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PROPOSAL AND APPLICATION OF THE INCREMENTAL MODAL PUSHOVER ANALYSIS (IMPA)

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ABSTRACT

Existing reinforced concrete frame buildings designed for vertical load only could suffer severe damage during earthquakes. In recent years, many research activities have been paid to develop reliable and practical analysis procedure to identify the safety level of existing structures. The Incremental Dynamic Analysis (IDA) is considered to be one of the most accurate methods to estimate seismic demand and capacity of structures. But it requires the execution of many nonlinear response history analyses (NL_RHA) in order to describe the entire range of structural response. The research discussed in this paper deals with proposal of an efficient Incremental Modal Pushover Analysis (IMPA) to obtain capacity curves by replacing the NL_RHA of the IDA procedure by Modal Pushover Analysis (MPA). In this work, the basic idea of IMPA is presented and the step-by-step computational procedure is then summarized. This new procedure, accounting the higher modes effects, does not need the execution of complex NL-RHA, but only simpler nonlinear static analysis. Then, the new procedure is applied to an existing irregular building. The capacity curves obtained by different procedures (standard pushover analysis, IMPA and IDA) are presented and discussed.

INTRODUCTION

In recent years, as a result of seismic events occurred in Italy, the safety of buildings has become a topic of considerable interest. Therefore it is very important to develop fast and reliable analysis procedures to identify the safety level of existing structures.

Incremental dynamic analysis (IDA) is a method for the estimation of the seismic response and capacity of structures over the entire range of structural response, from elastic behavior to global dynamic instability. The most accurate way to compute seismic demands of a structure under a given seismic action is to carry out a nonlinear response history analysis (NL_RHA) of a detailed three-dimensional (3D) mathematical model of the structure. IDA requires the execution of NL_RHA for an ensemble of ground motions, each scaled to many intensity levels, selected to cover a wide range of structural response, all the way from elastic behaviour to global instability. From the results of such computation, it is possible to determine structural capacities corresponding to various limit states (Vamvatsikos and Cornell, 2002). However, IDA is onerous for practicing engineers since it requires intensive computation of many NL_RHA. Therefore it is a rigorous procedure but not practical for a professional use.

Hence, nonlinear static procedures (NSP) attract the attention of both practicing engineers and the research community since it is more practical and faster to be implemented. Different NSPs have been developed a widely used for their conceptual simplicity, computational attractiveness and

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capability of providing satisfactory predictions of seismic response for buildings: the N2 method (Fajfar and EERI, 2000), the Capacity Spectrum Method (CSM) (Freeman, 1998), Adaptive Capacity Spectrum Method (ACSM) (Casarotti and Pinho, 2007) etc. Among the current nonlinear static analysis methods, modal pushover analysis (MPA) was developed by Chopra and Goel (2002) to take account of the contribution of higher modes to the total response; later, Geol and Chopra (2004), Chintanapakdee and Chopra (2004) reported that MPA yields better results compared to the traditional pushover analysis. However, most of the researches dealing with nonlinear static analysis procedures have been limited to planar structures. To date, focusing on the existing buildings characterized by a remarkable architectural and structural complexity, it is of significant importance to extend NSP to the complexity of 3D structure to discuss 3D effects of irregularities, the relevance of the control point position (both in plan and elevation). Fajfar et al. (2005) extended the N2 method to plan-asymmetric buildings. Moghadam and Tso (1996,2000) investigated the extension of NSP to multi-story asymmetric frame buildings with uni-directional eccentricity subjected to uni-directional excitation. Chopra and Goel (2004) extended the MPA concept to estimate seismic demands of plan-asymmetric buildings. Lin et al (2012) explained how to understand the torsional effects in asymmetric-plan buildings. Mahdi and Gharaie (2011) studied the seismic behavior of three intermediate moment-resisting concrete space frames with unsymmetrical plan in five, seven and ten stories by using pushover analysis.Due to the development of MPA to evaluate the seismic demands of the structure, it is of a great interest to replace the NL_RHA for each given seismic intensity level by MPA to reduce the computational effort required for IDA. Han and Chopra (2006) developed an approximate IDA procedure based on MPA, showing that the MPA-based IDA provides accurate estimation of seismic demand and capacity for structures. Therefore, the aim of this paper is to propose a more efficient incremental modal pushover analysis (IMPA) to obtain capacity curve of the structure, such as IDA curves, by MPA to evaluate the seismic demand: the procedure proposed has been applied to an existing irregular building. In the following, first, the basic idea of IMPA is presented and the step-by-step computational procedure is then summarized. Secondly, an existing building, which presents both vertical and plan irregularities, is selected as case study to check whether the IMPA procedure to asymmetric structures can be successful. Finally, capacity curves are obtained by different procedures (standard pushover analysis, IMPA and IDA) are presented and discussed.

