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Research Article

A Multi-mode Pushover Analysis Procedure to Estimate the Seismic Demands of Medium-rise Unsymmetric-plan Buildings

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Abstract: In this study a multi-mode, adaptive, spectra based pushover procedure is presented in order to estimate the structural performances of 3D medium-rise unsymmetric-plan buildings. Response Spectrum Analysis (RSA) procedure has become a standard analysis tool for buildings, however single-mode pushover analysis can be applied to only regular low-rise building structures. This presented procedure (IRSA) is an advanced multi-mode pushover analysis that takes into account the effects of higher modes and can be applied effectively to irregular buildings. IRSA procedure is based on using RSA at each piecewise linear incremental step between the formation of consecutive plastic hinges. For the purpose of comparison, storey displacements of unsymmetric-plan medium-rise buildings are computed using nonlinear Response History Analysis (RHA) and the results are compared with the presented method (IRSA) together with the Modal Pushover Analysis (MPA) method. It is illustrated that the proposed method can compute-estimate the seismic demands of the buildings with reasonable accuracy.

Keywords: Multi-mode pushover analysis, nonlinear behavior, reinforced-concrete buildings, unsymmetric-plan buildings

INTRODUCTION

Generally for evaluating the structural performance of existing buildings realistically, nonlinear Response History Analysis (RHA) or Nonlinear Static Procedure (NSP) are implemented for estimating the structural responses and demands. RHA is the most powerful tool for the assessment of the nonlinear seismic response of structures. Since this method requires an ensemble of ground motions, selection and scaling of them come out with several unresolved issues and the analysis has significant computational cost. In order to avoid the timely effort, complexity of the numerical analysis, unresolved issues and the various inherent disadvantages of RHA, engineering practitioners often prefer to apply NSP. In spite of RHA's complexity, NSP, namely the pushover analysis, is an "easy-to-use" alternative to RHA. The conventional nonlinear static procedure, assume that the seismic response is mainly controlled by the fundamental mode. With this procedure the structure is subjected to monotonically increasing predefined lateral forces until a pre-determined target displacement is reached. However this procedure is suitable for the structures that its dynamic behavior depends only on a single elastic vibration mode, as in general low-rise structures and medium-rise regular systems. When higher modes contribute to the structural response, such as high-rise or unsymmetric-plan buildings, single mode NSP may not be appropriate. In the recent years, several methodologies have been proposed to integrate the higher mode effects in pushover analysis. The single-run adaptive pushover procedures (Elnashai, 2001; Antoniou and Pinho, 2004; Casarotti and Pinho, 2007); adaptive response spectrum analyses (Gupta and Kunnath, 2000; Aydinoğlu, 2003, 2004a, 2007); N2 Method (Fajfar, 2000); modal pushover analysis (Chopra and Goel, 2004) are some of the well-known alternative methodologies. All of these procedures take higher mode effects into account and to propose a practical multi-mode pushover method that can be used in engineering practice.

Fajfar and Fischinger (1988) proposed a procedure called the N2 method. This pushover analysis procedure estimates target spectral displacement from the inelastic displacement response spectrum.

An adaptive methodology was proposed by Gupta and Kunnath (2000). According to the method, for each pushover step the modal properties of the structure are recalculated and updated. The storey forces for each mode can be estimated using the updated modal properties such as modal mass participation factor,

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mode shape and spectral amplitudes of the mode. Accordingly, static analysis is performed for each mode independently. Using SRSS combination method, the response results for each mode are combined. The current step results are added to the corresponding values from the previous step. The procedure is repeated until the target roof displacement or specified building base shear is reached. Demand estimation has not been implemented in this procedure.

Elnashai (2001) and Antoniou and Pinho (2004) proposed single-run adaptive pushover procedures. In these pushover procedures, equivalent modal seismic loads which are consistent with the instantaneous mode shapes are calculated at the end of each pushover step. Modal seismic loads are combined with an appropriate modal combination rule and then reapplied to the structure after each step. Target displacements used in the pushover analyses are obtained from the inelastic time history analyses of the MDOF systems.

According to Modal Pushover Analysis method (MPA) proposed by Chopra and Goel (2004), pushover analysis for each mode is conducted independently. The applied loads are consistent with the initial elastic mode shapes and this is the most specific assumption in this procedure. At the end of the modal pushover analysis, peak modal displacement demands for each mode are evaluated independently. The total demand is then determined by combining the peak modal demands using the SRSS rule.

Incremental Response Spectrum Analysis (IRSA) (Aydinoğlu, 2003) is a multi-mode adaptive pushover procedure in which the dynamic characteristics are updated at each increment. At each increment, eigenvalue analysis is conducted, then response spectrum analysis is carried out considering all modes contributions to compute the structural displacement and internal forces directly without forming pushover force vector. The incremental response is assumed piecewise linear at each pushover step in between the formation of two consecutive plastic hinges. Modal capacity diagrams are developed simultaneously during the pushover analysis. The calculated response quantities are combined with a modal combination methodology and added to the corresponding values from the previous step. This method takes into account the interaction between the different modes at the end of each step. The practical version of IRSA utilizes well-known equal displacement rule for each mode to estimate corresponding inelastic spectral displacement

MPA (Chopra *et al*., 2004) and IRSA (Aydinoğlu, 2003) are the only methods that can be considered not only as demand estimation tools, but capacity estimation tools as well (Aydinoglu, 2007).

The objective of this study is the presentation of multi-mode pushover procedures; IRSA and MPA and comparison of these procedures with single-mode pushover and nonlinear RHA for the approximate estimation of the seismic response of unsymmetric buildings.

