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Approximate two-component incremental dynamic analysis using a bidirectional energy-based pushover procedure

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ABSTRACT

Incremental dynamic analysis (IDA) is recognized as a valuable method for assessing the performance of structures under earthquake excitation. Since IDA is computationally intensive, a number of previous studies have attempted to approximate IDA curves using pushover analysis. As a requirement for assessments of asymmetric buildings, IDA under two-component ground motions has received minimal attention throughout these studies. To bridge this gap, the current research puts forth an approximate two-component IDA procedure on the basis of a bidirectional energy-based pushover (BEP) analysis. BEP uses the work done by lateral loads and torques through pushover analysis as an index to determine the characteristics of the modal single-degree-of-freedom systems. The suggested formula pertaining to this procedure allows for the simultaneous effect of both components of a ground motion on each mode. To combine the modal responses of this method, a modified complete quadratic combination (CQC) rule is also presented, which is specialized for two-component excitations. The accuracy of the proposed procedure was examined on a two-way asymmetric 3-story building. The findings suggest that BEP is capable of estimating two-component IDA results with a sufficient degree of accuracy.

1. Introduction

Incremental dynamic analysis (IDA) is recognized as a valuable method for performance assessments of structures under earthquake excitation [1]. IDA requires a large suite of ground motion pairs, each of which is scaled to different intensity levels, and a nonlinear response history analysis (NRHA) is performed for each pair at each intensity.

The great computational cost has caused IDA to be seldom used in practice [2]. Hence, a number of attempts have been made to approximate IDA curves using pushover analysis. Vamvatsikos and Cornell proposed the SPO2IDA method in which empirical equations are used to convert pushover curves into IDA curves [3]. Dolsek and Fajfar investigated an incremental version of the N2 method [4] as a simple alternative to IDA [5]. Han and Chopra proposed an approximate IDA procedure [6] using the well-known modal pushover analysis (MPA) [7]. Brozovic and Dolsek also presented an envelope based pushover procedure [8].

Although the aforementioned methods are effective in producing approximate IDA curves, the scope of these procedures is limited to one-component ground motions. In three-dimensional structures, given the probable irregularities in building plans, it is considered essential to assess building performance under both components of a ground motion simultaneously [9–12]. To address this matter, the current study puts forth a new approximate IDA procedure assessing three-dimensional asymmetric and symmetric buildings under two-component excitations. At the core of this procedure is a bidirectional energy-based pushover (BEP) analysis based on which the modal capacity curves (i.e., the force-deformation curves of the equivalent single-degree-of-freedom [ESDF] systems corresponding to building modes) are established.

The energy-based pushover approach was first introduced by Hernandez-Mountes et al. in 2004 to deal with the distortions observed in pushover curves of higher modes [13]. Further studies on this subject have also been performed [14–19]. Recently, this approach was extended to asymmetric-plan buildings by Soleimani et al., called E-MPA [20]. In contrast to the conventional approach that uses a roof displacement component as an index to establish capacity curves [21,22], E-MPA uses the work done by lateral loads and torques to produce capacity curves. As in the most similar procedures [23–25], the E-MPA analyses associated with the x and y components of a ground motion are separately performed; then, the results are combined using the SRSS combination rule (Square Root of Sum of Squares [26]).

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Nomenclature

$\boldsymbol{c}$	damping matrix
dE_n	absorbed energy in each step of nth-mode pushover analysis
EDP	engineering demand parameter
$\boldsymbol{f}_s$	resisting force matrix
IM	intensity measure
$\boldsymbol{l}_x$	influence vector for the x component of ground motion
$\boldsymbol{l}_y$	influence vector for the y component of ground motion
M_n	modal mass of the nth mode
$\boldsymbol{m}$	mass matrix
N	number of floors
q_n	nth–mode ESDF system effective force
r	total response
r_n	nth-mode response
r_o	optimum response
T_n	base torque
$\boldsymbol{u}$	displacement matrix
$\ddot{u}_{gx}$	y component of the ground acceleration
$\ddot{u}_{gy}$	y component of the ground acceleration
$u_{n,rc}$	roof-component displacement
V_{nx}	x component of the base shear
V_{ny}	y component of the base shear
y_n	displacement of the nth-mode ESDF system
α_n	resistance force of the nth-mode ESDF system
$\boldsymbol{\varphi}_n$	nth-mode vector
$\varphi_{n,rc}$	roof component of the nth mode
η_{ij}	correlation between two modes regarding subjected ground motion
ρ_{ij}	correlation between two modes regarding modal characteristics
ω_n	natural frequency of the nth elastic mode
ζ_n	damping ratio of the nth mode
Γ_{nx}	nth-mode participation factor associated with the x component of ground motion
Γ_{ny}	nth-mode participation factor associated with the y component of ground motion

In the current research, an energy-based index similar to that of the E-MPA procedure is used to generate capacity curves. However, the related formulas are adjusted in order to eliminate the need for separate analyses for each component of a ground motion. In the BEP formulation, the simultaneous effect of both components of a ground acceleration is allowed on each ESDF system. Thus, only one pushover analysis is conducted for each mode, the computational time is reduced by half, and the approximations associated with the SRSS combination rule are removed. To combine the modal responses of this case, a modified complete quadratic combination (CQC [26]) rule is also proposed, which is specialized for two-component excitations.

Through this paper, the theoretical background of BEP is first explained; a step-by-step procedure of the proposed methodology is presented. Then, the accuracy of BEP is evaluated by analyzing a variation of the 3-story SAC building model [27] with 15% mass eccentricity in both the x and y directions. For this evaluation, a set of 22, far-field, two-component ground motion records is used, adopted from the FEMA-P695 document [28]. Finally, the BEP results are presented in comparison with the results of E-MPA and the exact IDA method.

