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Story shear and torsional moment-based pushover procedure for asymmetric-plan buildings using an adaptive capacity spectrum method

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ABSTRACT

A single-run pushover procedure is proposed to assess the seismic response of asymmetric-plan buildings, when subjected to unidirectional earthquake ground motions. Effects of the higher and torsional modes are incorporated into an invariant load pattern, which is calculated based on the height-wise distribution of the modal story shear and torsional moment. In order to consider the effect of instantaneous changes in dynamic characteristics of the structure in the nonlinear phase, capacity curve of the structure is obtained using an adaptive capacity spectrum method. Results from numerical investigations indicate appropriate accuracy of the proposed procedure in capturing the relative displacement of structures when compared to the results from nonlinear response history analyses. The proposed load pattern can be utilized in seismic performance assessment software available for the engineering community for seismic assessment of asymmetric-plan buildings.

1. Introduction

Design of engineering structures according to a specific level of performance as well as assessing the seismic performance of existing structures have gained tremendous attention during the past decades. One of the challenging steps in performance-based earthquake engineering methodology is to determine the seismic response of structures with an appropriate accuracy, and yet by practically efficient methods. Due to the severe effect of a seismic loading, deformations beyond the linear behavior should be taken into account in a seismic assessment process. Nonlinear response history analysis, as an elaborative method, can be used to obtain time-varying responses of structures subjected to a specific ground-motion time series. However, implementation of the response history analysis in seismic assessment of structures is accompanied by some elusiveness such as the uncertainty in selecting appropriate ground motion time series and difficulties in processing the time-varying response of the structure. In this regard, nonlinear static analysis method has been proposed in seismic performance assessment guidelines, e.g., [1,2], as a practical method to estimate the seismic response of 2D models of building structures. In this regard, methods have been proposed to enhance the accuracy of pushover methods in estimating seismic responses of structures [3–10].

Since the actual response of 3D asymmetric-plan buildings can be considerably different from the response of its individual 2D frames, accurate seismic evaluation of building structures requires conducting response analysis of a 3D model of the structure and considering the effects of the higher modes and torsional behavior of the structure. Many attempts have been previously made to assess the seismic performance of asymmetric-plan building frames, using nonlinear static analysis procedures (e.g., [11–28]). A brief review of these procedures has been presented by Shakeri et al. [28]. Contribution of the torsional and higher modes in 3D frames can be considered through a multi-run modal pushover procedure, which requires multiple nonlinear analyses of the structural model (i.e., [19]). In multi-run methods, the effect of the interaction between responses from different modes in estimating the total response of the structure is neglected. On the other hand, the effect of the higher modes, as well as the torsional modes, can be incorporated into a single load pattern, so that, the pushover analysis can be performed through a single-run procedure (e.g., [28,7]). Since seismic evaluation of building structures using a 3D model of the structure requires more computational efforts than implementation of 2D models, application of single-run procedures for pushover analysis of 3D frames is more practical than multi-run procedures.

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In an effort to consider the instantaneous changes in dynamic characteristics of asymmetric-plan building structures during nonlinear analysis, effects of the higher and torsional modes, and also interaction between the modes in nonlinear phase, a single-run adaptive modal pushover procedure has been proposed by Shakeri et al. [28], denoted as the story **S**hear and **T**orsional moment **A**daptive (STA) pushover method. This method was an extension to the previously proposed story shear-based pushover procedure for 2D frames [7]. The load pattern in the STA method is derived based on the instantaneous distribution of the modal story shear and torsional moment in stories of a 3D structure. In the present study, a practically simplified version of the STA procedure is proposed to assess the seismic response of 3D asymmetric-plan buildings. The proposed method still makes use of the advantage of defining the load pattern based on the modal story shear and torsional moment [28], however, in the proposed procedure the load pattern is taken to be invariant during the pushover analysis, as opposed to the STA method in which the load pattern is being updated at each step of the analysis based on the instantaneous changes in modal characteristics of the structure. Since the instantaneous computation of the load pattern is a demanding task, and also is not applicable in conventional nonlinear analysis software for an engineering practice, the proposed invariant load pattern facilitates straightforward application of the procedure. The proposed procedure is a single-run method, therefore, responses of the structure can be obtained by performing a single nonlinear analysis of the 3D model, and the elusiveness associated with conducting multiple analyses is averted. In addition, the effects of the higher and torsional modes are incorporated into the proposed load pattern. The capacity curve of the structure in the proposed procedure is established based on the instantaneous deformed shape of the structure, using the adaptive capacity spectrum method (ACSM) proposed by Casarotti and Pinho [29]. Implementation of the ACSM is not requiring an extra computational effort during the analysis. The capacity curve of the structure can be established at the end of the nonlinear analysis, using the recorded responses of the structure. In the following sections, first, the proposed method is developed. Then the results from numerical analyses are presented and discussed. Finally, the concluding remarks are presented.

2. Development of the proposed procedure

Two main aspects of the proposed method: (a) derivation of the load pattern; and (b) establishing the capacity curve of the structure are presented separately in this section.