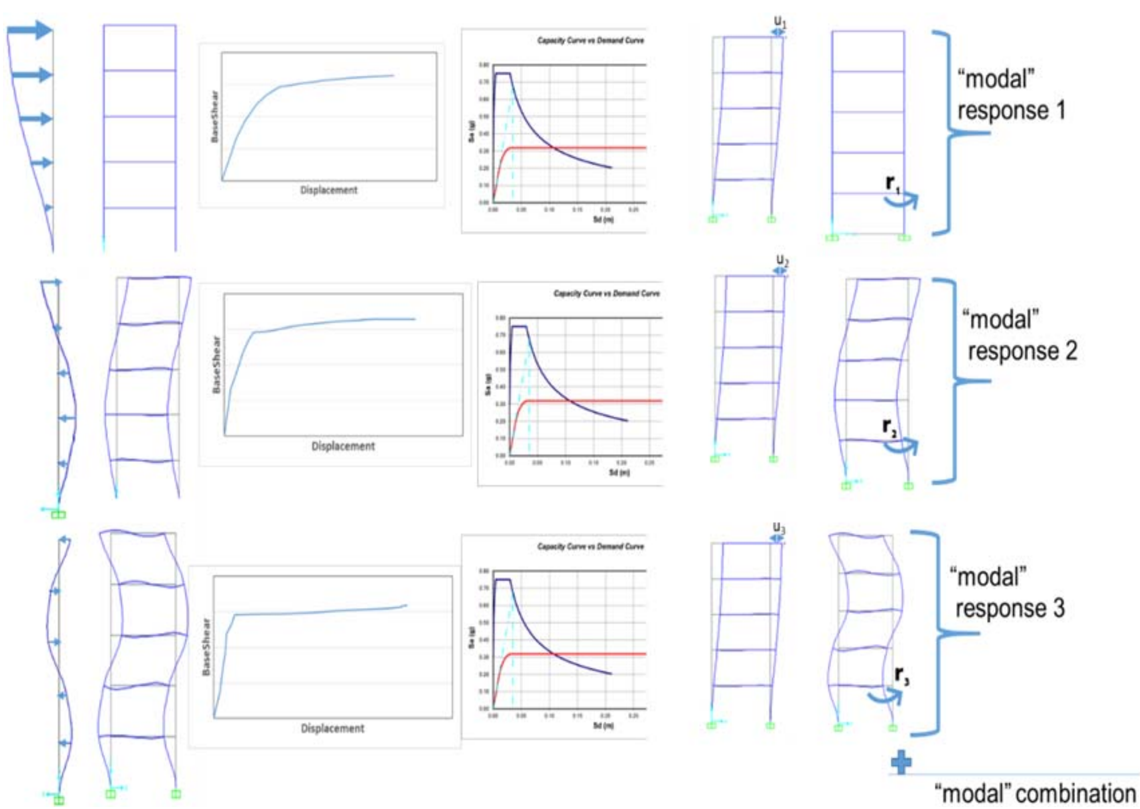


Fig. 1: Modal Pushover Analysis method (MPA)

THEORETICAL BACKGROUND

Since the nonlinear structural responses of 3D mid-rise unsymmetrical buildings will be comparatively evaluated, two handy procedures are considered and investigated in details. The first multi-mode nonlinear pushover procedure taken into account herein is the MPA by Chopra *et al*. (2004). According to the MPA, pushover analysis for each mode is conducted independently and the peak modal demand for each mode is evaluated independently at the end of the modal pushover analysis, which is illustrated in Fig. 1.

During the MPA, initially the natural frequencies ω_n and the corresponding modes ϕ_n for the elastic system is calculated. Then base shear-top story displacement curve (the pushover curve) for the n^{th} mode is obtained by employing the force distribution that is defined by the corresponding modal forces utilizing nonlinear static analysis. Gravity loads are applied before the lateral forces causing roof displacement ur_g. Pushover curve for each mode is converted to modal capacity diagram of the equivalent SDOF system. Bilinear idealization is implemented to the modal capacity diagram of the equivalent SDOF system. The reference displacement for a-component of the ground motion ($ur_{n,a}$) is calculated. Peak modal response quantities are calculated for each mode and gravity load effects are extracted from the peak response quantities to obtain modal response contributions ($r_{na}= r_{n+g,a} - r_g$). This procedure is repeated for as many modes as required. Modal response contributions are combined by using SRSS modal combination rule and then gravity load responses are added to the combined responses to obtain total response as given in Eq. (1):

$$r \approx \max\left[r_g \mp \left(\sum_{i=1}^{J} \sum_{i=1}^{J} \rho_{in} r_i r_n \right)^{1/2} \right] \tag{1}$$

In the Adaptive Response Spectrum Analyses, Gupta and Kunnath (2000) updated the applied lateral forcesat each calculation step. The eigenvalue analysis is carried out at each load increment and then a static analysis is carried out for each mode independently. The calculated structural responses are combined by

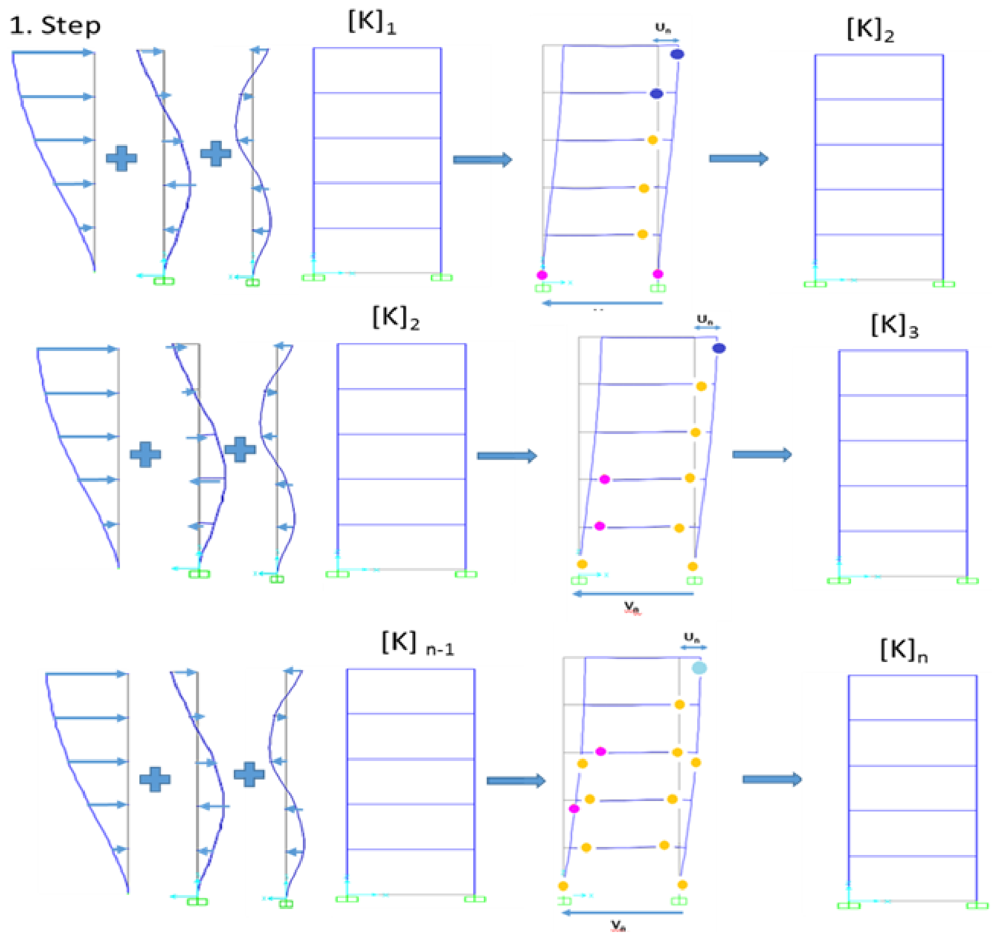


Fig. 2: Incremental Response Spectrum Analysis (IRSA) procedure

SRSS superposition rule and are added to the corresponding values from the previous step. Similarly, Aydinoğlu (2003, 2004a), Aydinoglu (2004b) and Aydinoğlu (2007) extended this method to estimate the peak demand quantities and developed Incremental Response Spectrum Analysis (IRSA).

