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# Improved Modal Pushover Analysis in seismic assessment of asymmetric plan buildings under the influence of one and two horizontal components of ground motions

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A B S T R A C T

The Improved Modal Pushover Analysis (IMPA) is a multimode procedure that has the advantage of redefining the lateral load applied, when comparing with the multimode current methods; hence, instead of considering the elastic deformed shape, it is possible to consider the deformed shape of the structure when it is behaving inelastically, as a pattern. The IMPA was proposed in the past and was successfully applied in the seismic assessment of bridges, the main objective of this work being to explore IMPA in buildings. For this purpose the seismic demands of two asymmetric plan buildings are herein estimated by means of IMPA and compared to Nonlinear Dynamic Analyses (NDA) and to current reference Nonlinear Static Procedures (NSPs): Modal Pushover Analysis (MPA) and two other NSPs that are proposed in American and European seismic codes (ASCE/SEI 41-06 NSP and N2 method respectively). In the latter, an extended version (extended N2) is considered, taking into account both the torsional and the higher mode effects.

The seismic response of the two buildings herein studied is obtained through two different approaches: the first regarding only one component of ground motion, while the second considers both components of ground motion acting simultaneously. The seismic assessment of both buildings is performed in terms of pushover curves, top displacement ratios, lateral displacements profiles, interstorey drifts, normalized top displacements and shear forces.



## 1. Introduction

It is indubitable that the most accurate method of seismic demand prediction and performance evaluation of structures is Nonlinear Dynamic Analysis. Nevertheless, it still has difficulties and drawbacks for what concerns application within a design office environment: it requires the selection and employment of an appropriate set of ground motions; it remains computationally demanding; and it still requires the use of preliminary simpler analyses (as linear static and dynamic) to calibrate the model. Thus, there is still room and, indeed, need, for simpler analysis tools which provides strong reasons for continuing the development and improvement of nonlinear static methods, so that these analyses can become even more reliable and applicable also for irregular structures.

The IMPA was introduced by Paraskeva and Kappos in 2008 as an improved version of the MPA procedure specially applicable to bridges, being further published [1–3]. In that initial work, the procedure aimed at overcoming the weakness of the control node localization and the invariability of the lateral force distribution. In buildings, the node control position is not an issue; on the other hand the lateral load redistribution considered in IMPA, taking into account the deformed shape of the structure in inelastic regime might be a valid alternative in order to improve results when the structure exhibits inelastic behavior.

Some attempts to consider the redistribution of inertial forces after structure yields were then suggested for a planar frame structure by Jianmeng et al. [4]. In this paper, such methodology is performed using IMPA in two 3D plan-asymmetric buildings.

The IMPA is obviously based in the MPA proposed by Chopra and Goel [5], which is known as a complete version of multi-mode pushover analysis. It is a multi-run method, where several pushover curves are obtained from different load patterns proportional to each mode of vibration. The final response is obtained combining the results corresponding to each pushover curve using an appropriate combination rule. In 2004 the application was extended to asymmetric plan buildings [6], while a modified

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approach assuming higher modes as elastic [7] was also proposed. In addition to the extension for asymmetric buildings, the MPA has been continuously improved and updated: MPA was adapted to consider both components of ground motion acting simultaneously in buildings by Reyes and Chopra [8,9], and recently some approaches based in MPA with new concepts related to the lateral load pattern [10] as well as equivalent single degree of freedom (SDOF) of the system [11] have been developed. In 2006, an extension of the MPA was proposed for bridges by Paraskeva et al. [12].

The IMPA is herein applied to assess the seismic behavior of two asymmetric plan buildings, along with three more NSPs: the MPA, the NSP proposed in ASCE/SEI 41-06 [13] and the extended N2 method proposed by Fajfar and his team [14], considering the newest extension of N2 method [14–16] whose original version is proposed and described in Eurocode 8 [17]. The extended N2 is able to capture both torsional behavior and higher mode effects. The described procedures are applied within a wide range of seismic intensities, considering two different approaches: (i) a simplified one with only one component of ground motion, and (ii) both components of ground motion acting simultaneously. These two approaches were considered as a means to compare the results from the original MPA procedure [5], where the seismic demands were evaluated only due to a single component of ground motion, and a more recent one [8], which accounts for the two horizontal components of ground motion.

The objectives of this paper are: i) to evaluate the accuracy of IMPA in estimating seismic demands of asymmetric plan buildings subjected to one and two horizontal components of the ground motions, especially when the structure exhibits inelastic behavior; ii) to compare two multimode methods, IMPA and MPA; and iii) to comparatively assess the accuracy of all methods herein studied: IMPA, MPA, the NSP proposed in ASCE/SEI 41-06 and the extended N2 method. The accuracy of the NSPs is evaluated by comparison with nonlinear dynamic analyses (NDAs), for several levels of seismic intensity.