INCREMENTAL MODAL PUSHOVER ANALYSIS (IMPA)

The IMPA proposed is a pushover based procedure that requires execution of MPA and evaluation of the performance of the structure for a range of intensity of seismic actions. The database resulting from the application of MPA with the detected range of seismic intensity provides all the response information needed to estimate seismic response due to different intensity levels. For each seismic intensity level, the corresponding Performance Point (P.P.) for the multi-degree-of-freedom (MDOF) system, in terms of roof displacement and corresponding base shear, can be obtained by combining the P.P. determined by applying the Capacity Spectrum Method (CSM) for the significant single modes: the P.Ps will be combined through Square Root of the Sum of Squares (SRSS) rule. This way it is possible to obtain a range of P.Ps, each one corresponding to a specified seismic intensity level: the CSM is applied with the Response Spectrum (RS) of the set of intensity. The RS will be scaled up to obtain a set of intensities such as in IDA with the time histories. By connecting all the P.Ps, a curve can be obtained: this curve has been named “Multimodal Capacity Curve” (MCC). The detailed step-by-step implementation of the IMPA procedure is presented below:

1. Compute the natural frequencies ω_n and modes φ_n for linearly elastic vibration of the building;

2. Select the ground motions and the RS for a range of intensity levels;

3. For the intensity level *i*, which is represented by Peak Ground motion Acceleration (PGA), CSM is adopted to search for P.P. for the predominate modes: for the *n*th mode, transform capacity curve, which is in terms of base shear and roof displacement, into a capacity spectrum and transform the RS into Acceleration Displacement Response spectrum (ADRS) format, plot them on the same

chart, their intersection is taken as the P.P., as shown in Fig.1a). Obtain the corresponding P.P. from the capacity curve, as shown in Fig.1b). It is worthy to note that, for the *n*th mode, if the structure enters nonlinear plastic stage, then the demand spectrum should be reduced by the spectral reduction factor which depends on the effective viscous damping of structure ξ_{ni}:

$$\xi_{ni} = \xi_0 + k\frac{1}{4\pi}\frac{E_{dni}}{E_{S0ni}} = \xi_0 + k\xi_{eqni} \tag{1}$$

where ξ_{ni} is the effective damping for n^{th} mode, ξ_0 is the inherent damping of the elastic structure, around 5% for reinforced concrete structures; E_{dni} is the energy dissipated in an ideal hysteretic cycle, in the sense which corresponds to the area of enclosed by the hysteresis loop; E_{s0ni} is the maximum strain energy that the structure dissipates, which corresponds to the area of hatched triangle; and *k* is modification factor of the damping.

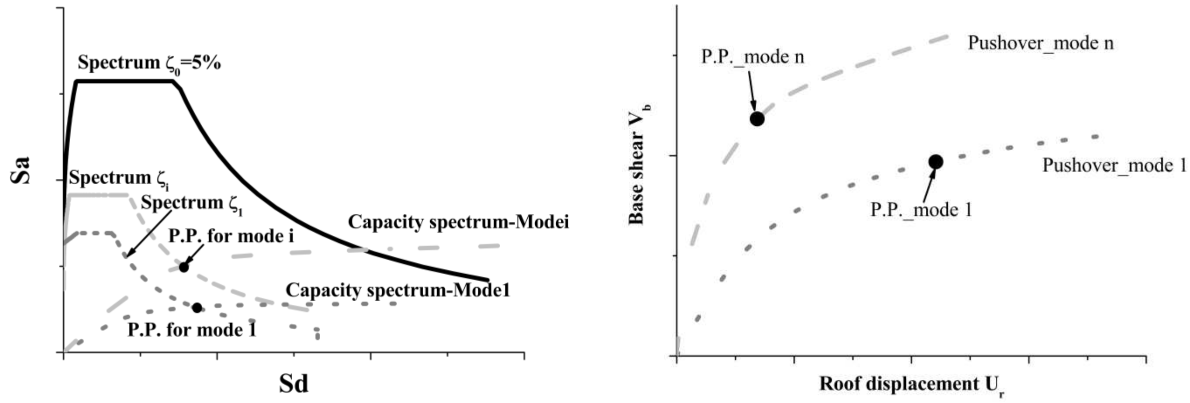

Figure 1. Evaluation of the performance points (P.P.) for each capacity curve that belongs from the pushover analysis with the selected load distributions: proportional to Mode1…Mode n. a) for each capacity curve the P.P. is determined via CSM. b) P.P. can be plotted in the V-U plane