2.1. Derivation of the load pattern

In the proposed method, the load pattern is calculated based on the height-wise distribution of the modal story shear and torsional moment in stories of a 3D model of the structure. This load pattern will induce the same distribution of relative displacements and torsional rotations in the structure as obtained from spectral dynamic analysis of the linear-elastic model of the structure. Although dynamic characteristics of a structure alter during a nonlinear analysis and distribution of the modal story shear and torsional moment will change accordingly [28,7], in order to maintain the simplicity and practicality of the proposed procedure, the proposed load pattern is chosen to be invariant during the analysis. Implementation of the invariant load pattern facilitates straightforward application of the method in common nonlinear analysis software for an engineering practice (such as SAP2000 [30]) and lowers the computational cost of the nonlinear analysis.

Spectral dynamic analysis of 3D building frames with in-plane rigid diaphragms is discussed here in order to illustrate the approach to derive the load pattern. Based on the spectral dynamic analysis approach [31], maximum modal forces and the torsional moment, corresponding to each mode of vibration, are computed by Eqs. (1)–(3):

$$f_{x_{ij}} = \Gamma_{y_j}\phi_{x_{ij}} m_{x_i} S_{a_{yj}} \tag{1}$$

$$f_{y_{ij}} = \Gamma_{y_j}\phi_{y_{ij}} m_{y_i} S_{a_{yj}} \tag{2}$$

$$T_{\theta_{ij}} = \Gamma_{y_j}\phi_{\theta_{ij}} I_{\theta_i} S_{a_{yj}} \tag{3}$$

where $\Gamma_{y_j} = \frac{\mathbf{\Phi}_j^T \mathbf{M}\mathbf{l}_y}{\mathbf{\Phi}_j^T \mathbf{M}\mathbf{\Phi}_j}$ is the modal participation factor of j-th mode for excitation in y direction; $\mathbf{\Phi}_j = \langle \mathbf{\Phi}_{x_j}\mathbf{\Phi}_{y_j}\mathbf{\Phi}_{\theta j}\rangle^T$ is mode shape vector of j-th mode consisting of the components in three directions of motion for floors of the 3D frame with in-plane rigidity; $\mathbf{\Phi}_{x_j} = \langle \mathbf{\Phi}_{x_{1j}}\mathbf{\Phi}_{x_{2j}} \ldots \mathbf{\Phi}_{x_{Nj}}\rangle^T$, $\mathbf{\Phi}_{y_j} = \langle \phi_{y_{1j}}\phi_{y_{2j}} \ldots \phi_{y_{Nj}}\rangle^T$, $\mathbf{\Phi}_{\theta_j} = \langle \phi_{\theta_{1j}}\phi_{\theta_{2j}} \ldots \phi_{\theta_{Nj}}\rangle^T$ are respectively mode shape vectors in translational (x and y) and rotational directions in j-th mode; $\phi_{x_{ij}}, \phi_{y_{ij}}, \phi_{\theta_{ij}}$ are mode shape components in x, y, and rotational directions of i-th story in j-th mode; $\mathbf{l}_y = \langle \mathbf{0}\ \mathbf{1}\ \mathbf{0}\rangle^T$ is the influence vector for seismic excitation in y direction; m_{x_i} and m_{y_i} are the translational mass of the i-th story in x and y directions; I_{θ_i} is the rotational mass of the i-th story; $\mathbf{M}$ is the mass matrix based on a 3D model of the structure; and $S_{a_{yj}}$ is the spectral acceleration ordinate in the seismic excitation direction corresponding to j-th mode of vibration.

The story shear in the translational directions and the torsional moment of each story are calculated by Eqs. (4)–(6), for each mode. Then, the combined modal story shear and combined modal torsional moment are calculated by Eqs. (7)–(9), using square-root-of-the-sum-of-the-squares (SRSS) rule, or other combination rules:

$$\mathrm{SS}_{x_{ij}} = \sum_{k=i}^{N} \mathrm{f}_{x_{kj}} \tag{4}$$

$$\mathrm{SS}_{y_{ij}} = \sum_{k=i}^{N} \mathrm{f}_{y_{kj}} \tag{5}$$

$$\mathrm{ST}_{\theta_{ij}} = \sum_{k=i}^{N} \mathrm{T}_{\theta_{kj}} \tag{6}$$

$$\mathrm{CSS}_{x_i} = \sqrt{\sum_{j=1}^{m} \mathrm{SS}_{x_{ij}}^2} \tag{7}$$

$$\mathrm{CSS}_{y_i} = \sqrt{\sum_{j=1}^{m} \mathrm{SS}_{y_{ij}}^2} \tag{8}$$

$$\mathrm{CST}_{\theta_i} = \sqrt{\sum_{j=1}^{m} \mathrm{ST}_{\theta_{ij}}^2} \tag{9}$$

where $\mathrm{SS}_{x_{ij}}$ and $\mathrm{SS}_{y_{ij}}$ and are respectively the shear in i-th story in x and y translational directions associated with mode j; $\mathrm{ST}_{\theta_{ij}}$ is the torsional moment in i-th story associated with mode j about the perpendicular direction to the floor at the mass center; CSS_{x_i} and CSS_{y_i} are the combined story shear of story i in x and y translational directions, respectively; CST_{θ_i} is the combined torsional moment of story i in rotational direction; m is the number of modes used to calculate the combined responses; and N is the number of the stories.

In order to induce the same distribution of relative displacements and torsional rotations in the structure as obtained from spectral dynamic analysis of the linear-elastic model of the