The main objective of IRSA, which is exhibited in Fig. 2, is to provide a rational methodology for multi-mode pushover analysis. IRSA was developed as a multi-mode process in which modal displacements are calculated incrementally until they reach their peak values, i.e., inelastic spectral displacements in each mode. This was achieved by applying a piece wise linear Response Spectrum Analysis (RSA) procedure at each incremental step in between the formation of the two consecutive plastic hinges. Once modal displacement increments are obtained for each mode at each step, the increments of all response quantities of interest, i.e., story displacements, story drifts, plastic hinge rotations, internal forces, etc. can be readily calculated using an appropriate modal combination rule. In the practical application of IRSA, the well-known equal displacement rule is utilized and the earthquake input is identified in the form of an elastic response spectrum (Aydinoğlu, 2003).

STRUCTURAL SYSTEM AND MODELING

In this study, a 3D mid-rise unsymmetric-plan frame system has been generated and shown in Fig. 3. In the building, each story is designed to have similar heights of 3.15 m and each bay length is 5.0 m for the entire system. Column cross-sections are 40 cm×50 cm, while the beam cross-sections are selected as 30 cm/60 cm. The longitudinal reinforcement is constant for all columns with a ratio of ρ = 1.6%, while the tensile reinforcement ratio varies between 0.8~1.0% for the beams. In the analytical model of the system, columns and beams are modeled by using line elements. Effective flexural stiffnesses of the structural elements are determined considering the cracked sections defined in the Turkish Earthquake Code (TEC) (2007). The floor diaphragm at each story level is assumed to be infinitely rigid. All degrees of freedoms at foundation level are assumed to be fixed.

Concentrated plastic hinge with zero length is used to introduce the nonlinear behavior of the reinforced concrete components. Plastic hinges are assumed to be located at each end of the columns and the beams.

For the nonlinear RHA, damping effect is considered through proportional (Rayleigh) damping matrix represented by a 5% of modal damping ratio.

Ground motions: The seismic design codes recommend the usage of at least three or seven ground motion records during the time-history analyses. Instead of the spectrum compatible artificial ground motions, real accelerograms are employed in the analyses. A set of 84 ground motion records are selected from the PEER Strong Ground Motion Database. The earthquake moment magnitudes M_w for the selected records ranged from 6.5 to 6.9. The selected ground motion records were recorded on firm soil with no marks of directivity effects. The acceleration response spectra of ground motions and their average spectrum have been obtained (Fig. 4). Among them, seven closest spectra to the average

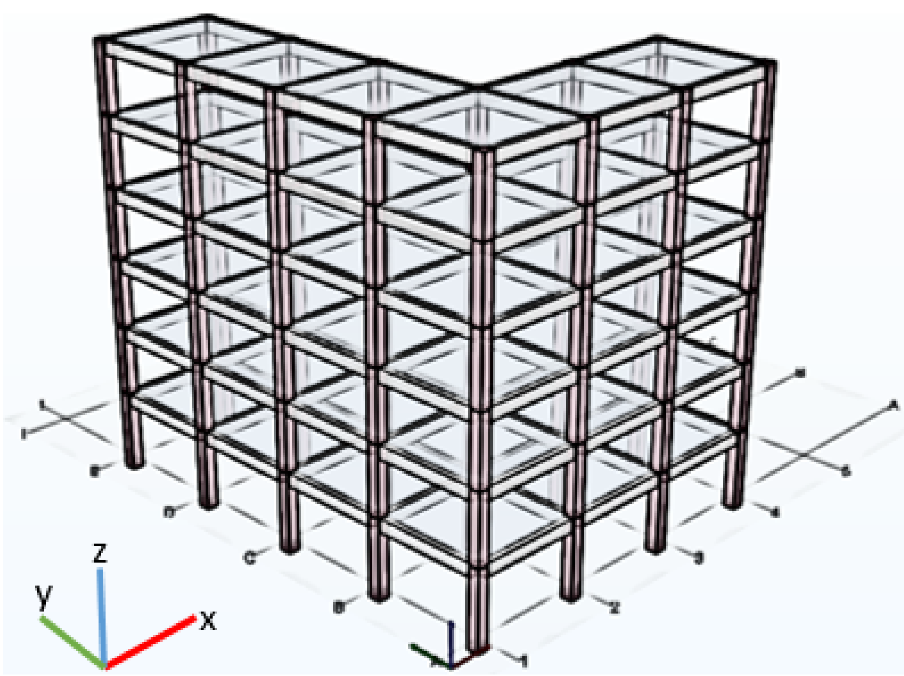


Fig. 3: 3D view of the generated structural system

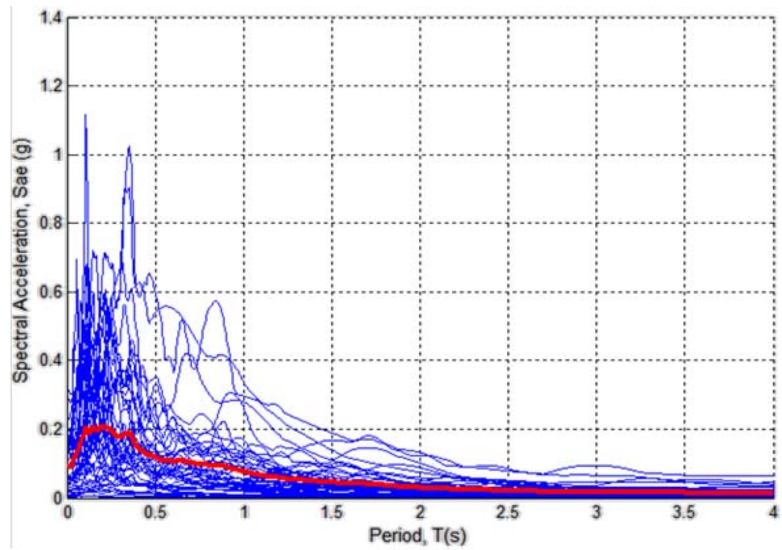
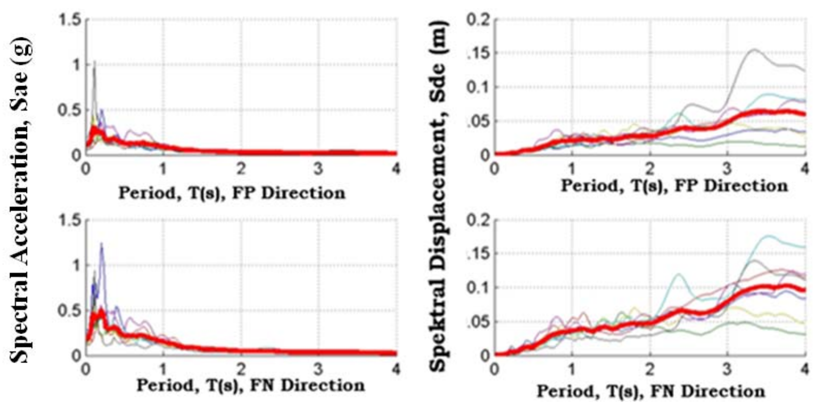