4. Determine Multimodal Performance Point (P.P.mm) in terms of multimodal base shear V_{bmmi} and multimodal roof displacement u_{rmmi} for seismic intensity level *i* by combining the single "modal" base shears (V_{b1i}…V_{bni}) and roof displacements (u_{r1i}…u_{rni}) using the SRSS rule:

$$u_{rmmi} = ((\sum_n u_{rni}^2)^{1/2}) \quad V_{bmmi} = ((\sum_n V_{bni}^2)^{1/2}) \tag{2}$$

5. Repeat steps 2–4 for as many intensity levels to form the IMPA curve, as shown in Fig.2.

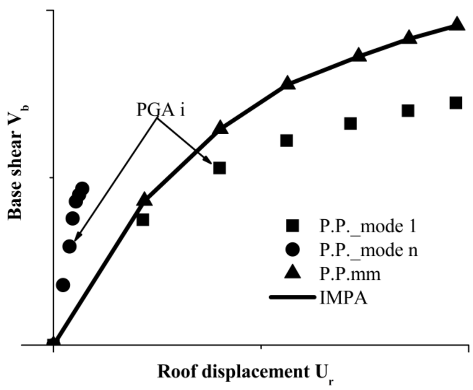

Figure 2. Construction multimodal capacity curve (MCC) from the IMPA procedure. By applying SRSS rule with the P.P. obtained with each load distribution (Mode1...Mode n) and for each intensity level (the response spectrum is scaled from lower to higher intensity levels) the MCC can be obtained.

CASE STUDY

The building detected as case study is an existing nine stories RC framed building located in Italy, designed for gravity loads only and was built in 1970s. The building consists of a ground floor, eight-storey elevation and a roof terrace. The heights of the floors are irregular and go from a minimum of 3.08 m up to 4.80m. From a structural point of view, the plan is an irregular polygon where the resistant elements are distributed unevenly: the concentration on one side of shear walls and the one way orientation of the beams cause a strong irregularity. A three-dimensional finite element model was built in SAP2000 software, as shown in Fig.3 and Fig.4.

