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# A consecutive modal pushover procedure for nonlinear static analysis of one-way unsymmetric-plan tall building structures

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ABSTRACT

Seismic responses of unsymmetric-plan tall buildings are substantially influenced by the effects of higher modes and torsion. Considering these effects, in this article, the consecutive modal pushover (CMP) procedure is extended to estimate the seismic demands of one-way unsymmetric-plan tall buildings. The procedure uses multi-stage and classical single-stage pushover analyses and benefits from the elastic modal properties of the structure. Both lateral forces and torsional moments obtained from modal analysis are used in the multi-stage pushover analysis. The seismic demands are obtained by enveloping the peak inelastic responses resulting from the multi-stage and single-stage pushover analyses. To verify and appraise the procedure, it is applied to the 10, 15, and 20-storey one-way unsymmetric-plan buildings including systems with different degrees of coupling between the lateral displacements and torsional rotations, i.e. torsionally-stiff (TS), torsionally-similarly-stiff (TSS) and torsionally-flexible (TF) systems. The modal pushover analysis (MPA) procedure is implemented for the purpose of comparison as well. The results from the approximate pushover procedures are compared with the results obtained by the nonlinear response history analysis (NL-RHA). It is demonstrated that the CMP procedure is able to take into account the higher mode influences as well as amplification or de-amplification of seismic displacements at the flexible and stiff edges of unsymmetric-plan tall buildings. The extended procedure can predict to a reasonable accuracy the peak inelastic responses, such as displacements and storey drifts. The CMP procedure represents an important improvement in estimating the plastic rotations of hinges at both flexible and stiff sides of unsymmetric-plan tall buildings in comparison with the MPA procedure.
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## 1. Introduction

The nonlinear static procedure or pushover analysis is increasingly used to establish the estimations of seismic demands for building structures. The pushover analysis is, however, restricted with a single-mode response. Then, the use of this procedure for unsymmetric-plan or tall buildings yields erroneous results. In order to cope with this limitation, attempts have been made to develop enhanced pushover procedures. During past years, multi-mode pushover (MMP) method [1], modal pushover analysis (MPA) [2], pushover results combination (PRC) [3], incremental response spectrum analysis (IRSA) [4], upper-bound pushover analysis [5], modified modal pushover analysis (MMPA) [6], adaptive modal combination (AMC) procedure [7] and improved modal pushover analysis [8] were proposed to consider the effects of higher modes. Lately, the consecutive modal pushover (CMP) procedure [9] was also developed in which the structural responses were obtained by enveloping the results of multi-stage and conventional single-stage pushover analyses. The CMP procedure was shown to be effective in predicting the seismic demands of tall buildings.

The above-mentioned procedures were limited to planar frames and symmetric buildings. Several research efforts have been made to extend and apply the pushover analysis to unsymmetric-plan buildings whose inelastic seismic responses are intricate. Kilar and Fajfar [10,11], De Stefano and Rutenberg [12], Faella and Kilar [13], Moghadam and Tso [14,15], Ayala et al. [16], Fujii et al. [17] and Barros and Almeida [18] investigated on the application of pushover analysis for seismic evaluation of unsymmetric-plan buildings. Recently, the modal pushover analysis (MPA) [19], the N2 method [20,21] and a simplified seismic analysis [22] were extended to the unsymmetric-plan buildings. In the MPA procedure, torsional moments were applied in addition to lateral forces at each floor level. The seismic demands were separately calculated for each of the modal pushover analyses and combined by

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