Fig. 4: Acceleration response spectra and their average for the selected ground motions



(a) FP Direction (b) FN Direction

Fig. 5: Spectral accelerations of the selected 7 ground motions and their average spectrum

Table 1: List of selected seven ground motions

	Earthquake name	Mw	Station name	Clst Dist. (km)	NEHRP Based on Vs30	PGA (g) (FP)	PGA (g) (FN)
1	Irpinia, Italy	6.90	Brienza	22.5	C	0.137	0.056
2	Irpinia, Italy	6.90	Rionero Vulture	30.0	C	0.277	0.112
3	Loma Prieta	6.93	Calaveras Reservoir	35.4	C	0.113	0057
4	Loma Prieta	6.93	Fremont-Mission	39.5	C	0.180	0.091
5	Northridge	6.69	Manhattan Beach -	39.2	C	0.170	0.189
6	Northridge	6.69	Lawndale-Osage Ave	39.1	C	0.117	0.076
7	San Fernando	6.61	Santa Felita Dam	24.8	C	0.225	0.146

spectrum are selected (Fig. 5a and 5b). The list of selected seven records is presented in Table 1. Ground motions are rotated to Fault-Normal and Fault-Parallel (FN/FP) directions before they are used as input for the nonlinear RHA of building structures.

ANALYTICAL STUDY

For comparative analytical study: For comparative purposes, the generated building is analyzed by nonlinear single-mode pushover analysis; MPA and IRSA. Furthermore, nonlinear dynamic analyses are also carried out, which is considered to be the 'exact' solution of the structural responses.

Single-mode pushover analysis, IRSA and MPA analyses are implemented with a developed MATLAB code (Fahjan, 2014). Nonlinear RHA is realized by PERFORM-3D computer program. On the other hand, the developed MATLAB code is capable of reading all the structural characteristics such as materials, cross-

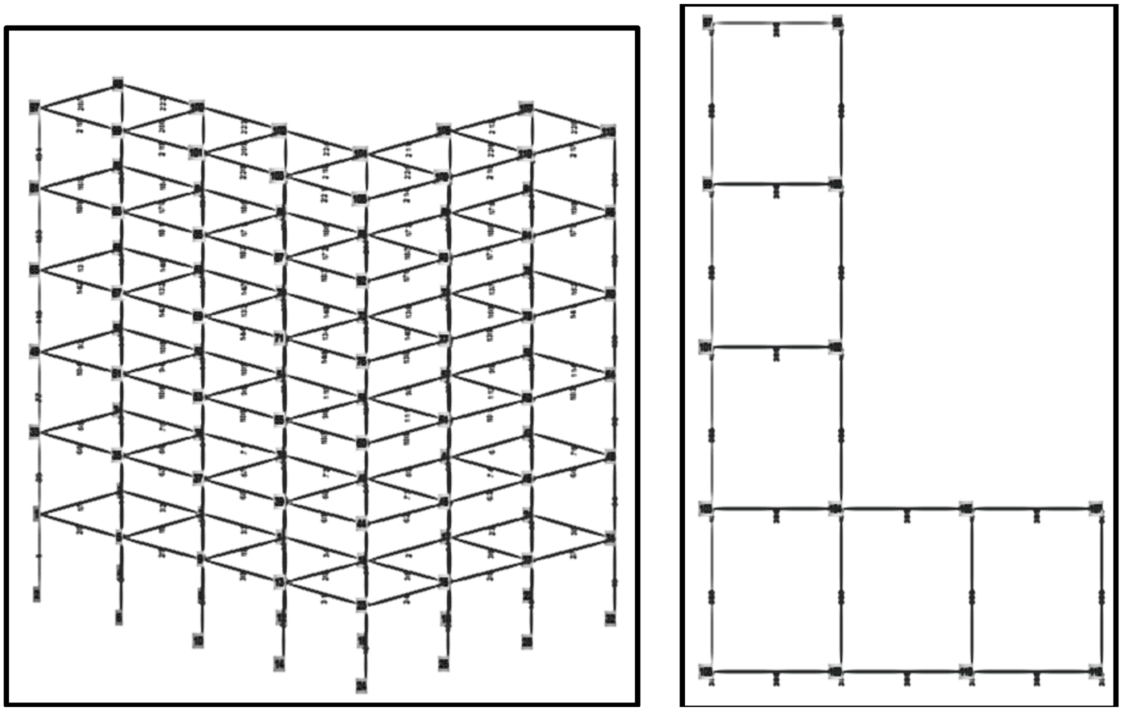


Fig. 6: Structural system developed with MATLAB code

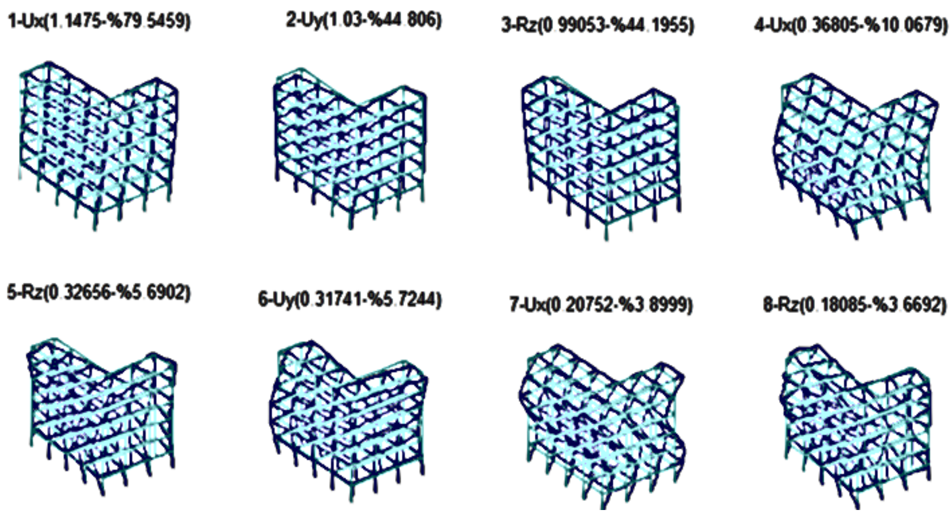


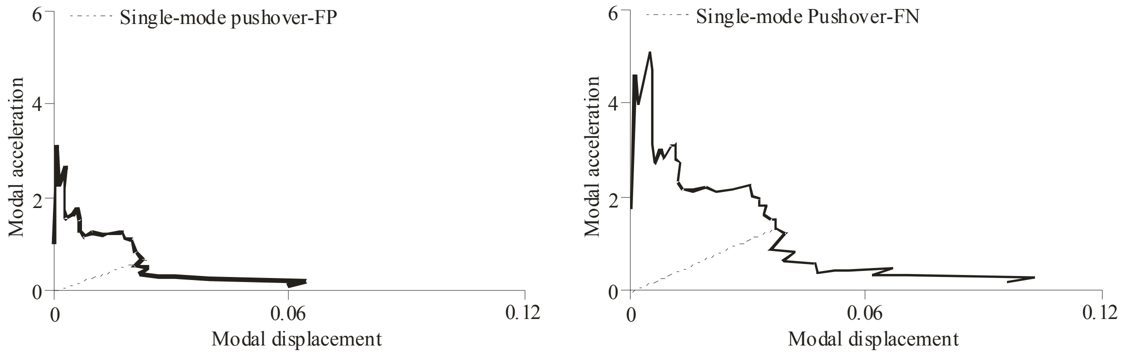
Fig. 7: Periods and modal participating mass ratios

