THE EFFECT OF DIFFERENT PARAMETERS ON A SINGLE INVARIANT LATERAL FORCE DISTRIBUTION TO CONSIDER THE HIGHER MODES EFFECT IN A PUSHOVER PROCEDURE

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Nonlinear response history analysis (NL-RHA) is a robust analytical tool for estimating the seismic demands of structures responding in the inelastic range. However, because of its conceptual and numerical complications, the nonlinear static procedure (NSP) is being increasingly used as a suitable tool for seismic performance evaluation of structures. The conventional pushover analysis methods presented in various codes (FEMA 356; Eurocode-8; ATC-40), are limited to the first-mode-dominated structures, and cannot take higher modes effect into consideration (Krawinkler and Seneviratna, 1998; Chopra and Goel, 2002). Therefore, since more than a decade ago, researchers (Chopra and Goel, 2002, 2004, and 2005; Chopra et al., 2004; Jan et al., 2004; Kim and Kurama, 2008; Poursha et al., 2009; Sucuoglu and Selim Gunay, 2011; Kreslin and Fajfar, 2011; Panyakapo, 2014) developed enhanced pushover analysis procedures to take higher modes effect into account.

The main objective of this study is to propose an enhanced single invariant lateral force distribution to take higher modes effect into consideration in performing the pushover analysis. For this purpose, the effect of different parameters such as the spectral pseudo-acceleration of ground motion, the modal participation factor, and the effective modal participating mass ratio on the lateral force distribution is investigated to find the best distribution. The major simplification of this procedure is that the effect of higher modes is concentrated into a single invariant lateral force distribution. Therefore, only one pushover analysis is sufficient without any need to utilize a modal combination rule. Four different modal lateral force distributions for the *n*th mode are defined as follows:

$$\boldsymbol{f_n} = \Gamma_n \boldsymbol{m}\boldsymbol{\Phi_n} \tag{1}$$

$$\boldsymbol{f_n} = \alpha_n \boldsymbol{m}\boldsymbol{\Phi_n} \tag{2}$$

$$\boldsymbol{f_n} = \Gamma_n \boldsymbol{m}\boldsymbol{\Phi_n} S_a\left(\zeta_n, T_n\right) \tag{3}$$

$$\boldsymbol{f_n} = \alpha_n \boldsymbol{m}\boldsymbol{\Phi_n} S_a\left(\zeta_n, T_n\right) \tag{4}$$

where $\boldsymbol{f_n}$ is the lateral force distribution for the *n*th mode, Γ_n is the *n*th modal participating factor, α_n is the effective modal participating mass ratio for the *n*th mode, $\boldsymbol{\Phi_n}$ is the corresponding mode shape, and S_a is the spectral pseudo-acceleration as a function of vibration period T_n and damping ratio ζ_n of the *n*th mode for a given earthquake ground motion. The invariant lateral force distribution for pushover analysis is then calculated by algebraically adding the modal story forces. The following expression is, therefore, used to compute the story forces:

$$F_k = \sum_{i=1}^{k} f_i \tag{5}$$

where F_k is the lateral force vector to be applied at the floor levels, and k is the number of vibration modes considered in obtaining the lateral force distribution. In addition to pushover analyses using the enhanced lateral force distributions, a conventional pushover analysis is performed by using an inverted triangular or a uniform load pattern. Finally, the seismic demands of the structure are obtained by enveloping the responses derived from the conventional and the enhanced single-run pushover analyses. The seismic demands resulting from the four different procedures are compared to those from the more accurate nonlinear response history analysis (NL-RHA) as a benchmark solution. Two structures of different heights including 10 and 20-story special steel moment resisting frames (MRFs) were selected and evaluated. Twenty ground motion records were used to conduct the NL-RHA.

The results show that more accurate responses can be obtained in comparison with the other modal lateral forces when the fourth modal lateral force distribution (i.e. Eq. (4)) is used. These accurate results are derived because of two main reasons. First, the modal lateral forces in Eq. (4) are weighted by a weighting factor S_a to account for the effect of the frequency content of a particular input ground motion in the lateral force distribution which could improve the results of the NSP. The second reason is that the sum of effective modal participating mass ratios over all modes is equal to unity. Thus, these ratios can better display the contribution of a particular mode in the lateral force distribution.

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