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A non-adaptive displacement-based pushover procedure for the nonlinear static analysis of tall building frames

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ABSTRACT

In order to account for the effect of higher modes in estimating the seismic demands of tall buildings, a non-adaptive displacement-based pushover (NADP) procedure based on structural dynamics theory is presented in this paper. The procedure utilizes some single-run conventional and enhanced pushover analyses. The single-run conventional pushover analysis is carried out using a displacement-based load pattern according to the first mode shape, whereas the single-run enhanced pushover analyses are performed by employing the lateral load distributions obtained by combining the modal story displacements. The modal story displacements are algebraically added; therefore, the signs of modal displacement vectors are retained and the sign reversals in the lateral load distributions are included. Since the NADP is performed in a non-adaptive framework, it does not require more computational effort and time cost. Furthermore, a new method for the determination of the target displacement for tall buildings is proposed using the response spectrum analysis (RSA). To evaluate the NADP procedure, three steel moment-resisting frames with different heights as well as a 9-story SAC building frame were selected. The seismic demands resulting from the NADP procedure were compared to those from the nonlinear response history analysis (NL-RHA) as a benchmark solution, as well as to those predicted by the modal pushover analysis (MPA) and displacement-based adaptive pushover (DAP) procedures. The results demonstrate that the NADP procedure can accurately estimate the seismic demands at the upper stories of tall buildings in which the effect of higher modes is substantially significant.

1. Introduction

Nonlinear response history analysis (NL-RHA) is the most accurate analytical procedure to estimate the seismic demands of structures responding in the nonlinear range. However, this procedure is relatively complicated and time-consuming. On the other hand, the nonlinear static procedure (NSP) or pushover analysis is widely used as a suitable tool for the seismic performance evaluation of building structures [2]. Earlier versions of pushover methods presented in various codes [13,6,5], are limited to the first-mode-dominated structures, and they cannot take the effect of higher modes into consideration [17,8]. Therefore, much research effort has been devoted in recent years to the development of enhanced pushover procedures to consider the effect of higher modes.

Chopra and Goel [8,9] proposed the modal pushover analysis (MPA) based on structural dynamics theory. This method uses an invariant modal lateral force distribution for implementing the pushover analysis for each mode, and the results obtained for each mode are combined with an appropriate modal combination rule. Plastic hinge rotations derived from this method are greatly underestimated at the upper stories of tall buildings, even if a large number of modes are included [8,24,25]. A modified version of the MPA (MMPA) was proposed by Chopra et al. [10], wherein the response contributions of higher vibration modes were computed with the assumption that the building remains linearly elastic. About the same time, an upper-bound pushover analysis procedure [14] was developed in which the upper-bound of the contribution ratio of the second mode in computing the lateral force distribution was used. In another investigation, the mass proportional pushover procedure (MMP) was proposed by Kim and Kurama [16] without any modal combination. In this method, the effect of higher modes is lumped into a single invariant lateral force distribution that is proportional to the total seismic masses at the floor and roof levels.

Later on, the consecutive modal pushover (CMP) procedure was proposed by Poursha et al. [24,26,27] to take higher modes effect into account. Multi-stage and single-stage pushover analyses are utilized in this procedure. The final responses are estimated by enveloping the results obtained from the multi-stage and single-stage pushover analyses. In another study, Kreslin and Fajfar [18]

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extended the N2 method [11] to take the effect of higher modes into account. The basic assumption is that the structure remains in the elastic range in higher vibration modes. In this method, the seismic demands are determined by enveloping the results of basic pushover analysis and those from elastic modal analysis. The estimation of plastic hinge rotations was not demonstrated with the aid of the EN2 method. About the same time, a generalized pushover analysis (GPA) procedure [31] was proposed, in which a set of pushover analyses was carried out by using different generalized force vectors. Each generalized force vector is obtained as a different combination of modal forces in order to simulate the effective lateral force distribution when the inter-story drift at a selected story reaches its maximum value during response history. Finally, the maximum value of a seismic response is obtained by enveloping the values produced by the GPAs.

More recently, a single-run multi-mode pushover (SMP) analysis [28] was proposed to account for the effect of higher modes in estimating the seismic demands of tall buildings. In this procedure, the effect of higher modes is concentrated into a single invariant lateral force distribution computed by algebraically adding the modal story forces whereby a single-run multi-mode pushover analysis is implemented. An important advantage of the SMP procedure is that the sign reversal in the story forces of higher modes is taken into account. The accuracy of some enhanced nonlinear static procedures in estimating deformation demands of regular and irregular steel moment-resisting frames was investigated by Ferraioli et al. [12].