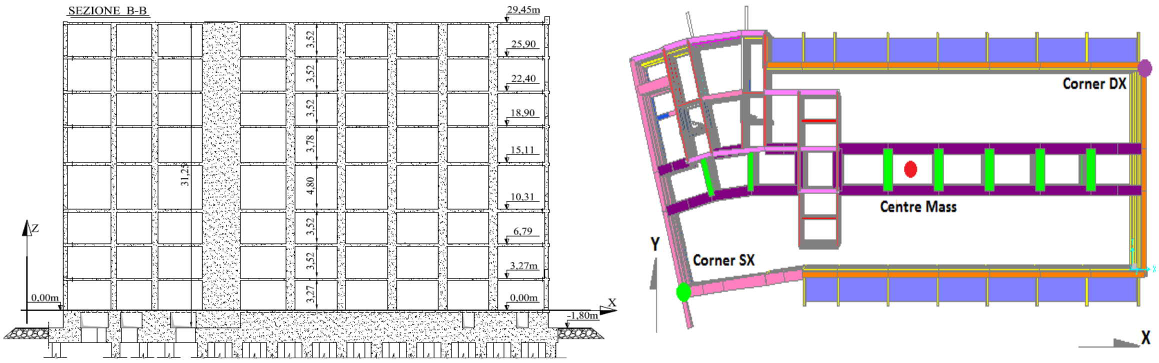

Figure 3. Longitudinal sections of the building

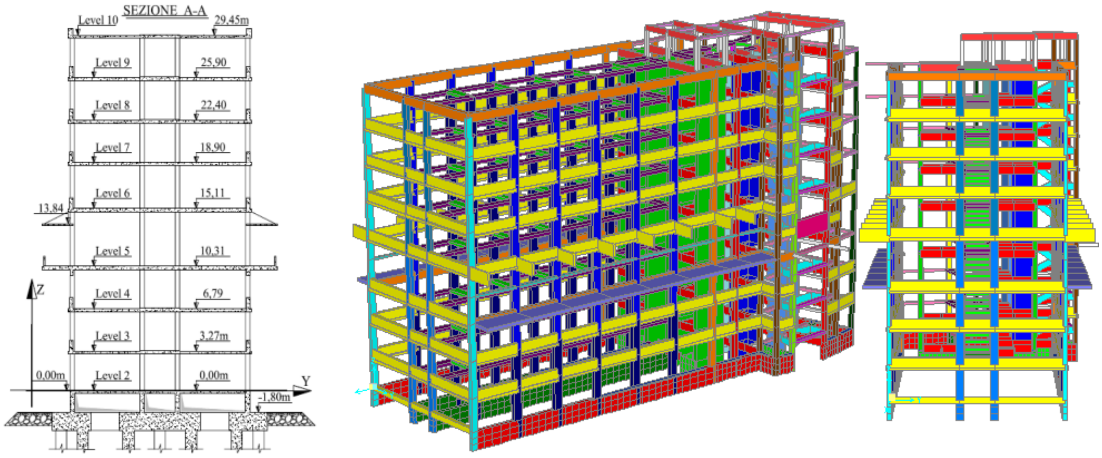

Figure 4.Transverse section of the building and 3D view of the numerical model

In this study, the seismic action has been defined using both elastic response spectrum according to Italian technical code (NTC'08) and a set of 7 natural time histories, which are defined using the software Rexel and named by TH1…TH7. In both cases, seismic action is described by two orthogonal components assumed as being independent and represented by the same response spectrum or by time history; the vertical component of the seismic action has been ignored. In Fig.5 the elastic response spectrums defined by NTC'08 is shown with the response spectrum of each time history record.

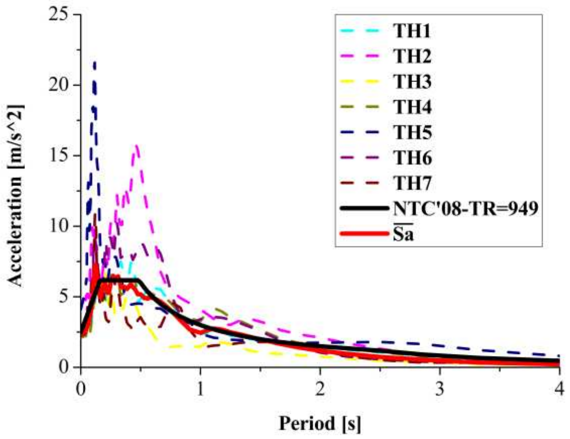

Figure 5. Response spectra of the code-compliant set of Time Histories (TH): TH1...TH7 are the selected ground motion records, NTC'08 is the response spectrum according to Italian technical code for a returning period of T_R=949 years, and $\overline{Sa}$ is the average response spectrum from the set.

RESULTS

Modal analysis is employed to identify the dynamic behavior of the existing structure and investigate the relevance of higher modes. The participating translational masses along X direction (*MT_X*), along Y direction (*MT_Y)* and rotational mass with respect to the vertical direction Z (*MR_Z*) of the first ten modes are plotted in Fig.6. It is clear that for X direction the dominant mode is the third one, the third, ninth and tenth modes exhibit more than 79% of participation mass, while for Y direction the first mode , the first, fourth and seventh modes exhibit more than 83% of the participation mass, these modes will be considered in the IMPA.

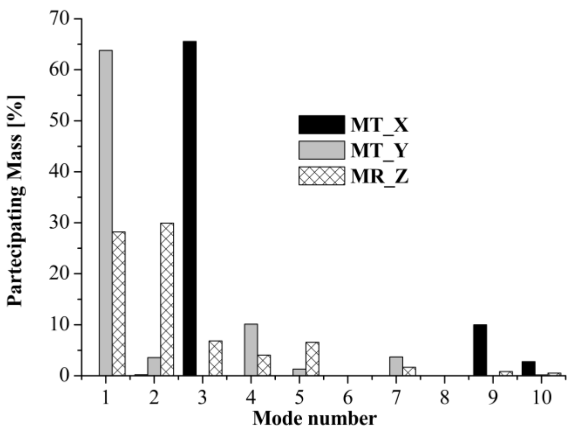

Figure 6. Modal mass participation

In this study, the center of mass (CM) and two corners (SX, DX) are taken as control points, as shown in Fig.3: the displacements associated to these three control points for the first four modes are shown in Fig.7. It can be found that the structure exhibits a behavior with decoupled translational and rotational along X direction, where there are strongly couple along Y direction especially in the right side of the building. This peculiarity is an indicator of lack of structural regularity in plan. The right side of the building is more deformable of the opposite side as a result of lack of vertical elements in this area.