## 2. Nonlinear Static Procedures (NSPs)

### 2.1. Modal Pushover Analysis for asymmetric-plan buildings (MPA)

The MPA considers a non adaptive force based pushover analysis based on modal proportional load patterns. The method takes into account the higher mode effects since in each run a different load pattern proportional to each mode of vibration of the structure is applied, and the results computed from each pushover curve are combined to obtain the final results. The complete methodology is described step by step in [6,8].

In MPA, and for asymmetric plan buildings, the seismic demand for each mode of vibration is evaluated by non-linear static analysis including in the load pattern two lateral forces and torque at each floor level. Nevertheless, a different loading type can be applied in order to replace the torque applied to the building. This loading type takes into account all nodes, that have mass assembled. In each node the modal displacements in both directions are obtained and normalized to the maximum modal displacement of the structure and multiplied by the mass in the respective node. The coupled torsion in the modal deformed shape leads to different displacements in the nodes at the same floor, leading lateral loads with different intensities to be assigned to the structure, generating the torque effect.

When examining both components of ground motion acting simultaneously, the process is repeated for the orthogonal direction for all the modes considered. In terms of values, the load vector used for each component can only vary in the sign, according to the mass participation factor which must be included in the load vector, for the reason that the signs of the peak modal demands are crucial to the accuracy of the CQC rule which is used to combine the seismic demands of the considered modes. After obtaining the seismic responses from both components of ground motion, they are combined by the SRSS multi-component combination rule to determine the seismic response of the structure, and then, the total responses may be computed by adding the gravity loads response.

### 2.2. Improved Modal Pushover Analysis (IMPA)

The key idea of the IMPA procedure is to use the deformed shape of the structure responding inelastically to the considered earthquake level in lieu of the elastic mode shape. So the IMPA, following the procedure performed for bridges by Paraskeva and Kappos [3], is divided in two phases: i) in the first phase, the seismic response is computed for each mode following the MPA procedure [6]; ii) in the second phase, the process is restarted using a lateral forces distribution proportional to the displacement shape vector corresponding to the peak deformation obtained in the first phase, the procedure being repeated. Similarly to MPA, the process is repeated for as many modes as required until sufficient accuracy is achieved. The seismic response due to each mode is computed and the total demand is obtained by combining gravity response and the peak modal responses using CQC combination rule.

The procedure can also be applied when considering both components of ground motion acting simultaneously in the buildings. In this case, seismic responses are computed for both components of the ground motion separately, in each mode, in a first phase. A second phase follows, where two more analyses are performed, one for each component, using the lateral forces distribution proportional to the displacement shape vector at the peak deformation obtained in the first phase. The seismic response for each component of ground motion is obtained by combining, firstly, the results of the required modes and then by using the SRSS rule, leading to the total seismic response of the structure.

A step-by-step summary of the IMPA procedure to estimate the seismic demands for an asymmetric plan multistory building is presented as a sequence of steps:

1) Compute the natural frequencies, $\omega_n$, and modes, $\phi_n$, for linearly elastic vibration of the building.
2) For the $n$th mode, develop the Base Shear–Reference Displacement, *Vn–urn*, pushover curve, by Nonlinear Static Analysis of the building, applying the force distribution $s_n{}^*$ proportional to the modal shape, $\phi_n$, defined as follows:

$$s_n^* = sign(\Gamma_n)\begin{bmatrix} m\phi_{xn} \\ m\phi_{xn} \\ I_0\phi_{\theta n} \end{bmatrix} \quad (1)$$

where $m$ defines the mass assembled and $I_{0,}$ the polar inertia. $\Gamma$ is the mass participation factor. The chosen component has the same direction of the dominant motion of the mode being considered.
3) Idealize the $V_n$–$u_r$ pushover curve as a bilinear curve, and convert it into the force–deformation, $F_{sn}/L_n - D_n$ , relation for the $n$th mode inelastic SDOF system by utilizing the following equations:
$F_{sn}/L_n = V_n/M_n^*$ and $D_n = (u_{rn} - u_{rg})/\Gamma_n\phi_{rn}$ .
$M_n^*$ is the effective modal mass of the $n$th mode.
4) Calculate the reference displacement taking into account roof displacement due to gravity loads ($u_{rg}$): $u_{rn} = u_{rg} + \Gamma_n f_{rn} D_n$. The peak deformation $D_n$ of the $n$th mode inelastic SDF system,