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An energy-based pushover-analysis with torque-effects in assessment of the structures with asymmetric plan

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ABSTRACT

The current paper aims to investigate the pushover schemes for buildings with asymmetric plan in nonlinear static procedures (NSPs). Moreover, this paper will propose an extension of the energy-based adaptive pushover analysis (EAPA) procedure for the seismic design/assessment of 3D irregular structures, which will be denoted as energy-based pushover-analysis with torque-effects (EPT). This innovative single-run adaptive method is proposed based on the work done produced by modal force in each step of analysis; and is validated on 3D steel structures with asymmetric plan composed from moment-resisting frames. EPT uses the concepts of energy to produce an incremental, adaptive load pattern that takes into account the effects of structural deterioration due to seismic loads, the higher modes of vibration, and the characteristics of the frequency content of the excitations. Also, an innovative MDOF-to-SDOF transformation method is proposed based on energy concept, removing the ambiguity of choosing a controlling point in asymmetric plan buildings. The seismic response obtained from nonlinear analyses under 20 earthquake excitations are plotted over the height of the structures. The results of the analytical studies of these buildings show that the EPT method provides a good prediction of maximum inter-story drifts and displacements over the height of the structures.

1. Introduction

Pushover analysis is one of the most important parts of every nonlinear static procedure, in which a load pattern is applied to the system until the global collapse or a predefined control point is reached [1]. The applied load pattern is established by one or more mode shapes [2–4]. If the load pattern is unchanged throughout the analysis, the method is described as conventional pushover; by comparison, if the load pattern is changed to account for variations in the deterioration progressive of the structure in the inelastic range, the method is known as adaptive pushover [1,5].

FEMA-356 [6], FEMA-440 [7], and Eurocode 8 [8] recommended the use of nonlinear static procedures to predict the capacity/demand of structures [9–12]. However, these provisions often utilize unchanged lateral load patterns during all stages of analysis, assuming that the structure will behave in one fundamental mode shape [13]. Code provisions also recommend that consideration is given to the effect of torsional deformation; however, these provisions are typically related to the elastic ranges of deformations and are strictly applicable to cases of elastic analyses [14,15]. In addition, most of the lateral load patterns are originally developed for symmetric buildings [16–19], while the influence of torsional modes in asymmetric-plan buildings on seismic demands may be significant [20–23].

In recent years, some investigators have proposed extensions to methods that were previously developed for two-dimensional (2D) frames to apply them to three-dimensional (3D) models with asymmetric plans. These have included both non-adaptive [4,24–27] and adaptive [28,29] methods.

In this paper, a single-run adaptive pushover is proposed which is an extension of the energy-based adaptive pushover analysis (EAPA) procedure [30] to 3D building structures with asymmetric plan. In which the structure is loaded according to the current distribution of modal forces in two translational directions and torques in the height of the building. Including the effects of torsion in asymmetric-plan buildings is considered as the mainly improvement of the extended work. Also, in this work, an innovative adaptive MDOF-to-SDOF transformation method is proposed based on that was proposed by Casarotti and Pinho [31] for the seismic assessment of plan asymmetric buildings. This method will be denoted as energy-based pushover-analysis with torque-effects (EPT). EPT uses the concepts of energy to produce an incremental adaptive load pattern that takes into account the effects of progressive changes in structural properties, higher modes, and the

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characteristics of the frequency content of the excitations. To achieve this aim, the displacement and inertia force in each level of the structure must first be obtained in each stage of the analysis. Next, the work done over the height of the structure is easily determined. Finally, the applied load pattern is established and updated using the current structural properties in each stage of the analysis. The proposed method simultaneously considers the effect of higher modes, site specific, inelastic ranges, and deteriorations of strength and stiffness in each step of the analysis.

2. 3D pushover procedures

2.1. Non-adaptive schemes

To estimate the responses and damage to buildings Moghadam and Tso [32] proposed a simplified procedure in which the results of two 3D pushover analyses are combined. In these methods, it is assumed that the structure will behave in a dominant mode shape [33].

Fajfar et al. [34] extend the N2 method for asymmetric plan buildings, although the basic limitations of N2 method remain [35]. In the extended method, it is assumed that the effects of higher modes are the same in both the inelastic and elastic ranges. As such, the responses of the higher modes are defined by standard elastic modal analysis [36]. The extended N2 method mainly yields overestimate predictions in results of higher modes [37].

Chopra and Goel [4] have extended the well-known modal pushover analysis (MPA) for asymmetric-plan buildings. In the extended MPA method, the load patterns, composed of translation directions and torque corresponding to the considered elastic mode shapes, are applied to the structure in mass centers; then the total seismic response is estimated by combining the responses derived from each modal load pattern [4,28,38].

2.2. Adaptive schemes

A shortcoming of conventional schemes is that they are restricted to a constant load pattern during analysis, ignoring the progressive changes in structural properties, and therefore cannot capture the effect of strength and stiffness deterioration in their analysis [39]. To address this, studies have attempted to develop adaptive pushover algorithms which account for the effects of reduced stiffness during the analytical process [17,28,29].

Recently, Pinho et al. [40] employed the displacement-based adaptive pushover procedure [13] on a 3D asymmetric-plan building. Also Shakeri et al. developed an extension of the story shear-based adaptive pushover (SSAP) procedure [16] to 3D buildings with asymmetric plan that called story-shear-and-torque-based adaptive (STA) procedure [28,41].

Bhatt and Bento proposed an extension of CSM-FEMA440 procedure in order to overcome the torsional problem of plan-asymmetric buildings. This extension employs correction factors that are computed based on a linear RSA and on a pushover analysis. The proposed method was verified on three RC plan-asymmetric buildings with differing numbers of stories [42]. Also, in order to consider the progressive changes in the structural features, an extended adaptive capacity spectrum method (ACSM) was proposed for the seismic assessment of plan-asymmetric buildings [43].

In development and implementation of nonlinear static methodologies for the seismic assessment and design of structures, it is aimed to approach real responses of existing irregular structures [44–46]. In this paper, a new single-run adaptive modal procedure is implemented and validated for steel moment resisting structures, in which the lateral load pattern is updated based on work done in each level of the structure and distributed over the height of the system.

3. Review of structural dynamic for 3D models

The equation governing the response of a multi-degree of freedom (MDOF) system subjected to earthquake motion is given by Eq. (1) (adopted from Ref. [2]):

$$M\ddot{u} + C\dot{u} + Ku = -Ml\ddot{u}_g(t) \tag{1}$$

Where, M, C, and K are the matrices of mass, damping, and stiffness of the structure, respectively; $\ddot{u}$, $\dot{u}$, and u are the acceleration, velocity, and displacement vector of the system; and $\ddot{u}_g(t)$ indicates the acceleration of base due to an earthquake in time of t. The influence vector, l, defines the direction of induced ground motion. Here, it is assumed that there is a rigid diaphragm in each level of the structure and the mass of each floor is lumped in center of mass (CM), hence we have two translation DOFs (along the x-direction and y-direction) along with a rotational DOF about the perpendicular axis to plan (z-axis). If the plan of the structure is symmetric in y-direction and asymmetric in x-direction, Eq. (1) is rewritten as Eq. (2):

$$\begin{bmatrix} \mathbf{m} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{m} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I_o} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}_\mathbf{x} \\ \ddot{\mathbf{u}}_\mathbf{y} \\ \ddot{\mathbf{u}}_\theta \end{Bmatrix} + \begin{bmatrix} \mathbf{k_{xx}} & \mathbf{k_{xy}} & \mathbf{k_{x\theta}} \\ \mathbf{k_{yx}} & \mathbf{k_{yy}} & \mathbf{k_{yx}} \\ \mathbf{k_{\theta x}} & \mathbf{k_{\theta y}} & \mathbf{k_{\theta\theta}} \end{bmatrix} \begin{Bmatrix} \mathbf{u_x} \\ \mathbf{u_y} \\ \mathbf{u_\theta} \end{Bmatrix} = -\begin{bmatrix} \mathbf{m} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{m} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I_o} \end{bmatrix} \begin{Bmatrix} \mathbf{1} \\ \mathbf{0} \\ \mathbf{0} \end{Bmatrix} \ddot{\mathbf{u}}_\mathbf{gx}(\mathbf{t}) \tag{2}$$

The right-hand side of Eq. (2) shows the effective earthquake force, which can be expressed as Eq. (3):

$$-\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_o \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix} \ddot{u}_{gx}(t) = -s\ddot{u}_{gx}(t) = P_{eff}(t) \tag{3}$$

Where, $P_{eff}(t)$ is the effective earthquake force in time of t; s represents the spatial distribution of this force that can be expressed as a summation of modal inertia force distributions, s is given by Eq. (4) [Ref. [2] Section 13.3]; in the diagonal sub- matrices of M, m is the translational mass in directions of x and y, and I_o is the rotational mass about the z-axis:

$$s = \sum_{n=1}^{3N} s_n = \sum_{n=1}^{3N} \begin{Bmatrix} s_{xn} \\ s_{yn} \\ s_{\theta n} \end{Bmatrix} = \sum_{n=1}^{3N} \Gamma_n \begin{Bmatrix} m\phi_{xn} \\ m\phi_{yn} \\ I_o\phi_{\theta n} \end{Bmatrix} \tag{4}$$

In Eq. (4), s_n is the contribution of n-th mode of vibration; s_{xn}, s_{yn}, and $s_{\theta n}$ are the sub-matrices of s_n associated with the components of ground motions; ϕ_{xn}, ϕ_{yn}, $\phi_{\theta n}$ indicate the three sub-matrices of Φ_n, the n-th natural vibration mode shape of the structure representative of two translation mode shape in directions of x and y and the rotation about the z-axis; and N is the number of floors [2,4].

As such, if the earthquake excitation applied to the structure in direction of x, L_n can be calculated by Eq. (5) and then the modal participation factor, Γ_n, is obtained from Eq. (6) for each mode.

$$L_n = \phi_{xn}^T m1 \tag{5}$$

$$\Gamma_n = \frac{L_n}{M_n} \tag{6}$$

Where $M_n = \Phi_n^T M\Phi_n$ is the modal mass in mode shape of n.

4. Energy-based three dimensional pushover

In this pushover method a 3D mathematical model of the system is made and subjected to an adaptive load scheme until the predetermined control point is reached. This algorithm is comprised of two horizontal load patterns along with a torque load pattern that are applied in the center of masses of the structure levels. The algorithm is outlined in the following sections.