sections, joint coordinates, restraints, storey diaghprams, loadings and load combinations from SAP2000 $2k file. With these capabilities the developed code regenerates the structural system under MATLAB program (Fig. 6) and can run the eigen value analysis, single-mode pushover, spectrum, incremental response spectrum and modal pushover analyses. After eigen value analysis is utilized, structural periods and modal participating mass ratios are obtained, which are given in Fig. 7.

To consider in the further analyses, fundamental modes and participating modal mass ratios are determined and shown in Fig. 7.

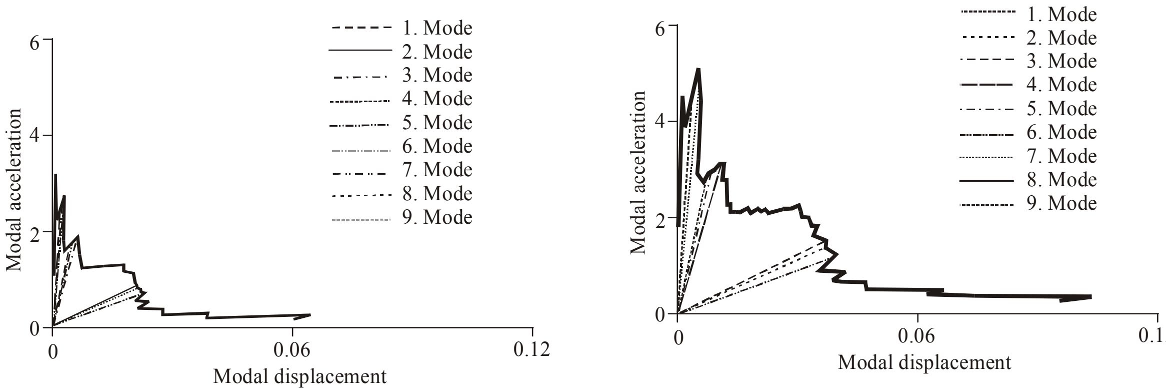
Earthquake-induced demands for the selected building determined by four analyses: Single-mode pushover considering the fundamental mode for the selected building direction; MPA considering three “modes” in each structural direction (for FP and FN directions independently) and IRSA considering “all fundamental modes” as well as nonlinear dynamic analysis. Gravity load effects are included in all analyses.

Selected ground motions are scaled by 1.0, 1.5 and 2.0 to represent the elastic and inelastic response of building. Average response spectrum of selected ground motions is used for single-mode pushover, MPA



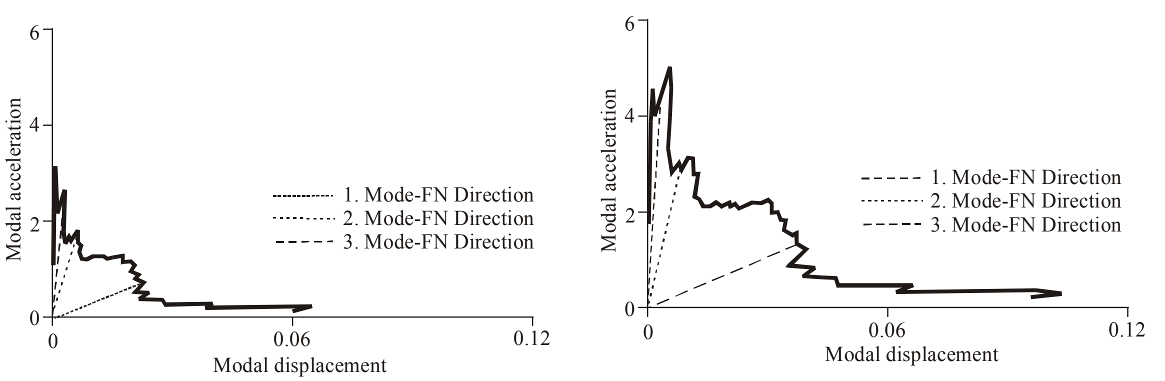
(a) Fault Parallel Direction (b) Fault Normal Direction

Fig. 8: Modal acceleration-modal displacement relation for the building for FP and FN directions: Single mode pushover (Spectrum scale factor 1.0g)



(a) Fault Parallel Direction (b) Fault Normal Direction

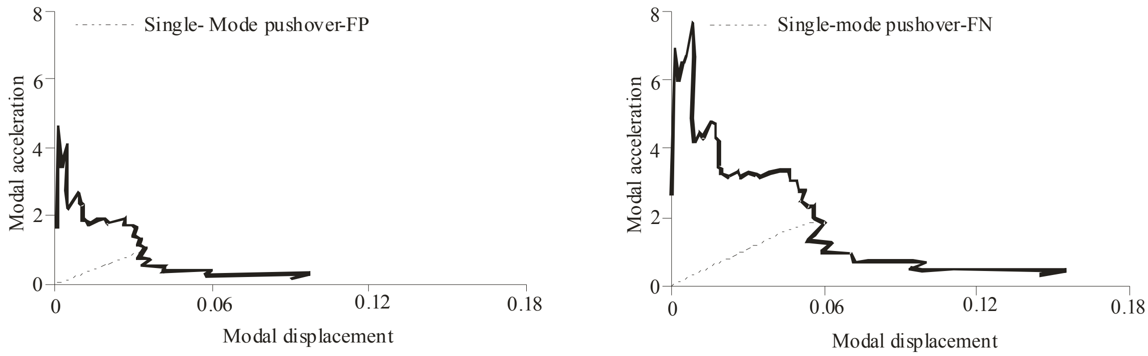
Fig. 9: Modal acceleration-modal displacement relation for the building for FP and FN directions: IRSA (Spectrum scale factor 1.0g)



(a) Fault Parallel Direction (b) Fault Normal Direction

Fig. 10: Modal acceleration-modal displacement relation for the building for FP and FN directions: MPA (Spectrum scale factor 1.0g)