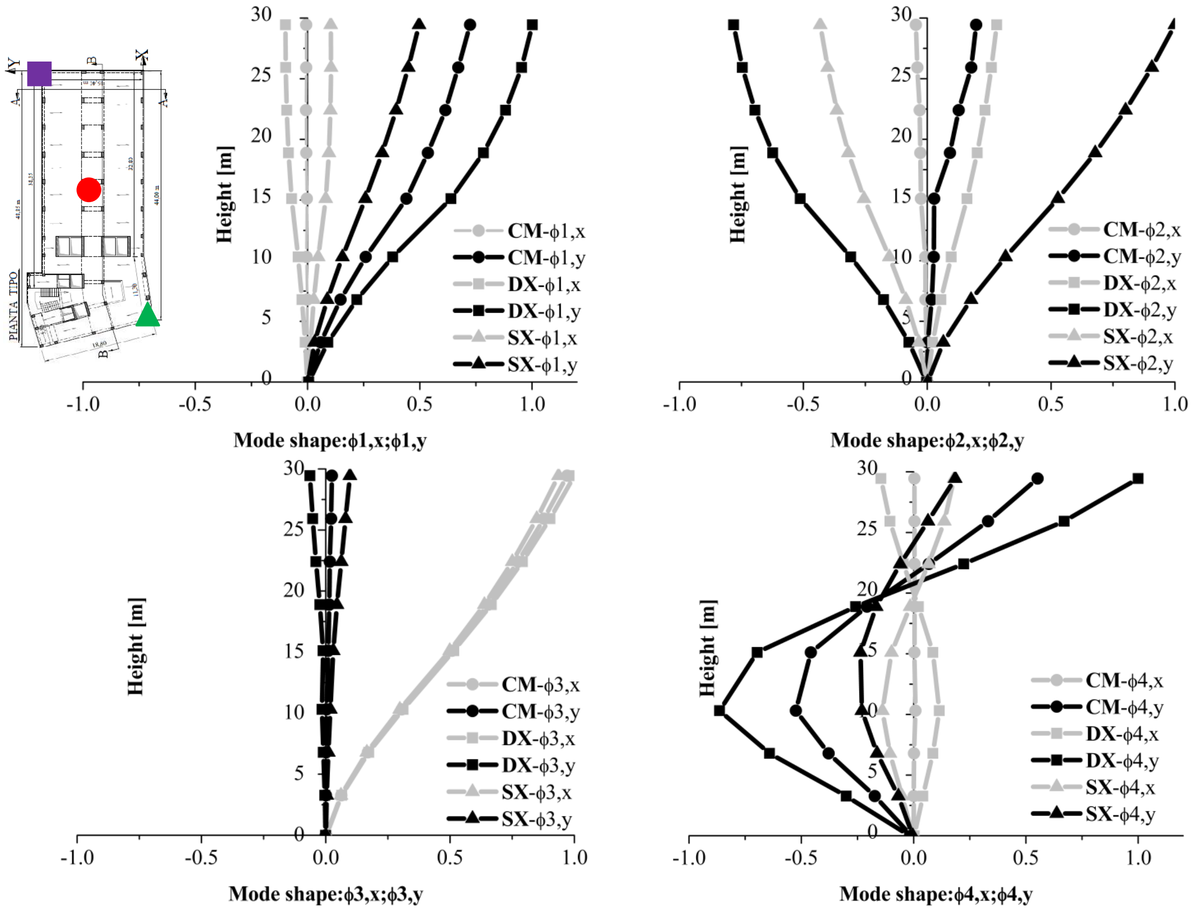

Figure 7. Modal shape (ϕ1... ϕ 4) configurations considering different control nodes: CM, DX, SX a) ϕ 1,b) ϕ 2, c) ϕ 3, d) ϕ 4

Fig.8 shows the performance point (P.P.) obtained from capacity spectra for PGA=0.25g. CSM is used to search the P.P. of the i^{th} mode inelastic SDF system. The elastic response spectra defined by NTC'08 is taken as the demand spectrum. It is observed that along X direction, the third mode of the structure exhibits its inelastic behavior and the remaining modes are still in almost linear elastic state. Along Y direction, the structure enters in the nonlinear state for the first mode, and linear elastic state for fourth and seventh mode. According to CSM, when structure enters nonlinear plastic stage, and the spectral reduction factor depends on the effective viscous damping of equivalent Single Degree of Freedom (SDF) system ξ_i.

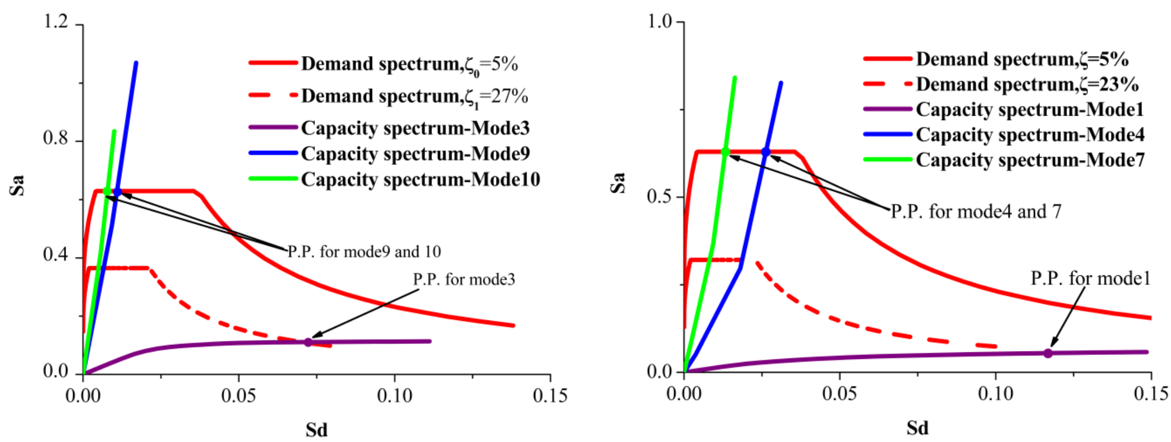

Figure 8. P.P. for the CM is determined via CSM from original and reduced demand spectrum for the predominate modes. a) Capacity spectra along X direction, b) Capacity spectra along Y direction.

Repeat this procedure for other intensity levels, then determine the corresponding P.P. for the modal MDOF system, in terms of roof displacement and corresponding base shear, to form the Multimodal Capacity Curve (MCC). By combining the individual modal responses through SRSS rule, both for roof displacements and base shear are determined and then all those pairs, each relative to corresponding intensity level, form the multimodal capacity curve, which is defined as MCC by the writers as shown in Fig.9.

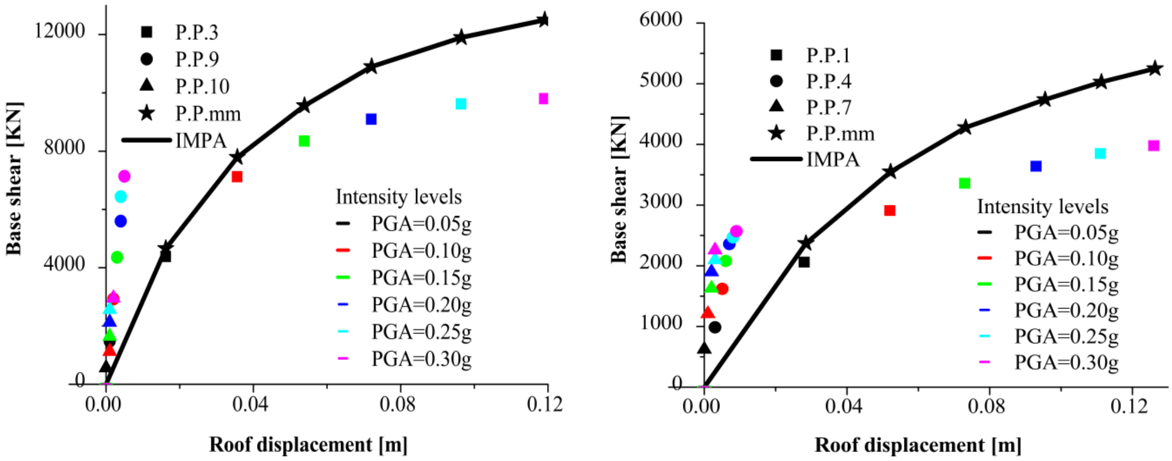

Figure 9. Construction MCC from the IMPA procedure. The P.P.mm is obtained by applying SRSS rule with the P.P. obtained from single mode pushover (Mode1...Mode n) and for each intensity level, repeat this procedure for a range of intensity levels (the response spectrum is scaled from lower to higher intensity levels) and the MCC can be obtained, a) MCC for X direction, b) MCC for Y direction

The P.P. obtained from the single mode pushover curve and IMPA together with IDA are shown in Fig.10~Fig.12. It is worthy to note that the maximum base shear is asynchronous with the maximum roof displacement in the NL_RHA, the mean of maximum base shear and maximum roof displacement to an ensemble of earthquake excitations are used to form the capacity curve in the IDA procedure.

From the projection onto the PGA-roof displacement plane, the superimpose the single mode pushover curve on the IMPA curve indicate that IMPA will not increase the roof displacements. From the projection onto the PGA-base shear plane, it is clear that IMPA curve including the contribution of higher modes to the base shear is more close to th IDA curve, but a big errors in the inelastic phase. From the base shear-roof displacement plane, compared to standard single mode pushover curve, the increase of base shear in the IMPA make the capacity curve from IMPA more stiff , and more close to the IDA curve.

For the X direction, the capacity curves are almost the same, it is also another indication that the pure translation along this direction. When the structure enters into inelastic state, IMPA would underestimate the base shear compared to IDA. For Y direction, the underestimation of base shear for the inelastic phase is more evident. The static pushover cannot fully catch up the torsional effect on base shear for the irregular structure, so there are big errors for the corners in the inelastic phase.

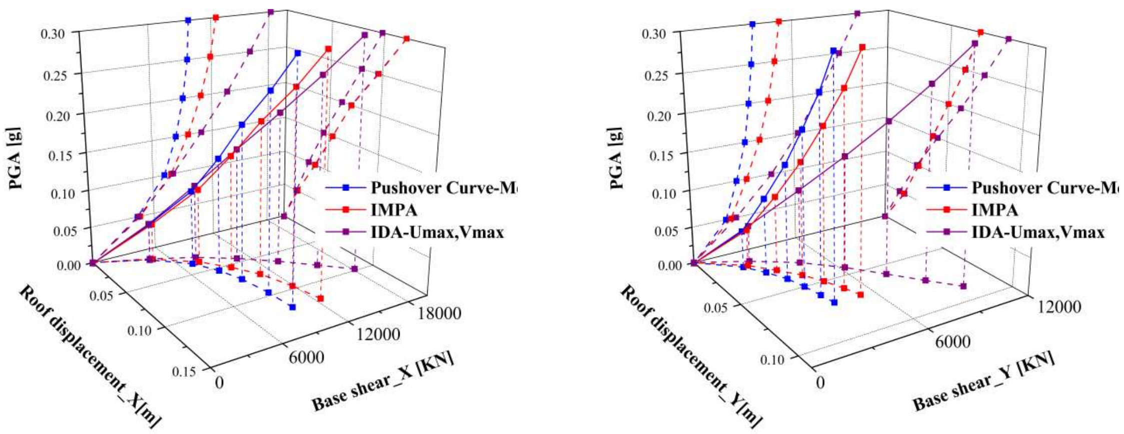

Figure 10. Capacity curves obtained from different methods: the standard pushover analysis (for the predominate mode), IMPA method and IDA method for the left edge of building (SX), a) capacity curves along X direction, b) capacity curves along Y direction.

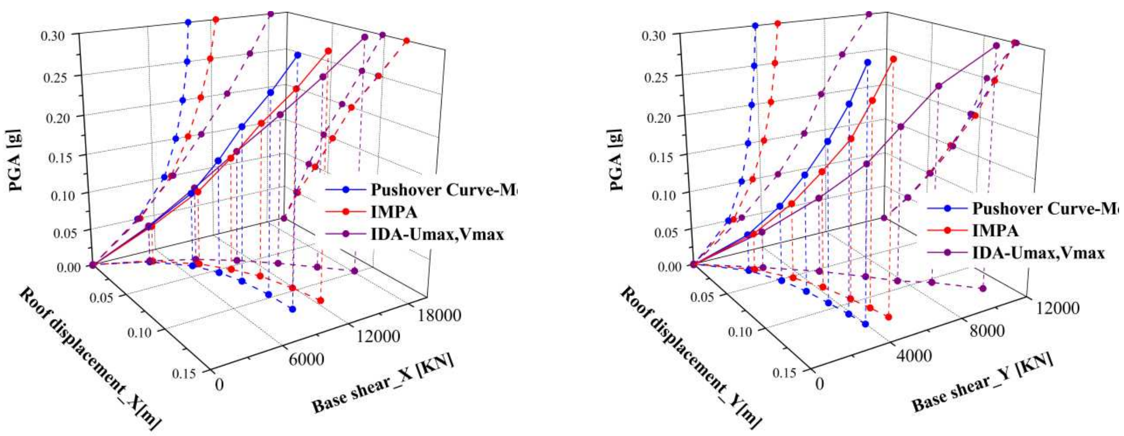

Figure 11. Capacity curves obtained from different methods: the standard pushover analysis (for the predominate mode), IMPA method and IDA method for the center of building (CM), a) capacity curves along X direction, b) capacity curves along Y direction.

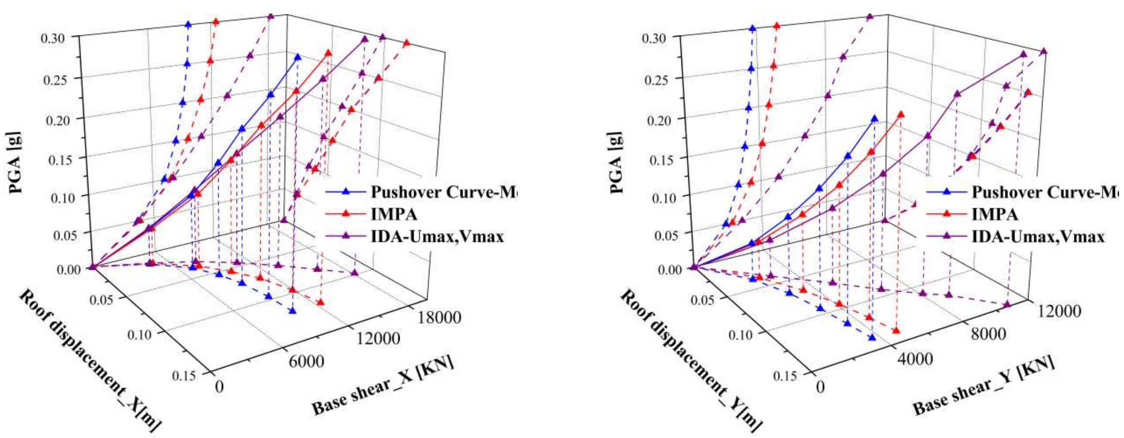

Figure 12. Capacity curves obtained from different methods: the standard pushover analysis (for the predominate mode), IMPA method and IDA method for the right edge of building (DX), a) capacity curves along X direction, b) capacity curves along Y direction.

CONCLUSION

In this work, an Incremental Modal Pushover Analysis (IMPA) is proposed to evaluate the seismic capacity, which in terms of the roof displacement and base shear, and then applied to an existing irregular building. IMPA replaces the NL_RHA by MPA to estimate the seismic demand and capacity of structures over the entire range of structural response to reduce the computational effort required for IDA. The proposed procedure, which is relatively simple as it is based on static nonlinear analysis, proves to be effective and efficient: for each seismic intensity level, the corresponding performance point (P.P.) for MDOF system can be obtained from MPA by superimposing the roof displacement and base shear through SRSS rule; repeat this way to a range of intensities, a range of P.P., each one corresponding to a specified seismic intensity level can be obtained to form a modal capacity curve, in this procedure, no dynamic analysis is required. The effectiveness of the procedure based on the non linear static analysis has been shown through applications to an existing irregular building. Compared to the conversional static capacity curve, IMPA including the contribution of higher modes to the base shear will provide a better estimate the capacity curve. The static pushover cannot fully catch up the torsional effect on base shear for the irregular structure, so there are big errors for teh corners in the inelastic phase. For the advantage of a more rapid execution of the IMPA compared to IDA, IMPA curve may be considered, however a certain level of error for the inelastic phase, a valid indicator of the structural capacity.

REFERENCE

Casarotti, C. and Pinho, R. (2007), “An adaptive capacity spectrum method for assessment of bridges subjected to earthquake action,” *Bulletin of Earthquake Engineering*, 5(3), 377–390.

Chopra, A.K. and Chintanapakdee, C. (2004), “Evaluation of Modal and FEMA Pushover Analyses: Vertically “Regular” and Irregular Generic Frames”, *Earthquake Spectra*, 20(1), 255-271.

Chopra, A.K. and Goel, R.K. (2004), “A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings,” *Earthquake Engineering & Structural Dynamics*, 33(8), 903-927.

Chopra, A.K. and Goel, R.K. (2002), “A modal pushover analysis procedure for estimating seismic demands for buildings,” *Earthquake Engineering & Structural Dynamics*, 31(3), 561-582.

Fajfar, P. and EERI, M. (2000), “A nonlinear analysis method for performance-based seismic design,” *Earthquake Spectra*, 16(3), 573-592.

Fajfar, P., Marušić, D. and Peruš, I. (2005), “Torsion effects in the pushover-based seismic analysis of buildings,” *Journal of Earthquake Engineering*, 9(6), 831-854.

Freeman, S.A. (1998), “The Capacity Spectrum Method as a Tool for Seismic Design,” *Proceedings of the 11th European Conference on Earthquake Engineering*, Paris, France, January.

Geol, R.K. and Chopra, A.K. (2004), “Evaluation of Modal and FEMA Pushover Analyses SAC Buildings”, *Earthquake Spectra*, 20(1), 225-254.

Han, S.W. and Chopra, A.K. (2006), “Approximate incremental dynamic analysis using the modal pushover analysis procedure,” *Earthquake Engineering & Structural Dynamics*, 35(15), 1853-1873.

Lin, J.L., Tsai, K.C. and Chuang, M.C. (2012), “Understanding the trends in torsional effects in asymmetric-plan buildings,” *Bulletin of Earthquake Engineering*, 10(3), 955-965.

Mahdi, T., and Gharaie, V. S. (2011), “Plan irregular RC frames Comparison of pushover with nonlinear dynamic analysis,” *Asian journal of civil engineering (building and housing)*, 12(6), 679-690.

Moghadam, A.S. and Tso, W.K. (2000). “3-D push-over analysis for damage assessment of buildings,” *JSEE*, 2(3), 23-31.

Moghadam, A. S. and Tso, W.K. (1996), “Damage assessment of eccentric multistory buildings using 3-D pushover analysis,” *Proceedings of the 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, June.

Vamvatsikos, D. and Cornell, C.A. (2002), “Incremental dynamic analysis,” *Earthquake Engineering & Structural Dynamics*, 31(3), 491-514.