2. Theoretical background

The governing equation of motion for a three-dimensional building subjected to the x and y components of a ground motion is as follows:

$$\boldsymbol{m}\ddot{\boldsymbol{u}}(t) + \boldsymbol{c}\dot{\boldsymbol{u}}(t) + \boldsymbol{f}_s(t) = -\boldsymbol{m}\boldsymbol{l}_x\ddot{u}_{gx}(t) - \boldsymbol{m}\boldsymbol{l}_y\ddot{u}_{gy}(t) \tag{1}$$

where $\boldsymbol{u}$ is the displacement vector defined as $\boldsymbol{u} = (\boldsymbol{u}_x,\boldsymbol{u}_y,\boldsymbol{u}_\theta)^T$, and the subvectors $\boldsymbol{u}_x$, $\boldsymbol{u}_y$, and $\boldsymbol{u}_\theta$ represent the x and y and rotational components of the floor displacements, respectively, each in order of $1\times N$; N is the number of floors; $\boldsymbol{m}$ and $\boldsymbol{c}$ are the mass and classical damping matrixes, respectively; $\boldsymbol{f}_s$ is the resisting lateral force, and the terms $\boldsymbol{l}_x$ and $\boldsymbol{l}_y$ are the "influence vectors" associated with the x and y components of the ground motion, respectively:

$$\boldsymbol{l}_x = (\boldsymbol{1},\boldsymbol{0},\boldsymbol{0})^T \quad \boldsymbol{l}_y = (\boldsymbol{0},\boldsymbol{1},\boldsymbol{0})^T \tag{2}$$

$\boldsymbol{1}$ and $\boldsymbol{0}$ are $1\times N$ vectors with all elements equal to unity and zero, respectively.

The terms on the right side of Eq. (1) are known as "effective earthquake forces," which can be decomposed into modal forces as follows:

$$-\boldsymbol{m}\boldsymbol{l}_x\ddot{u}_{gx}(t) - \boldsymbol{m}\boldsymbol{l}_y\ddot{u}_{gy}(t) = -\left(\sum_{n=1}^{3N}\Gamma_{nx}\boldsymbol{m}\boldsymbol{\varphi}_n\right)\ddot{u}_{gx}(t) - \left(\sum_{n=1}^{3N}\Gamma_{ny}\boldsymbol{m}\boldsymbol{\varphi}_n\right)\ddot{u}_{gy}(t) \tag{3}$$

where

$$\Gamma_{nx} = L_{nx}/M_n \quad L_{nx} = \boldsymbol{\varphi}_n^T\boldsymbol{m}\boldsymbol{l}_x$$
$$\Gamma_{ny} = L_{ny}/M_n \quad L_{ny} = \boldsymbol{\varphi}_n^T\boldsymbol{m}\boldsymbol{l}_y$$
$$M_n = \boldsymbol{\varphi}_n^T\boldsymbol{m}\boldsymbol{\varphi}_n \tag{4}$$

$\boldsymbol{\varphi}_n$ is the nth elastic mode defined as $\boldsymbol{\varphi}_n = (\boldsymbol{\varphi}_{xn},\boldsymbol{\varphi}_{yn},\boldsymbol{\varphi}_{\theta n})^T$, where $\boldsymbol{\varphi}_{xn}$, $\boldsymbol{\varphi}_{yn}$ and $\boldsymbol{\varphi}_{\theta n}$ are respectively x, y, and rotational subvectors, each in order of $1\times N$.

The first assumption made in this study is that the total response of the system to the effective earthquake forces can be expressed as the summation of responses to the individual modal forces represented in Eq. (3). Otherwise stated, the superposition principle is assumed to remain valid in both linear and nonlinear ranges of deformation. In this case, the outcome remains accurate if the ground motion is not strong enough to push the building beyond the linear limit, yet the results are approximate through the nonlinear range of building behavior. Therefore,

$$r(t) = \sum_{n=1}^{3N} r_n(t) \tag{5}$$

where $r_n(t)$ is the response of the building when subjected to the nth-mode forces:

$$\boldsymbol{m}\ddot{\boldsymbol{u}}_n(t) + \boldsymbol{c}\dot{\boldsymbol{u}}_n(t) + \boldsymbol{f}_{sn}(t) = -(\Gamma_{nx}\boldsymbol{m}\boldsymbol{\varphi}_n)\ddot{u}_{gx}(t) - (\Gamma_{ny}\boldsymbol{m}\boldsymbol{\varphi}_n)\ddot{u}_{gy}(t) \tag{6}$$

When the system is elastic, the response of the building obtained from Eq. (6) is proportional to the nth mode. Hence, in the elastic range, the displacement vector is expressed by the mode vector $\boldsymbol{\varphi}_n$ multiplied by a time-variant scaler $y_n(t)$ as follows:

$$\boldsymbol{u}_n(t) = y_n(t)\boldsymbol{\varphi}_n \tag{7}$$

As the second assumption in the current procedure, Eq. (7) is presumed to be valid in both the inelastic and elastic ranges of building behavior. In other words, the outcome of Eq. (6) is assumed to remain fully proportional to the nth elastic mode. This assumption is supported by previous research that shows when a structure is subjected to the forces proportional to the nth mode, the contribution of other modes to the response of the structure is normally less than 10%. This finding was obtained through the modal decomposition of the structural responses in both symmetric [7] and asymmetric buildings [29] where the seismic forces were strong enough to induce nonlinearity to the system.

Given Eq. (7), all terms of Eq. (6) except for $\boldsymbol{f}_{sn}$ can be written as a factor of $\boldsymbol{m}\boldsymbol{\varphi}_n$; therefore, it can be concluded that $\boldsymbol{f}_{sn}$ must be a factor of