All of the above-mentioned enhanced pushover procedures are force-based pushover analyses. However, because of the present tendency for the development and implementation of displacement-based design and assessment methods, it would seem that applying displacement loading, rather than force actions, in pushover methods would be theoretically a proper option for the nonlinear static analysis of structures [4,23]. Therefore, attempts have been made to develop displacement-based pushover procedures in recent years.

Antoniou and Pinho [4] developed a displacement-based version, called displacement-based adaptive pushover (DAP), as the counterpart of their force-based adaptive pushover (FAP) procedure [3] to improve the prediction of seismic demands of building structures. In the FAP method, the lateral load pattern is calculated at each step by combining the story forces of each vibration mode using an appropriate combination rule. However, because of implementing a quadratic modal combination rule to combine the modal loads, the effect of sign reversal in the higher modes forces is not taken into consideration in the applied load pattern. Therefore, the DAP procedure was developed in which at each step a displacement loading is applied rather than force actions. In this method, the story forces are calculated as a response of the applied displacement loads and the reversal of sign in the story force profile can be taken into account. Seismic demands of the structures predicted by the DAP procedure were better than those from the FAP [4].

Recently, a displacement-based adaptive modal pushover method, called APAM, was developed that is based on effective modal mass combination rule [1]. In this combination rule, a modification factor associated with each mode is applied to the corresponding load vector. The modified modal load vectors are algebraically added and subtracted, and give a range of load patterns. These load patterns are independently applied to the structure within an adaptive framework and the seismic demands are determined by enveloping the demand values obtained from different pushover analyses.

These displacement-based pushover procedures may provide accurate seismic responses; nevertheless, because of their adaptive nature, an eigenvalue analysis is required to be implemented at each loading increment. Therefore, they require more computational effort and time cost. Moreover, only lateral displacements as well as story drifts were estimated by using the DAP and APAM methods, and the prediction of plastic hinge rotations has not been examined with the aid of these methods. It is important to note that in another research the last version of the MPA method [29] was introduced in which a non-adaptive displacement-based pushover analysis was employed to estimate plastic hinge rotations from the story drifts. For this purpose, a set of displacements compatible with the calculated story drifts is applied at the center of mass of the building.

The main objective of the present study is to develop a non-adaptive displacement-based pushover (NADP) procedure to take higher modes effect into consideration in estimating the seismic responses of tall building frames. In this new procedure, the seismic demands are calculated by enveloping the results obtained from two or three single-run displacement-based pushover analyses. The major simplification of this method is that the effect of higher modes is concentrated into a single invariant lateral displacement distribution as a load pattern. Consequently, only single-run non-adaptive pushover analyses are sufficient without any need to apply a modal combination rule to the results. An advantage of the proposed method is that the spectral displacement of ground motions is incorporated into the lateral load distribution. Moreover, the NADP procedure not only reduces the computational cost compared to adaptive pushover analyses, but also can provide an accurate prediction of seismic demands at the upper stories of tall buildings. In the present study, a new method for the determination of the target displacement in pushover analysis of tall buildings is also proposed. The NADP method is verified for four steel moment-resisting frames. The seismic demands obtained by the NADP procedure are compared with those from the NL-RHA as the most accurate method of seismic demand evaluation, as well as with those predicted from the MPA and DAP procedures.

2. Proposed pushover procedure

This section presents a non-adaptive displacement-based pushover procedure to evaluate the seismic demands of tall building frames. In the following, the basic principles of the proposed procedure are described.

2.1. The conceptual basis of modal response analysis

The differential equations governing the response of a multi-degree-of-freedom (MDOF) system to earthquake-induced ground motion are given by [7]:

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

where $\boldsymbol{m}$, $\boldsymbol{c}$, and $\boldsymbol{k}$ are the mass, damping, and stiffness matrices of the structure, respectively, and $\boldsymbol{i}$ is the unit vector. The floor displacements of an N-degree-of-freedom system can be defined as:

$$\boldsymbol{u}(\boldsymbol{t}) = \sum_{n=1}^{N} \boldsymbol{\Phi_n} q_n(t) \quad (2)$$

where $\boldsymbol{\Phi_n}$ is the nth mode shape and $q_n(t)$ is the modal co-ordinate which is governed by:

$$\ddot{q}_n + 2\zeta_n\omega_n\dot{q}_n + \omega_n^2 q_n = -\Gamma_n\ddot{u}_g(t) \quad (3)$$

in which ω_n and ζ_n are the natural frequency and damping ratio of the nth mode, respectively. Γ_n is the nth modal participating factor and is obtained as follows: