Chapter 18
Evaluating the Efficiency of Recent Nonlinear Static Procedures on the Seismic Assessment of an Asymmetric Plan Building

A. Belejo and R. Bento

Abstract The Seismic Assessment of an asymmetric plan building is performed through an assemblage of recent Nonlinear Static Procedures (NSPs); some of them are extensions of known NSPs. Among these methods are included two multi-mode methods: Modal Pushover Analysis (MPA) and Improved Modal Pushover Analysis (iMPA); the Extended N2 which considers the higher modes effects in both plan and elevation; and the 3D Pushover wherein each step derives from a different known NSP in order to obtain the most reliable results.

The seismic response of an asymmetric plan building is studied considering both components of ground motion acting simultaneously. The seismic assessment of the building is performed in terms of pushover curves, top displacement ratios, lateral displacements profiles, interstorey drifts, normalized top displacements and shear forces. Such seismic quantities are compared with the results obtained by means of Nonlinear Dynamic Analysis (NDA).

18.1 Introduction

Over the years, NSPs have been constantly modified and improved in order to overcome the drawbacks and inaccuracies discerned in the studies previously performed. The capture of the torsional behavior of the buildings, the influence of higher mode effects and the load pattern considered are included among the most common issues faced by the scientific committee in the application of NSPs in buildings.

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The original version of MPA was created by Chopra and Goel (2002) and is 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 attained combining the results corresponding to each pushover curve using an appropriate combination rule. In 2004 the application was extended to the case of plan asymmetric buildings (Chopra and Goel 2004), and also a modified approach assuming higher modes as elastic was proposed (Chopra et al. 2004). The MPA has been permanently improved and updated until the most recent version which is an adaptation to consider both components of ground motion acting simultaneously in buildings, developed by Reyes and Chopra (2011a, b, 2013).

In 2008 Paraskeva et al. introduced an improved version of the MPA procedure (iMPA) for application in bridges, which was published after (Bento and Pinho 2008; Paraskeva and Kappos 2010). The aim of iMPA was to overcome the weakness of the control node localization and the invariability of the lateral force distribution. In buildings, the node control position is not, in general, 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 may be a valid alternative in order to improve results when the structure exhibits inelastic behavior.

Some attempts to consider the redistribution of inertia forces after structure yields were already suggested for a planar frame structure by Jianmeng et al. (2008); and recently this methodology was tested in 3D asymmetric plan buildings (Belejo and Bento 2014).

Also Fajfar and his team, who proposed the original N2 method (Fajfar and Fischinger 1988) which is recommended in Eurocode 8 (CEN 2004), continued to develop their method through extensions applied to the original version in order to consider the torsion effects (Fajfar et al. 2005), the higher mode effects (Kreslin and Fajfar 2011) and most recently, both effects simultaneously (Kreslin and Fajfar 2012). The extensions are based on the assumption that the structure remains in the elastic range when vibrating in higher modes, therefore the seismic demands are obtained combining the results obtained through a simple Pushover analysis with corrective factors obtained through linear response spectrum dynamic analysis.

Recently due the available set of methods, studies were performed in order to understand which the best approach for the seismic assessment of plan asymmetric buildings, considering the most known procedures. Thus, as result of this study, in Bhatt (2012) the 3D Pushover was proposed, also called as Extended Adaptive Capacity Spectrum method in Bhatt and Bento (2014). This method has as sources the known methods: ACSM (Casarotti and Pinho 2007) regarding to the lateral distribution applied and type of pushover curve obtained, CSM proposed in FEMA440 (Freeman 1998; Freeman et al. 1975; ATC 2005) to obtain the damping considered in the reduced spectrum and consequently the peak displacement and Extended N2 in order to capture the torsional behavior.

The objectives of this paper are to evaluate the individual efficiency of the methods mentioned before in their most recent versions when applied to an asymmetric plan structure. The reliance of the results obtained by the NSPs is evaluated through comparison with Nonlinear Dynamic Analyses (NDAs) for two different levels of seismic intensity.

18.2 Nonlinear Static Procedures

18.2.1 Modal Pushover Analysis for Asymmetric-Plan Buildings (MPA)

The MPA considers a conventional force based pushover analysis based on the vibration modes of the structure. In each run, a different load pattern proportional to the considered vibration mode of the structure is applied, and the results computed from each run are combined in order to obtain the final results. The complete methodology as a whole is described step by step in Chopra and Goel (2004).

The load pattern applied in the scope of MPA for asymmetric plan buildings includes two lateral forces and torque at each floor level as explained in Chopra and Goel (2004). However, in order to substitute the torque a different loading can be applied in the building in the nodes with mass assembled, normalizing the modal displacements of each node for both directions to the maximum modal displacement of the structure and multiplying by the respective mass.

Since both components of ground motion are considered acting simultaneously, the process is repeated for both orthogonal directions for all the modes considered. After obtaining the seismic response due both components of ground motion, they are combined by the SRSS multi-component combination rule to determine the seismic response of the structure.

18.2.2 Improved Modal Pushover Analysis (iMPA)

The iMPA procedure is a two-phase method wherein the deformed shape obtained in the first phase of the method, when the structure is responding inelastically to the considered earthquake level, leads to the load pattern, which is applied in the second phase. The steps of the second phase are the same as in MPA for each mode, but considering the new load pattern.

The iMPA, was originally created for bridges by Paraskeva and Kappos (2010), and tested in buildings by Belejo and Bento (2014).

Considering both components of ground motion acting simultaneously in buildings, in the first phase seismic responses are computed for both components of the ground motion separately for each mode, and in the second phase two more analyses are performed per mode, one for each component. Similar as MPA, SRSS combination rule is used in order to obtain the total seismic response of the structure.

In order to estimate member forces, when combining the seismic response of each mode would lead to forces that exceed the capacity of the elements in cases where both ends of an element deform into the inelastic range, by analyzing the plastic hinge rotations. To overcome this disadvantage, the extension proposed by Reyes and Chopra (2011a) to calculate member forces, is applied in both multi-mode procedures.

18.2.3 Extended N2

The extension of N2 method herein applied is the most recent which takes into account the higher mode effects in both plan and elevation. It corresponds to extended versions of the original N2 method, which is described in Eurocode 8, in order to overcome the torsional problem in asymmetric plan structures and simultaneously considering the higher mode effects, which affects high-rise buildings or buildings irregular in height. This version intends to handle both issues by adjusting the pushover results, computed with the original N2 method, by means of correction factors based on linear dynamic response spectrum procedures, as described in Kreslin and Fajfar (2011).

The method is applied separately, and the results obtained for both directions are combined through SRSS combination rule.

18.2.4 3D Pushover

The 3D Pushover method (Bhatt 2012; Bhatt and Bento 2014) was intended to overcome the problems of a simple pushover analysis using known methods in each step of the procedure. The selection of the method was performed in order to apply the best procedure in each step with the purpose of obtain the most reliable results. The most common issues in performing a pushover analysis are the invariability of the lateral load, the damping associated to the seismic action and the torsional behavior capture. In order to overcome all these problems, all studies performed along the time until this proposal were considered, and the approach which leads to better results was chosen for each step, and combining all steps, a new NSP was created. The methods by which 3D Pushover is based, are essentially the ACSM (Casarotti and Pinho 2007), following its guidelines regarding to the lateral load application; the CSM (Freeman 1998; Freeman et al. 1975) following FEMA 440 (ATC 2005) guidelines in considering the damping associated to the seismic action and to obtain the peak displacement and the extended N2 (Fajfar et al. 2005) to capture the torsional behavior of the structure. The procedure as a whole is described in Bhatt (2012).

After a short description of the procedures, the variants of each method are summarized in Table 18.1.

Table 18.1 Summary of studied nonlinear static procedures

	3D Pushover	Extended N2	MPA	iMPA
Pushover analysis type	Adaptive displacement based	Conventional forced-based	Multi-mode conventional force-based	Multi-mode conventional force-based: two phases
Load pattern	Adaptive displacements loading	First mode proportional loading	All significant modes proportional loading	1st Phase: MPA
				Proportional to the deformed shape correspondent to the peak deformation obtained in the 1st phase
	Direction of translational motion	Direction of translational motion	Both directions	Both directions
Capacity curve(s)	One per direction		One per mode in each direction (dominant direction of motion)	1st Phase: MPA 2nd Phase: one per intensity (in both directions) of seismic ground motion for all modes in each direction
Demand curve	Elastic viscous damping-based reduced spectrum	Inelastic ductility-based reduced spectrum		
Additional corrective factors	Ratio between the normalized roof displacements obtained by an elastic response spectrum analysis and by the pushover analysis $(\Pi_{RSA}/\Pi_{PA}) \geq 1$			None
		Ratio between the normalized interstorey drifts obtained by an elastic response spectrum analysis and by the pushover analysis $(\Pi_{RSA}/\Pi_{PA}) \geq 1$		

18.3 Case Study

In this work, the case study analyzed is a bi-asymmetric plan nine-story steel building (Fig. 18.1), the same analyzed in Belejo and Bento (2014).

All floors present the same height of 3.96 m and all structure shows 9.14 m spans. The identified columns and the girders that connect them are characterized as Moment Resisting Frames (MRF), whereas gravity frames whose only function is to support the gravity loads compose the remaining structure. Member sizes are governed by drift instead of strength requirements and are defined in Reyes (2009). Due to the lack of available models to define the panel zones in the software used in this work, braced frames were introduced in the alignments C1–C8, C3–C9, C9–C12 and C14–C18 in order to obtain the same modal characteristics of the building studied by Reyes (2009). The translational masses considered in 1st–8th floors are 1,212 tones and 1,074 tones in the roof.