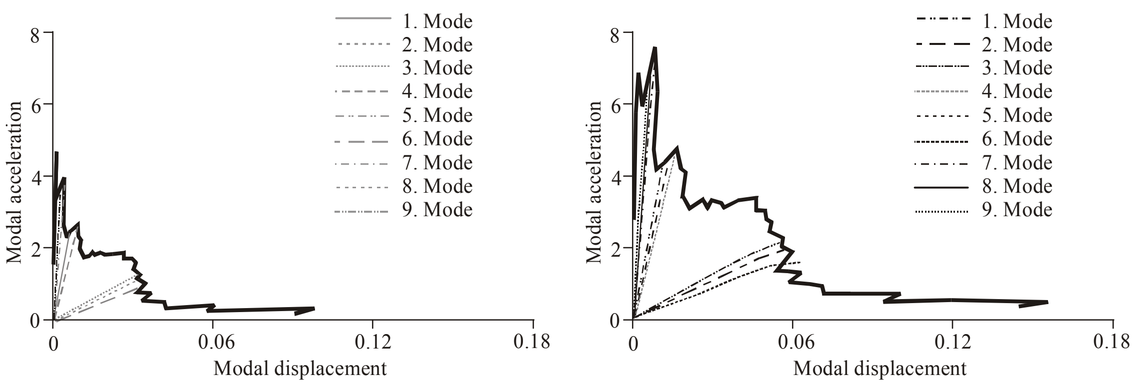
and IRSA to determine the performance point. Figure 8 to 10 show "Modal Acceleration-Modal Displacement Variation" of the building for single-mode pushover analysis, IRSA and MPA respectively. In these graphics, spectrum scale factor is 1.0 g and both FP and FN directions are considered. Similarly Fig. 11 to 13 show "Modal Acceleration-Modal Displacement Variation" for a spectrum scale factor of 1.5 g and Fig. 14 to 16 show the corresponding results for a scale factor 2.0 g.



(a) Fault Parallel Direction

(b) Fault Normal Direction

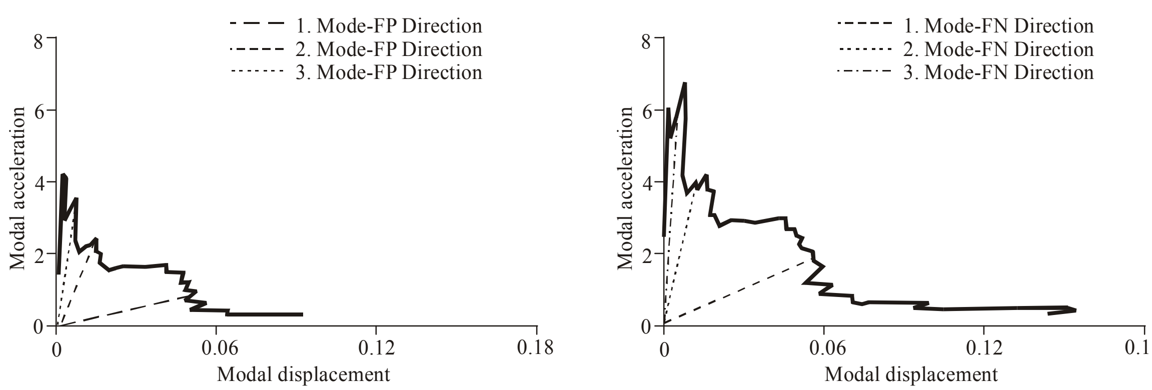
Fig. 11: Modal acceleration-modal displacement relation for the building for FP and FN directions: Single mode pushover (Spectrum scale factor 1.5g)



(a) Fault Parallel Direction

(b) Fault Normal Direction

Fig. 12: Modal acceleration-modal displacement relation for the building for FP and FN directions: IRSA. (Spectrum scale factor 1.5g)

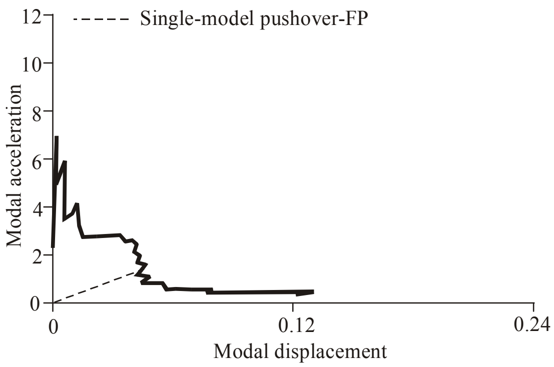


(a) Fault Parallel Direction

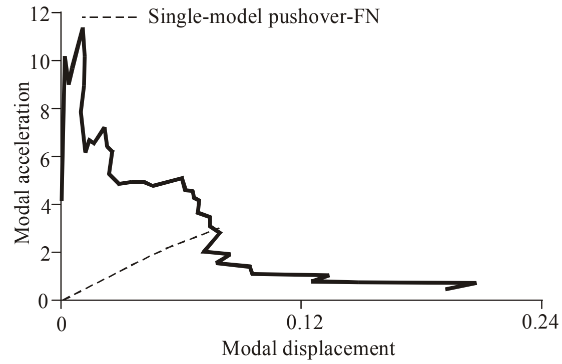
(b) Fault Normal Direction

Fig. 13: Modal acceleration-modal displacement relation for the building for FP and FN directions: MPA (Spectrum scale factor 1.5g)

For the purpose of comparison, storey displacements of unsymmetric-plan medium-rise buildings are computed using nonlinear response history analysis (RHA), IRSA, MPA and single-mode pushover. Nonlinear RHA is realized with selected ground motions (for scale factors of 1.0, 1.5 and 2, respectively) by PERFORM-3D computer program. Storey displacement is computed for the closest node to center of mass of the building.

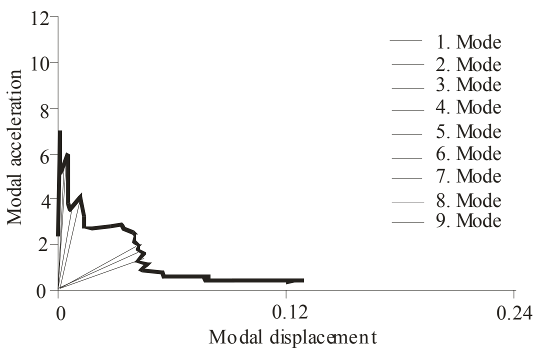


(a) Fault Parallel Direction

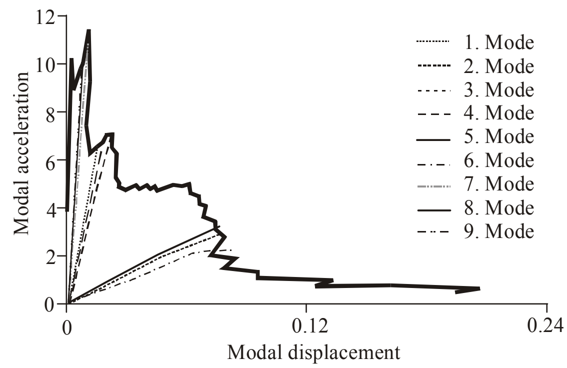


(b) Fault Normal Direction

Fig. 14: Modal acceleration-modal displacement relation for the building for FP and FN directions: Single mode pushover (Spectrum scale factor 2.0g)

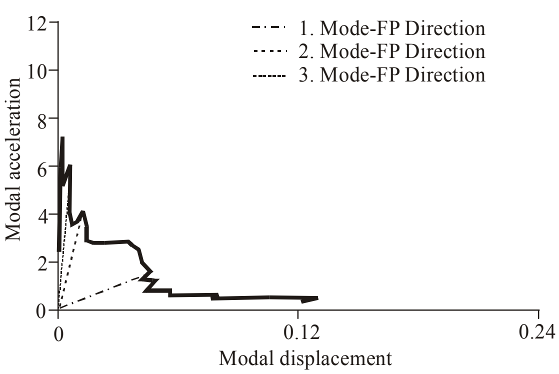


(a) Fault Parallel Direction

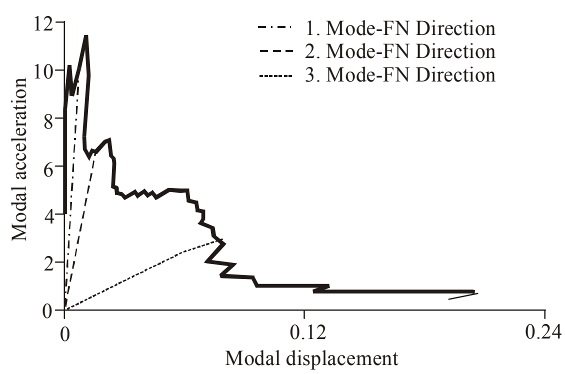


(b) Fault Normal Direction

Fig. 15: Modal acceleration-modal displacement relation for the building for FP and FN directions: IRSA. (Spectrum scale factor 2.0g)



(a) Fault Parallel Direction



(b) Fault Normal Direction

Fig. 16: Modal acceleration-modal displacement relation for the building for FP and FN directions: MPA (Spectrum scale factor 2.0g)

Figure 17 to 22 present the comparison of storey displacements for two horizontal components of ground motions, independently.

CONCLUSION

An incremental spectrum analysis procedure for the approximate estimation of the seismic response of an unsymmetric-plan building is presented here in this study. For estimating the seismic responses, story displacements and drifts are very important indicators. For estimating the floor deformations; single mode pushover, MPA, nonlinear RHA and IRSA analyses were implemented for two horizontal components of ground motions, independently. For the comparison of the structural responses calculated by each procedure,

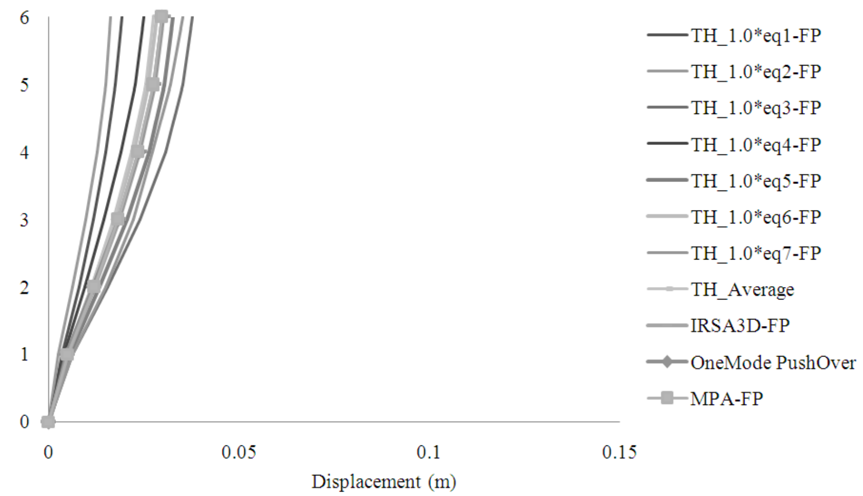


Fig. 17: Comparison of RHA, single-mode pushover, IRSA and MPA (ground motion scale factor 1.0)

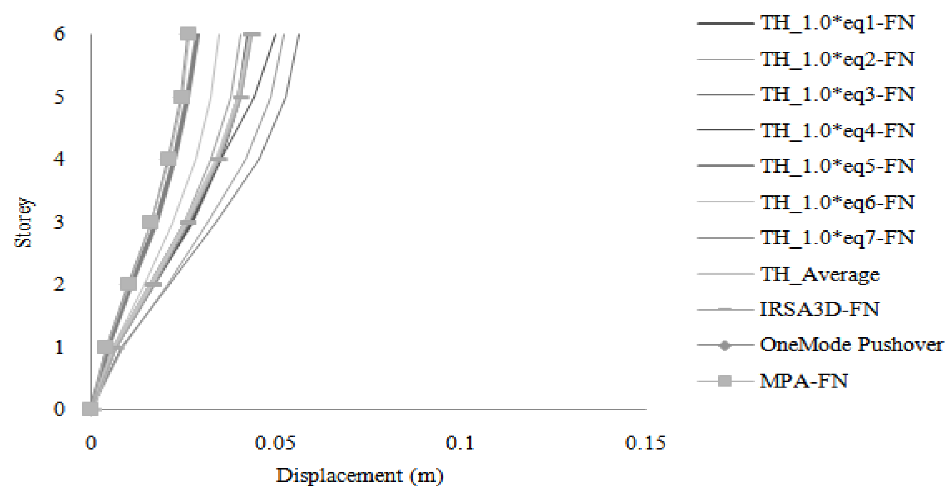


Fig. 18: Comparison of time history, One-mode pushover, IRSA and MPA (Ground motion scale factor 1.0)

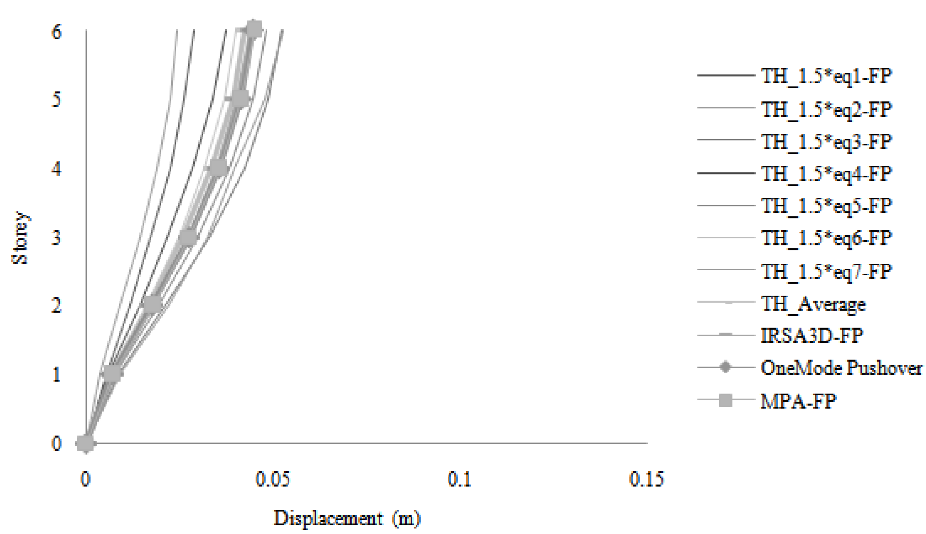


Fig. 19: Comparison of time history, One-mode pushover, IRSA and MPA (Ground motion scale factor 1.5)

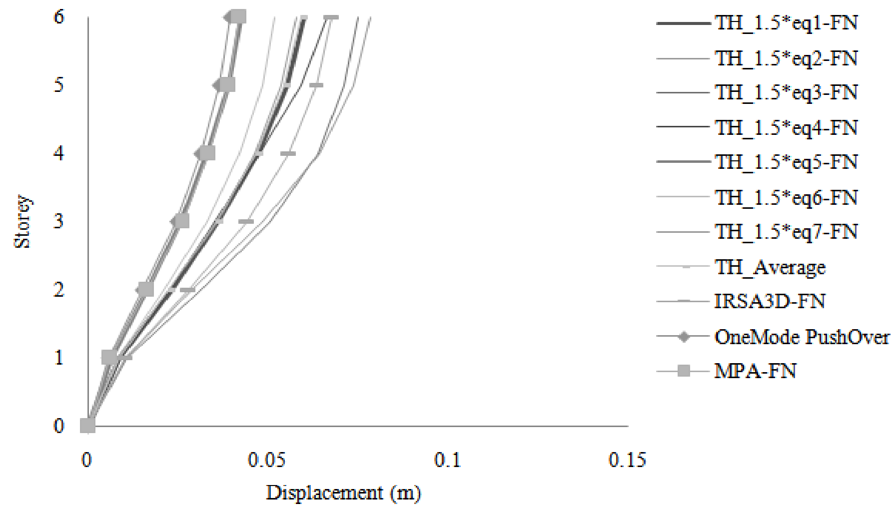


Fig. 20: Comparison of time history, one-mode pushover, IRSA and MPA (Ground motion scale factor 1.5)

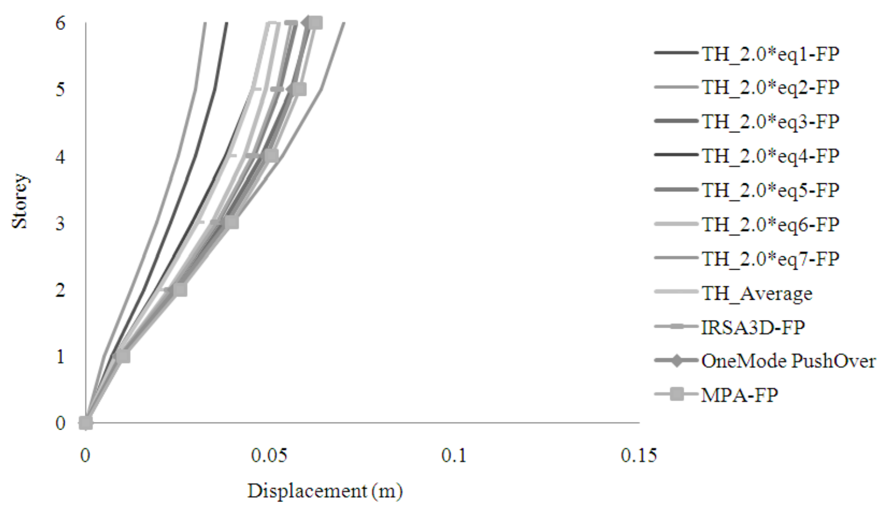


Fig. 21: Comparison of time history, one-mode pushover, IRSA and MPA (Ground motion scale factor 2.0)

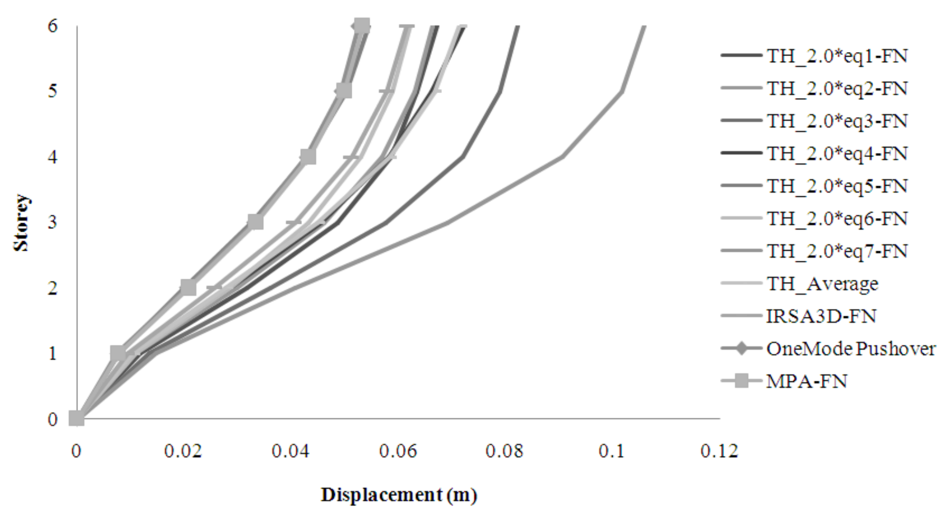


Fig. 22: Comparison of time history, one-mode pushover, IRSA and MPA (Ground motion scale factor 2.0)

the mean of the nonlinear dynamic analyses are considered as exact solution. To evaluate the elastic and inelastic responses of building, selected ground motions are scaled by 1.0, 1.5 and 2.0.

Comparison of IRSA, MPA, single-mode pushover and nonlinear RHA for storey displacements shows that for the ground motion scale factor 1.0, the structural behavior is found out to be linearly elastic. The story displacements are very small and all four analyses results are close to each other for the FP direction. For FN direction, the IRSA results are almost the same with the mean of the RHA, however single-mode pushover analysis and the MPA underestimates the story displacements. When the ground motion scale factor is increased, IRSA estimates the story displacements very close to the mean of the RHA. For FP direction single-mode pushover analysis and the MPA over estimate the story displacements and for FN single-mode pushover analysis and the MPA underestimate the results specifically in the upper stories. The distinction between the increases in the results is proportional to the increase in the scale of the ground motion.

On the other hand, these results are implemented for a single unsymmetric-plan building. Therefore, although the proposed analysis procedure seems to be very promising, it is also recommended that more buildings with different torsional irregularities, number of stories and structural characteristics should be handled, so that the general findings are adequate and precise.

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