildings. In ESPA, a linear response spectrum analysis procedure is incorporated into SPA to consider the modal combination in the linear stage of vibration. A case study of two high-rise, special steel moment-resisting frame buildings subjected to different levels of ground-motion intensity is conducted to investigate the applicability and accuracy of the ESPA method. Comparisons of the results of earthquake-induced forces are made among ESPA, nonlinear response time history analysis (NLRHA), N2 method, modal pushover analysis (MPA) and consecutive modal pushover analysis (CMP). It is seen that the earthquake-induced forces, including bending moments and shear forces, predicted by the proposed ESPA method agree very well with those of NLRHA.

1. Introduction

The performance-based design procedure is widely used in both design and evaluation of the performance of building structures under seismic action. In seismic performance-based design, the building deformation is a control parameter that governs the overall seismic performance of buildings. During the past decades, many research efforts have been devoted to the fast prediction of seismically induced deformations for the seismic evaluation of building structures [1–18]. In the 1990s and early 2000s, conventional pushover analysis methods, including the N2 method [1] and capacity spectrum methods [2–5], were developed for evaluating the seismic demand of buildings, where buildings are treated as a single-degree-of-freedom system. However, the higher mode effect significantly affects the seismic performance of a tall building, thus the conventional pushover methods are not suitable for estimating the seismic demand of tall buildings. To estimate the seismic demand accurately, advanced pushover methods were developed with considering the effect of higher modes [6–17]. By ignoring the interaction of the modes in nonlinear vibration of structures and assuming the final demand of tall buildings are the combination of nonlinear response of different modes, modal pushover analysis (MPA) method [11,12] was developed, which provides a much better estimate of the seismic demand than the conventional pushover analysis method. On the other hand, the consecutive modal pushover analysis (CMP) [13], where structures were consecutively subjected to forces with mode-shape distributions and the seismic demand of modes is not separately considered, provides a more accurate estimate of the seismic demand of tall buildings, as compared with the conventional pushover analysis methods. Recently, a method of spectrum-based pushover analysis (SPA) [16] was proposed with simplifying the coupling effect of vibration modes, which provides an efficient, yet accurate, estimate of the seismic demand and earthquake-induced deformations of tall buildings.

In addition, it is of equal importance to estimate earthquake-induced forces in tall buildings [20,21]. However, most of the methods of advanced pushover analysis mentioned above are only primarily focused on the calculation of earthquake-induced deformations; few of them are practically used for calculating earthquake-induced forces in tall buildings [15,19].

In the paper, a method of analysis, named as the extended spectrum-

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based pushover analysis (ESPA), is proposed based on the SPA procedure [16] for the fast and accurate estimation of earthquake-induced forces in tall buildings. In ESPA, a linear response spectrum analysis procedure is added into the SPA procedure, counting for the combination of modal forces in the linear stage. Two special steel moment-resisting frames (SSMRF) that have different structural heights were studied under different ground-motion intensities to investigate the applicability and accuracy of the ESPA method. A comparative study of NLRHA and different methods of pushover analysis, including N2, MPA, CMP and the proposed ESPA method was conducted. It is shown from the comparative study that the ESPA method can estimate the earthquake-induced forces very well, while the accuracy of the ESPA method is comparable with that of the code required NLRHA method.

2. Method of spectrum-based pushover analysis (SPA)

The equation of motion of an N-degree of freedom system subjected ground motion is given by

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -\mathbf{m}\mathbf{i}\ddot{u}_g(t) \tag{1}$$

where $\mathbf{u}$ is the displacements vectors, $\mathbf{m}$, $\mathbf{c}$ and $\mathbf{k}$ are the mass, classical damping and stiffness matrices of the system, respectively, and $\ddot{u}_g(t)$ is ground acceleration. Since lateral force is independent of the loading history, by assuming that $u(t) = \sum_{n=1}^{N} \phi_n q_n(t)$, where ϕ_n is the mode shape of nth mode of vibration and $q_n(t)$ is modal coordinator, Eq. (1) is decoupled and can be expressed as a summation of motion equations of vibration modes, which are independent of each other and can be solved separately. When the structure yields, the lateral force is dependent of the loading history,

$$F_s = F_s(\mathbf{u}, t) \tag{2}$$

Thus, the equation of motion of a nonlinear system is written as

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + f_s(\mathbf{u}, sign\dot{\mathbf{u}}) = -\mathbf{m}\mathbf{i}\ddot{u}_g(t) \tag{3}$$

It is well known that vibration modes are dependent of each other in the nonlinear vibration of structures, and the decoupled method in solving Eq. (1) is not applicable. To consider the coupling of modes while keeping the efficiency of the pushover method, it is assumed in the SPA method [16] that under the action of earthquakes, vibration modes of the structure start in a row that when the ith vibration mode starts, the roof displacements of all the previous modes have got to the target values and the structural conditions, including internal stress and strain of ith mode keep unvaried after the roof displacement of ith mode reaches the target value, so as to simplify the mode coupling in the nonlinear state. In the SPA method, modal pushover analysis procedures are performed consecutively to reproduce the structure state and obtain the seismic demand. These consecutive pushover procedures are that after completing one pushover analysis, the initial structural state, including stress and strain, of next pushover procedure is the same as that at the end of previous pushover analysis procedure. Forces with distribution of mode-shape are used to carry out the pushover analysis. The sequence of different pushover procedures is from the 1st mode to higher modes. The SPA method includes modes fulfil the following condition,

$$\lambda_n = \frac{m_{eff}}{\sum_{i=1}^{N} m_j} = \frac{1}{\sum_{i=1}^{N} m_j} \frac{L_n^2}{M_n} \geqslant 1\% \tag{4}$$

where λ_n is effective modal participating mass ratio; $\sum_{i=1}^{N} m_j$ is the sum seismic mass and L_n can be calculated by

$$\Gamma_n = \frac{L_n}{M_n}, \quad L_n = \phi_n^T \mathbf{m}\mathbf{i}, \quad M_n = \phi_n^T \mathbf{m}\phi_n \tag{5}$$

The overall estimated total roof target and the target roof displacement of ith pushover procedure can be obtained as

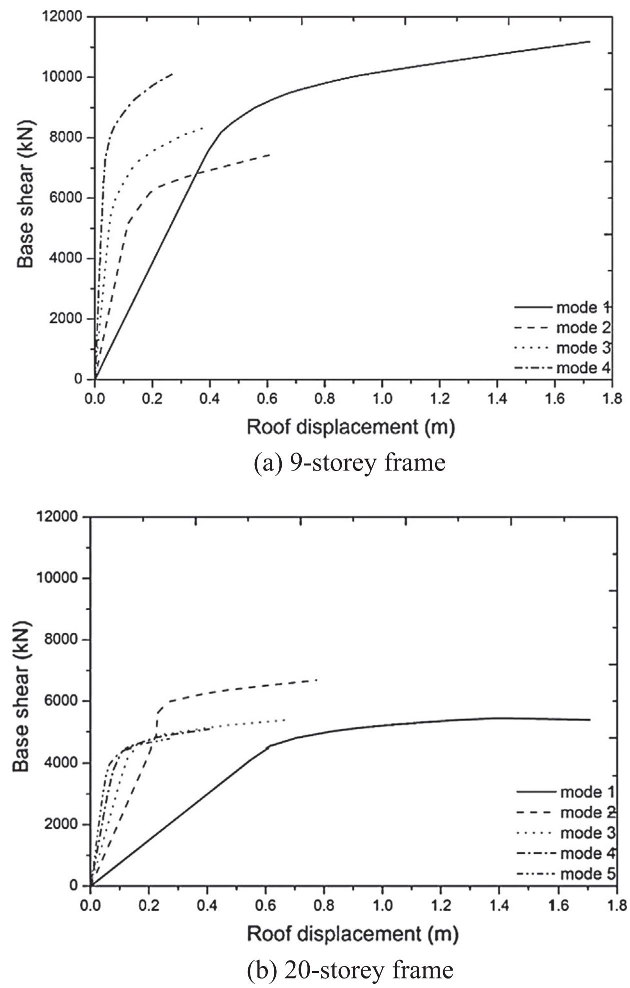

Fig. 1. Base shear-roof relations of two structures.

$$u_{r0} \approx \left(\sum_{i=1}^{N} (u_{ri0})^2\right)^{0.5} = \left(\sum_{i=1}^{N} (\beta_i |\Gamma_i| \phi_{ri} D_i)^2\right)^{0.5} \tag{6}$$

$$u_{ir} = \alpha_i \times u_{r0} \tag{7}$$

where u_{ro} is the overall estimated roof displacement of the structure; D_i is the spectrum displacement of ith mode; α_i is the roof displacement contribution factor of ith mode; u_{ir} is the estimated target roof displacement of ith mode; β_i is a roof displacement reduction factor that can be calculated by

$$\beta_i \simeq \begin{cases} 1.0, i = 2,3,...,N \\ \cos(\omega_1 \times t_{N-1}) = \cos\left[\omega_1 \times \left(\frac{-\pi}{2 \times \omega_{N-1}}\right)\right], \quad i = 1 \end{cases} \tag{8}$$

where ω_1 and ω_{N-1} are the natural frequency of first mode and $(N-1)$th mode respectively; t_{N-1} is the time point that $(N-1)$th mode of vibration should start to ensure that all the modes have the target roof displacements at the same time. As for the roof contribution factor α_i, it should include modal participation factor and dynamic input, as well as the reduction factor β_i. Thus, the target roof displacement contribution factor of ith mode is expressed as

$$\alpha_i = \frac{u_{ri0}}{\sum_{i=1}^{N} u_{ri0}} = \frac{\beta_i |\Gamma_i| \phi_{ri} D_i}{\sum_{i=1}^{N} \beta_i |\Gamma_i| \phi_{ri} D_i} \tag{9}$$

According to the previous study, the SPA method is capable of estimating the earthquake-induced deformation with high accuracy and efficiency.