18.4 Modeling Issues

The building was modeled in SeismoStruct v6.0 (SeismoSoft 2006), a downloadable fiber element based finite element software. The model was built using space frames assuming the centerline dimensions. All sections were defined with 100 fibers and each fiber was characterized by the material relationship.

Hysteretic damping is implicitly included in the nonlinear fiber model formulation of the inelastic frame elements. In order to take into account the possible non-hysteretic sources of damping, it was modeled by Rayleigh damping with its two constants selected to give 2 % damping ratio at the fundamental period of vibration T1 and a period of 0.2T1, following the work of Reyes (2009). According to Priestley and Grant (2005), the non-hysteretic damping represents the energy dissipation due to phenomena like friction between structural and non-structural

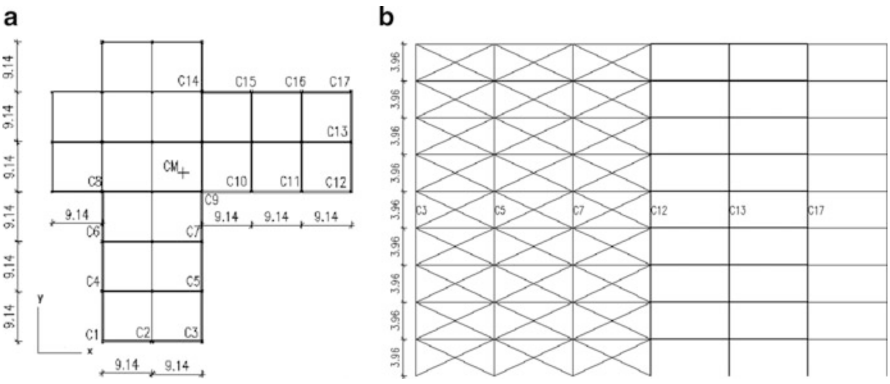

Fig. 18.1 Case study; (**a**) Plan view; (**b**) Lateral view, dimensions in [m] (Belejo and Bento 2014)

members, energy radiation through the foundation, etc., and which is mobilized during the seismic response of the structure. The scientific and engineering community still does not have definitive answers about the type and values of viscous damping used to represent such energy dissipation.

A simplified bilinear stress-strain relationship with 3 % of strain hardening was assumed for steel, based on Byfield et al. (2005) exhibiting an average yield strength around 248 MPa and an ultimate strength of 400 MPa.

Nodal Constraints were modeled with a Penalty Functions option with exponent 10^7 in order to take into account the rigid diaphragm effect. The mass of each floor was applied lumped in the nodes, according to the respective tributary area.

18.5 Seismic Features

Seven ground motion records were randomly selected from the set of records used by Reyes which criteria were defined in Hancock et al. (2006). All records were matched to the seismic hazard spectrum with 2 % probability of exceedance in 50 years.

Table 18.2 shows the Earthquakes and respective station of the records considered.

In the records considered, SeismoMatch v2.0.0 (SeismoSoft 2008) was used to match them to the hazard spectrum for the period range between 0.2T1 and 2T1. SeismoMatch is an application capable of adjusting earthquake accelerograms to match a specific target response spectrum. The method used for spectral matching adjusts the time history in the time domain by adding wavelets to the acceleration time-series as described in Hancock et al. (2006).

The mean spectrum of each component and the overall mean spectrum are shown in Fig. 18.2 as well as all matched spectra and the Seismic Hazard spectrum.

In order to reduce the time of analysis, an interval between the build-up of 5 and 95 % of the total Arias intensity (Bommer and Martínez-Pereira 1999) is considered.

Due to the uncertainty of knowing the position of the buildings relatively to the components of the records, all records were assigned to the building in two different ways: X component of the record according to the X component of the building and Y component of the record assigned to the Y component of the building; and the opposite, i.e. the X component of the record assigned to the Y direction of the

Table 18.2 Ground motion records considered

Earthquake name	Station name
Northridge 1994	Beverly hills
Duzce 1999	Bolu
Kobe 1995	Snishi – Akashi
Superstition Hills 1987	Poe
San Fernando 1971	LA Hollywood
Imperial Valley 1979	Sahop Casa Flores
Hector Mine 1999	Hec

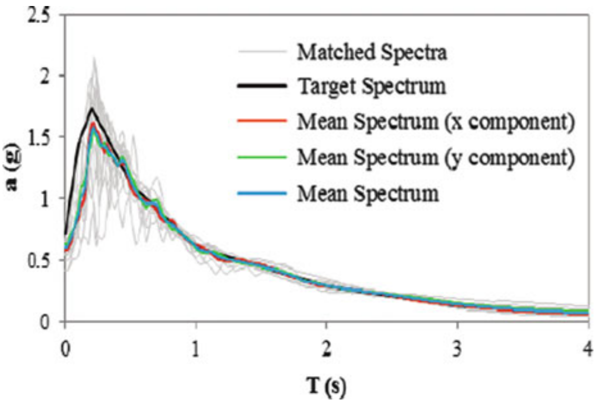

Fig. 18.2 Seismic hazard spectrum and the median response spectra of seven scaled ground motions (X and Y directions and overall)

building and the Y component of the record assigned to the X component of the building. Therefore the final seismic response is determined by the mean of the 14 results obtained. Consequently, for each intensity level, the spectrum used to compute the peak deformation in NSPs, corresponds to the mean spectrum obtained from the 14 records (two components for each ground motion).

18.6 Numerical Results and Discussion

In this section, the seismic response of the building obtained through the NSPs and NDAs, is shown in terms of pushover curves, top displacements ratios, lateral displacement profiles, interstorey drifts, normalized top displacements and Shear Forces for two different levels of seismic intensity, considering both components of ground motion acting simultaneously.

The modal properties of the building are displayed in Table 18.3, which shows the periods and the effective modal mass percentages in both X and Y directions (Ux and Uy) for the two first triplet of modes (6 modes).

The first mode of the building is characterized by torsion motion, the second mode shows translation along both axes, but predominantly in X direction, and the third mode has translational behavior in Y direction coupled with torsion; which means torsional flexibility in both directions. The second triplet of modes (4th to 6th modes) assumes the same order regarding to the nature and directions of motion when comparing with the first triplet.

These two triplets of modes were selected in order to estimate the seismic demands in both directions for the two multi-mode methods. In such procedures, for each mode, only pushover curves in the dominant direction of motion are considered: the pushover curves in the X direction were considered for the 2nd mode and in Y direction for the 1st and 3rd modes for both triplets of modes.

Figures 18.3 and 18.4 display the pushover curves obtained for the MPA (and the 1st phase of iMPA) for each mode considered together with peak displacements obtained for all intensities of ground motion considered, wherein two different

Table 18.3 Periods (in seconds) and effective modal mass percentages of the studied building

Mode	Period (s)	[Ux] (%)	[Uy] (%)
1	1.86	8.0	26.7
2	1.70	59.9	20.5
3	1.57	12.7	33.0
4	0.68	1.1	3.1
5	0.59	7.3	3.5
6	0.55	2.3	4.2

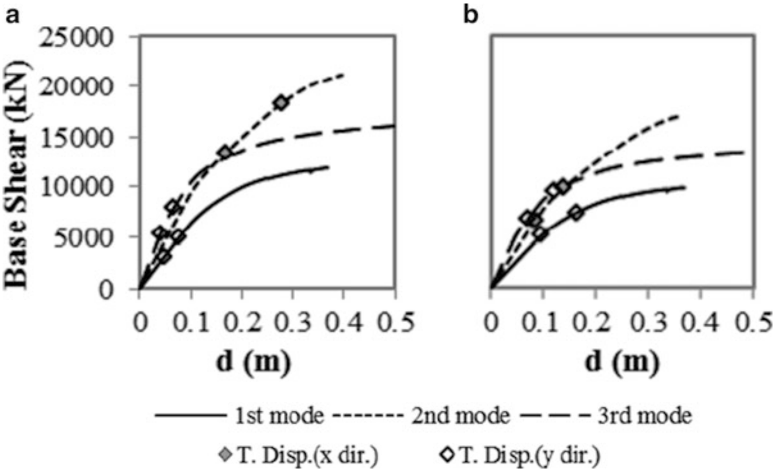

Fig. 18.3 Pushover curves of the 3 modes in MPA procedure: (**a**) 1st triplet of modes, X direction; (**b**) 1st triplet of modes, Y direction

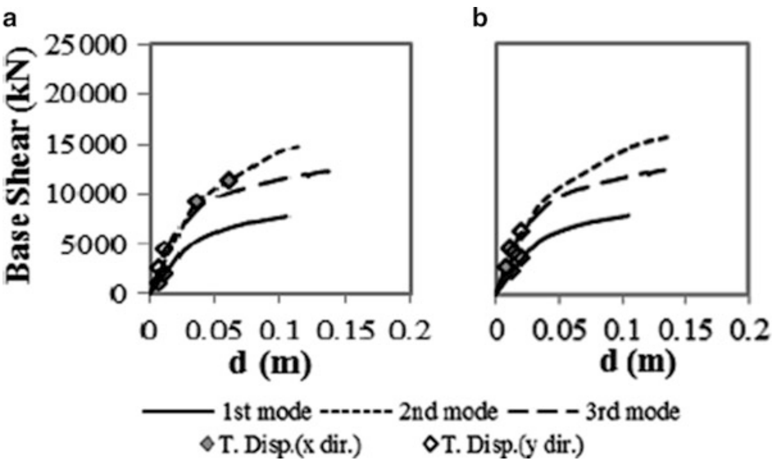

Fig. 18.4 Pushover curves of the 3 modes in MPA procedure: (**a**) 2nd triplet of modes, X direction; (**b**) 2nd triplet of modes, Y direction

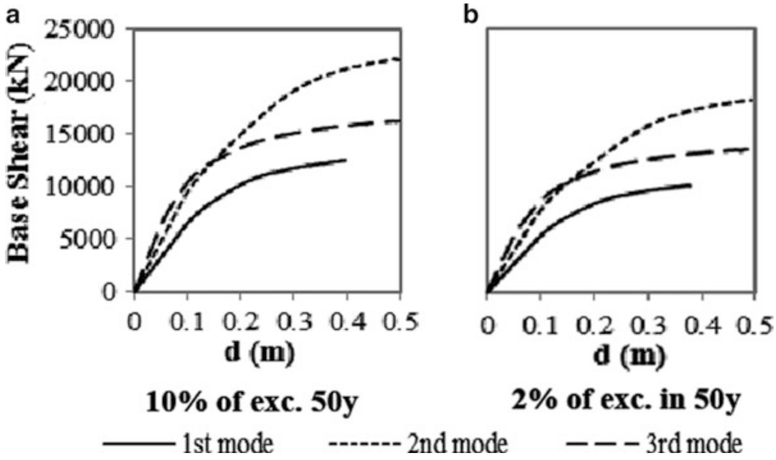

Fig. 18.5 Pushover curves of the 2nd phase of iMPA procedure in X direction

intensities are tested: the first intensity corresponds to a 10 % probability of exceedance in 50 years and the second one to a 2 % probability of exceedance in 50 years.

As mentioned in Sect. 18.2, iMPA is a double-run method, in which the final lateral load pattern for each mode is dependent of a first peak of displacement obtained. This means that for each intensity of seismic action and direction considered, a second pushover curve is achieved, from which seismic response is captured. This phase of the method was not performed for the second triplet of nodes for the reason that the higher mode equivalent SDOF systems do not contribute much to the inelastic response when the structure reaches the peak deformation in the first phase as shown in Fig. 18.3b, and that the errors arising from elastic computation in calculating the response of higher-mode equivalent SDOF systems can be neglected (Gupta and Kunnath 2000). For the first triplet of modes, pushover curves from the second phase of the method are shown in Figs. 18.5 and 18.6.

In extended N2, pushover curves are obtained by applying a lateral load proportional to the 1st mode shape in each direction (Fig. 18.7). Whereas the capacity curves obtained through 3D Pushover are derived from displacement adaptive Pushover analysis in separated directions, which are displayed in Fig. 18.8.

From the curves plotted in Figs. 18.7 and 18.8, as those obtained according to the three first modes in multi-mode methods, one can conclude that the building shows different behavior for both intensities studied: transition between elastic and inelastic behaviors when considering 10 % probability of exceedance in 50 years, and inelastic behavior for 2 % probability of exceedance in 50 years.

Taking into account the Pushover Curves plotted in Figs. 18.3, 18.4 and 18.5, all the seismic demands are obtained.

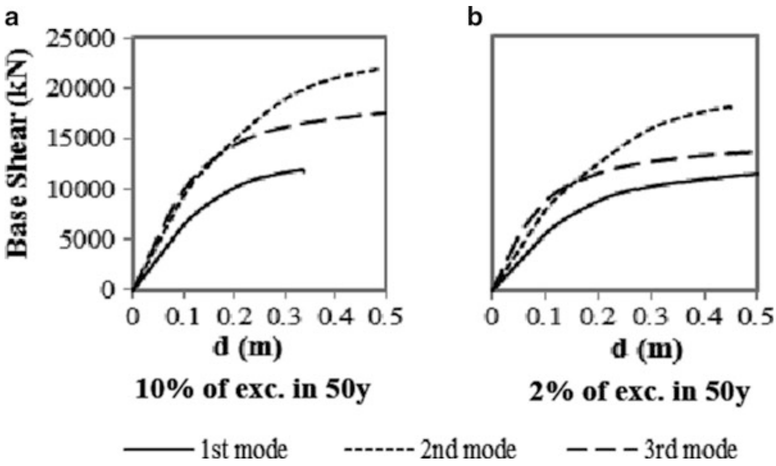

Fig. 18.6 Pushover curves of the 2nd phase of iMPA procedure in Y direction

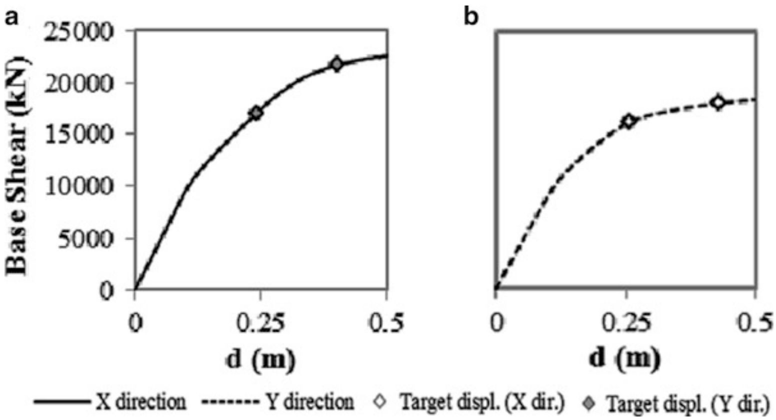

Fig. 18.7 Pushover curves in X and Y direction, respectively, in extended N2

Displacement ratios between the values obtained with the analyzed NSPs and the corresponding mean estimates coming from NDAs are computed (18.1). The NSPs must never lead to underestimated results, therefore these ratios should always be higher than 1.

$$\text{Top Displacement ratio} = \frac{\text{NSP's top displacement}}{\text{NDA mean top displacement}} \tag{18.1}$$

The nonlinear dynamic results obtained are used to compare with NSPs results. Therefore, by this analysis, one would desire such ratios to tend to unity, which means that the NSPs would match to the NDA mean results. These ratios, defined in terms of top displacements in the center of mass, are plotted in Fig. 18.9.

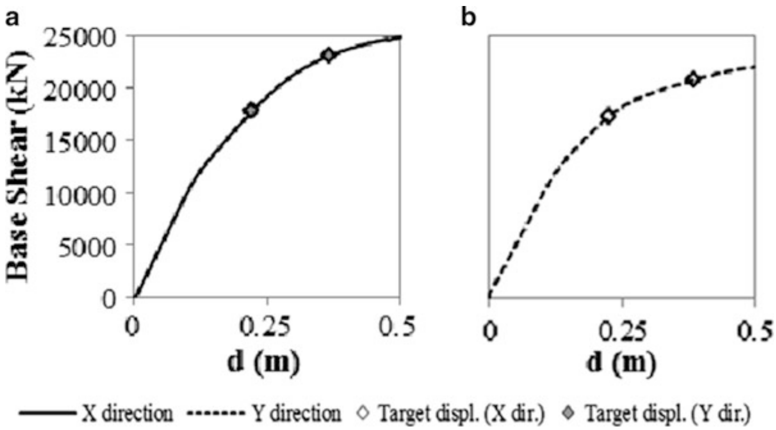

Fig. 18.8 Pushover curves in X and Y direction, respectively, in 3D Pushover

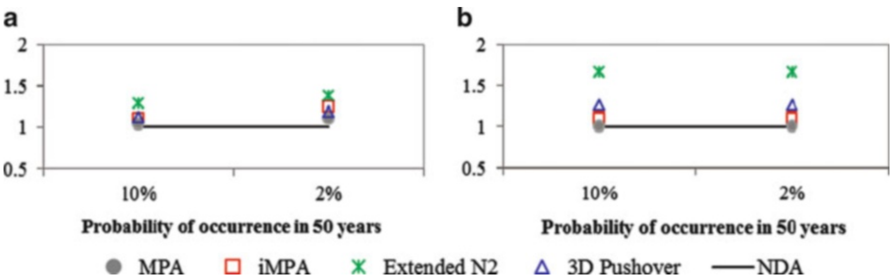

Fig. 18.9 Top displacement ratios in the center of mass: (**a**) X direction; (**b**) Y direction

The Extended N2 is the procedure with highest top displacements values and it is justified by the factor applied to take into account the higher mode effects, which increases considerably the top displacements. On the other hand, the top displacements obtained in the center of mass by the other procedures match with accuracy with the ones obtained through NDAs.

The lateral displacement profiles and interstorey drifts were obtained in center of mass and in edge columns of the building (columns C1 and C17) and are displayed in Figs. 18.10 and 18.11 respectively.

When focusing on the lateral displacement profiles and interstorey drifts obtained, the 3D Pushover and the multi-mode methods generally lead to smaller values when compared to Extended N2, however they generally lead to accurate results. Extended N2 overestimates the results for the two intensities of ground motion in both directions.

In terms of lateral displacements profiles, the multi-mode methods show good accuracy, where Improved MPA is slightly more conservative than MPA, more noticeable in the inelastic range of the structure. Extended N2 overestimates the

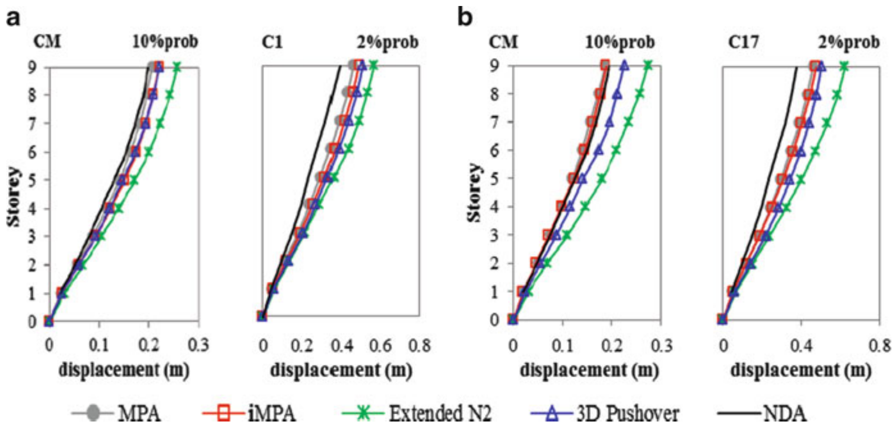

Fig. 18.10 Lateral displacement profiles: (**a**) X direction; (**b**) Y direction

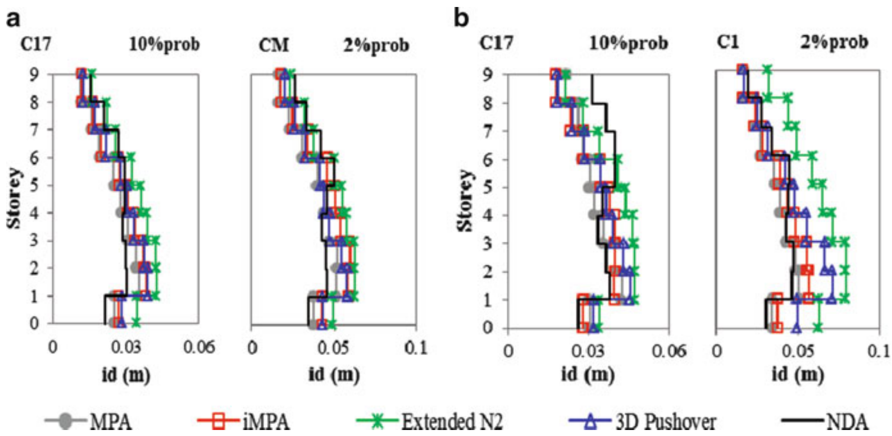

Fig. 18.11 Interstorey drifts: (**a**) X direction; (**b**) Y direction

lateral displacements in all columns, for both intensities considered. The lateral displacements obtained with 3D Pushover match perfectly with NDA in X direction, and are shown as a little conservative in Y direction.

Regarding to the Interstorey Drifts obtained, all methods lead to conservative results in terms of maximum values obtained. Generally the results obtained by 3D Pushover and multi-mode procedures are very close among them and achieve a good approximation to NDA results in the most of the stories for all situations. In few cases interstorey drifts in the upper stories are not well captured by these methods, mainly in Y direction. On the other hand, Extended N2 is able to capture the drifts in the upper stories and show conservative results for the other stories in both directions for the intensities studied.

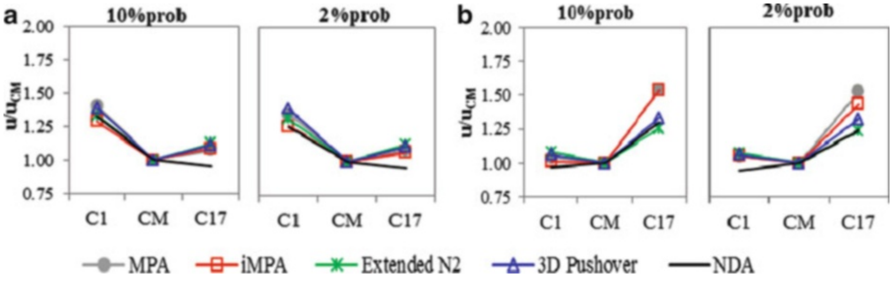

Fig. 18.12 Normalized top displacements: (**a**) X direction; (**b**) Y direction

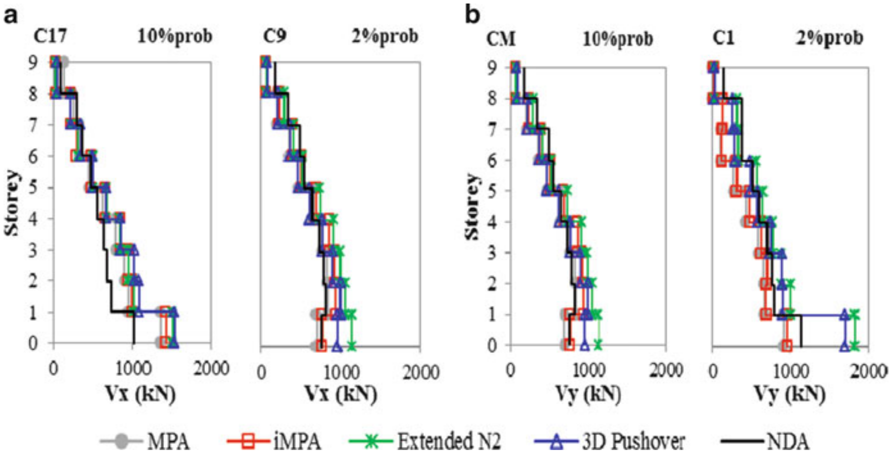

Fig. 18.13 Shear forces: (**a**) X direction; (**b**) Y direction

In order to study the torsional behavior of the building, the trend of normalized top displacements is analyzed and the results are shown in Fig. 18.12. This measurement is obtained by normalizing the edge displacement values with respect to those of the center of mass. The torsional response in NDAs is taken from the stage of the analysis correspondent to the maximum top displacement (in absolute value) in the center of mass.

All studied methods show great accuracy in the capture of the torsional amplification in the edge sides of the building in inelastic regime for both directions. Only the multi-mode procedures show conservative results in the flexible side of the building in Y direction.

Respecting to Shear Forces, the extension to MPA proposed by Reyes and Chopra (2011a) to estimate internal forces in the structure, was herein applied for the multi-mode procedures and when the elements deform into the inelastic range.

In addition to the columns that show displacement results, the column C9, which is close to the center of mass, was added to, in order to obtain a more widespread behavior of the structure in terms of Shear. Hence Shear forces were obtained in both directions of the building and results are shown Fig. 18.13.

All methods provide a good approximation in terms of shear forces for both intensities and in both X and Y directions, as displayed in Fig. 18.13. However 3D Pushover and Extended N2 present slight conservative results in the first stories where the maximum values of Shear Force are achieved.

The shear capacity of the studied columns, calculated by Eurocode 3, is far from being achieved in all columns analyzed.

18.7 Conclusions

In this paper, the nonlinear static procedures MPA, Extended N2, 3D Pushover and an improved version of MPA (iMPA), were applied in order to evaluate their respective individual performance. With this as the main objective, all the aforementioned methods were applied to an asymmetric nine-storey plan building, considering both components of seismic motion acting simultaneously. The results obtained were herein compared with the ones evaluated by means of Nonlinear Dynamic time-history Analyses.

According to all results achieved, one can conclude that all these recent methods or extensions to methods, which had been proposed in the past, lead to very accurate results, as far as this steel building concerned. Since the studied building is torsional flexible in both directions, the capture of its torsional behavior was the most concerning achievement and the results obtained regarding to the capture of the torsional behavior by all methods matched with accuracy the NDA results. Other considerable fact is the height of the building, which some higher modes of vibration are relevant to the seismic performance; however these methods were effective in overcome this issue as well, i.e. taken into account the higher modes of vibration effects.

Notwithstanding the effectiveness of all methods, MPA and iMPA seemed to present the best approach to NDA in terms of lateral displacement profiles and interstorey drifts wherein generally iMPA is slightly more conservative between both methods. The 3D Pushover and mainly Extended N2 generally overestimate these results. On the other hand, in terms of torsional behavior of the building, Extended N2 and 3D Pushover are closer to NDA. Finally, one can say the shear forces values are quite close among all methods and also fit with NDA results.

Having four different approaches which lead to good results, the choice of the method in order to perform an eventual seismic assessment of an asymmetric plan building would be probably sustained by the less time-spending required. In fact, to apply Extended N2 or 3D Pushover, an extra dynamic response spectrum analysis is required and in the case of multi-mode methods, pushover analysis per mode has to be performed, and specifically in iMPA, doubled time-consuming is needed when compared with MPA. Nevertheless, it is important to note that, to apply the 3D Pushover, it is important that the software used is able to perform an adaptive analysis, which is not a common feature of the finite element programs usually used to perform nonlinear static analysis.

Finally it is important to highlight that these methods have already been applied to other asymmetric plan buildings and the same conclusions have been reached about the efficiency of the procedures on the seismic assessment of the buildings.

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