Soil Dynamics and Earthquake Engineering 69 (2015) 1–15

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

A pushover procedure for seismic assessment of buildings with bi-axial eccentricity under bi-directional seismic excitation

Kazem Shakeri*, Samaneh Ghorbani

Faculty of Engineering, University of Mohaghegh Ardabili, Ardabil 56199-11367, Iran

ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form
26 September 2014
Accepted 26 October 2014

Keywords:
Nonlinear static analysis
Bi-axial eccentricity
Bi-directional excitation
Shear
Torque

ABSTRACT

A new modal pushover procedure is proposed for seismic assessment of asymmetric-plan buildings under bi-directional ground motions. Although the proposed procedure is a multi-mode procedure and the effects of the higher and torsional modes are considered, the simplicity of the pushover procedure is kept and the method requires only a single-run pushover analysis for each direction of excitation. The effects of the frequency content of a specific ground motion and the interaction between modes at each direction are all considered in the single-run pushover analysis. For each direction, the load pattern is derived from the combined modal story shear and torque profiles. The pushover analysis is conducted independently for each direction of motion (x and y), and then the responses due to excitation in each direction are combined using SRSS (Square Roots of Sum of Squares) combination rule. Accuracy of the proposed procedure is evaluated through two low- and medium-rise buildings with 10% two-way eccentricity under different pairs of ground motions. The results show promising accuracy for the proposed method in predicting the peak seismic responses of the sample buildings.

1. Introduction

Nowadays, the performance based design (PBD) methodology has been widely accepted by earthquake engineering community as a rigorous approach in design of civil structures. Since structures experience inelastic deformation in low performance levels (e.g., Life Safety), PBD methodology requires using nonlinear analysis to quantify the seismic response of structures. Nonlinear static procedures (NSPs) have been widely proposed as a practical tool in seismic evaluation guidelines and design codes [1–4]. Recently, to improve the efficiency of these procedures numerous advanced pushover procedures have been proposed [5–13]. Furthermore, application of the pushover procedures is extended to seismic assessment and design of non-building structures such as bridges [14–16].

However, most of these pushover procedures are originally developed for two dimensional (2D) models of building structures. Although in some procedures the effect of the torsional modes in asymmetric-plan buildings subjected to one-directional ground motion are considered [17–32], it is well recognized in the literature that for a reliable seismic assessment, considering the influence of simultaneous bi-directional ground motions (angle of incidence) on seismic demands of inelastic asymmetric-plan structures is inevitable [33–34].

In this regard, Fajfar et al. have extended the N2 method in order to take into account the bi-directional ground motions effects on asymmetric-plan structures [35]. Recently, Reyes and Chopra have also extended the well-known modal pushover analysis (MPA) to analyze asymmetric-plan buildings subjected to two horizontal components of ground motions [36]. Furthermore, the extended versions of the conventional pushover procedures are adopted by seismic codes [2–3]. These extended versions of original procedures are developed based on the superposition principle and the original pushover procedure is implemented independently in each horizontal direction and the resulting responses from each direction are combined by SRSS (Square Roots of Sum of Squares) rule. In the extended version of the MPA procedure, the effects of the higher and torsional modes are considered; however, since the original MPA procedure requires running several independent pushover analyses according to the considered modes in each direction, the extended version of the MPA procedure for bi-directional ground motions requires additional analyses.

Recently, Manoukas et al. have also developed a multi-mode pushover analysis similar to the extended MPA procedure for asymmetric-plan buildings under bi-directional ground motions, which leads to a significant reduction in computational cost [37]. In this procedure, it is assumed that the two components of the

* Corresponding author. Tel.: +98 914 451 3150; fax: +98 451 7720202.
E-mail addresses: Shakeri@uma.ac.ir, ka.shakeri@gmail.com (K. Shakeri).

http://dx.doi.org/10.1016/j.soildyn.2014.10.018
0267-7261/

bi-directional excitation are proportional to each other and based on this assumption a new concept of the equivalent single degree of freedom system is introduced. Therefore it is not required independent analysis in each direction of excitation and the directional combination in the nonlinear range is avoided. Manoukas and Avramidis have also proposed improved version of multi-mode pushover procedure for tall asymmetric-plan buildings under bi-directional seismic excitation [38].

Furthermore, Poursha et al. have extended the consecutive modal pushover procedure for seismic assessment of asymmetric-plan tall buildings subjected to two horizontal components of ground motions [39]. In pursue of developing advanced pushover methods to assess the seismic response of the building structures under bi-directional excitation, in this paper, a new multi-mode pushover procedure is proposed. Nevertheless the proposed procedure is a multi-mode approach and the effects of the higher and torsional modes are considered in the procedure, the method requires only a single-run analysis for each direction of motion. The single-run pushover analysis is run independently for each direction of motion (x and y), then the responses from each direction are combined through a combination rule proposed for multi-direction motions (e.g., SRSS) [40–42]. The proposed procedure is denoted as ST-Bi (story-Shear-and-Torque-based pushover procedure for Bi-direction excitation). As the proposed method roots from dynamics of structures, the related equations are presented in the following section.

2. Equation of motion

The equations of motion governing the displacements U of a multi degree of freedom (MDOF) system with $3\times$n degrees of freedom (n: number of story with rigid diaphragm in a building) subjected to simultaneous ground motion along two horizontal components are:

$$M\ddot{U}(t)+C\dot{U}(t)+KU(t)=-MI^x\ddot{u}_g^x(t)-MI^y\ddot{u}_g^y(t) \tag{1}$$

where M, C and K are respectively the mass, damping and stiffness matrices. $\ddot{U}(t)$, $\dot{U}(t)$ and $U(t)$are respectively acceleration, velocity and displacement vectors. $\ddot{u}_g^x(t)$ and $\ddot{u}_g^y(t)$ are the ground motion acceleration in x and y directions. I^x and I^y are excitation influence vectors respectively corresponding to x and y directions.

$$I^x=\langle 1 \quad 0 \quad 0\rangle^T \quad I^y=\langle 0 \quad 1 \quad 0\rangle^T \tag{2}$$

where 1 and 0 are vectors of dimension n with all elements equal to unity and zero, respectively.

Based on the superposition principle in linear elastic system, the vector of displacement $U(t)$ could be divided into two components $U^x(t)$ and $U^y(t)$ due to seismic excitations in x and y directions (i.e.,$\ddot{u}_g^x(t)$ and $\ddot{u}_g^y(t)$), respectively.

$$U(t)=U^x(t)+U^y(t) \tag{3}$$

The $U^x(t)$ and $U^y(t)$ vectors could be expressed in the following expanded forms:

$$U^x(t)=\left\langle U_x^x(t) \quad U_y^x(t) \quad U_\theta^x(t)\right\rangle_{3n\times 1}^T \tag{4}$$

$$U^y(t)=\left\langle U_x^y(t) \quad U_y^y(t) \quad U_\theta^y(t)\right\rangle_{3n\times 1}^T \tag{5}$$

where $U_x^x(t)$, $U_y^x(t)$ are the $n\times 1$ displacement vectors of n stories along x and y translational directions, respectively, due to excitation in x direction $\left(\ddot{u}_g^x(t)\right)$; $U_\theta^x(t)$ is the $n\times 1$ rotation vector of n stories around z (vertical to x and y plane) axis, due to excitation in x direction; $U_x^y(t)$, $U_y^y(t)$, and $U_\theta^y(t)$ are the same vectors as $U_x^x(t)$, $U_y^x(t)$ and $U_\theta^x(t)$, respectively, but due to excitation in y direction $\left(\ddot{u}_g^y(t)\right)$.

Based on Eq. (3), Eq. (1) could be expressed for each horizontal component of bi-directional ground motions ($\ddot{u}_g^x(t)$ and $\ddot{u}_g^y(t)$) in x and y direction, independently by the following equations:

$$M\ddot{U}^x(t)+C\dot{U}^x(t)+KU^x(t)=-MI^x\ddot{u}_g^x(t) \tag{6}$$

$$M\ddot{U}^y(t)+C\dot{U}^y(t)+KU^y(t)=-MI^y\ddot{u}_g^y(t) \tag{7}$$

Based on the modal decomposition concept, the responses of the structure due to excitation in each horizontal direction (i.e., $\ddot{u}_g^x(t)$ or $\ddot{u}_g^y(t)$) can be decomposed into responses of individual modes:

$$U^x=\sum_{j=1}^{3n}U_j^x=\sum_{j=1}^{3n}\Phi_j q_j^x \tag{8}$$

$$U^y=\sum_{j=1}^{3n}U_j^y=\sum_{j=1}^{3n}\Phi_j q_j^y \tag{9}$$

where Φ_j is the mode shape vector; q_j^x and q_j^y are respectively the generalized modal coordinate for jth mode due to excitation in x and y direction.

By transforming the total response due to each horizontal excitation into the modal coordinate, each of Eqs. (6) and (7) are decomposed into $3\times n$ (n is the number of stories) equations (Eqs. (10) and (11)):

$$\ddot{q}_j^x+2\xi_j\omega_j+\omega_j^2q_j^x=-\Gamma_j^x\ddot{u}_g^x \tag{10}$$

$$\ddot{q}_j^y+2\xi_j\omega_j+\omega_j^2q_j^y=-\Gamma_j^y\ddot{u}_g^y \tag{11}$$

where $\Gamma_j^x=L_j^x/M_j$ and $\Gamma_j^y=L_j^y/M_j$ are the modal participation factor corresponding to excitation in x and y directions, respectively.

$$M_j=\Phi_j{}^TM\Phi_j \quad L_j^x=\Phi_j{}^TMI^x \quad L_j^y=\Phi_j{}^TMI^y \tag{12}$$

The Φ_j vector consists of two translational vectors in x and y directions and rotational vector as presented in Eqs. (13)–(16).

$$\Phi_j=\langle\Phi_{x_j}\ \Phi_{y_j}\ \Phi_{\theta_j}\rangle^T \tag{13}$$

$$\Phi_{x_j}=\langle\phi_{x_{1j}} \quad \phi_{x_{2j}} \quad \cdots \quad \phi_{x_{nj}}\rangle^T \tag{14}$$

$$\Phi_{y_j}=\langle\phi_{y_{1j}} \quad \phi_{y_{2j}} \quad \cdots \quad \phi_{y_{nj}}\rangle^T \tag{15}$$

$$\Phi_{\theta_j}=\langle\phi_{\theta_{1j}} \quad \phi_{\theta_{2j}} \quad \cdots \quad \phi_{\theta_{nj}}\rangle^T \tag{16}$$

The maximum induced modal forces and torques in each mode, because of excitation in x direction are computed by Eqs. (17)–(19) and also, the maximum induced modal forces and torques in each mode due to the excitation in y direction are computed by Eqs. (20)–(22).

$$F_{x_{ij}}^x=\Gamma_j^x\Phi_{x_{ij}}m_{x_i}S_{a_j}^x \tag{17}$$

$$F_{y_{ij}}^x=\Gamma_j^x\Phi_{y_{ij}}m_{y_i}S_{a_j}^x \tag{18}$$

$$T_{\theta_{ij}}^x=\Gamma_j^x\Phi_{\theta_{ij}}I_{\theta_i}S_{a_j}^x \tag{19}$$

$$F_{x_{ij}}^y=\Gamma_j^y\Phi_{x_{ij}}m_{x_i}S_{a_j}^y \tag{20}$$

$$F_{y_{ij}}^y=\Gamma_j^y\Phi_{y_{ij}}m_{y_i}S_{a_j}^y \tag{21}$$

$$T_{\theta_{ij}}^y=\Gamma_j^y\Phi_{\theta_{ij}}I_{\theta_i}S_{a_j}^y \tag{22}$$