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Seismic evaluation of vertically irregular building frames with stiffness, strength, combined-stiffness-and-strength and mass irregularities

Moosa Ebrahimi Nezhad and Mehdi Poursha*

Faculty of Civil Engineering, Sahand University of Technology, Tabriz, Iran

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Abstract. In this paper, the effects of different types of irregularity along the height on the seismic responses of moment resisting frames are investigated using nonlinear dynamic analysis. Furthermore, the applicability of consecutive modal pushover (CMP) procedure for computing the seismic demands of vertically irregular frames is studied and the advantages and limitations of the procedure are elaborated. For this purpose, a special moment resisting steel frame of 10-storey height was selected as reference regular frame for which the effect of higher modes is important. Forty vertically irregular frames with stiffness, strength, combined-stiffness-and-strength and mass irregularities are created by applying two modification factors (MF=2 and 4) in four different locations along the height of the reference frame. Seismic demands of irregular frames are computed by using the nonlinear response history analysis (NL-RHA) and CMP procedure. Modal pushover analysis (MPA) method is also carried out for the sake of comparison. The effect of different types of irregularity along the height on the seismic demands of vertically irregular frames is investigated by studying the results obtained from the NL-RHA. To demonstrate the accuracy of the enhanced pushover analysis methods, the results derived from the CMP and MPA are compared with those obtained by benchmark solution, i.e., NL-RHA. The results show that the CMP and MPA methods can accurately compute the seismic demands of vertically irregular buildings. The methods may be, however, less accurate especially in estimating plastic hinge rotations for weak or weak-and-soft top and middle storeys of vertically irregular frames.

Keywords: vertically irregular frame; stiffness irregularity; strength irregularity; combined-stiffness-and-strength irregularity; mass irregularity; nonlinear response history analysis (NL-RHA); consecutive modal pushover analysis

1. Introduction

Irregular buildings constitute a large portion of urban infrastructures. Studying the performance of structures during past earthquakes illustrates that many structures have suffered severe damage or collapse due to irregularities (Dutta and Das 2002, Salawdeh 2009). In most cases, seismic codes deal with the irregularity along the height and in plan, separately. In a general manner,

*Corresponding author, Ph.D., E-mail: poursha@sut.ac.ir

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vertically irregular building structures have been classified mostly into two categories in the previous investigations: a) irregular structures with considerable changes in the plan along the height, such as setback buildings; b) irregular structures which undergo abrupt changes in dynamical properties such as mass, lateral stiffness and strength along the height. Vertical irregularities result from a number of causes including different storey applications, extra heavy mass in one or more storeys, and different storey heights. Also, omitting exterior bracings or shear walls in the first storey of a building causes an abrupt change in stiffness at that storey. Studies conducted on the seismic behavior of vertically irregular structures indicate the influence of irregularity on the increase of seismic demands of irregular storeys, and the change of distribution of storey drifts. Various investigations were performed to study the seismic behavior of vertically irregular structures. Duan and Chandler (1995) studied the seismic behavior of setback structures and showed that static and modal spectrum analyses are insufficient in predicting the damage of elements located near the setback elevation. Valmundsson and Nau (1997) studied 5, 10 and 20-storey frames in order to evaluate the uniform building code (UBC) requirements for mass, strength, and stiffness irregularities. They concluded that the strength irregularity results in a larger increase in response quantities than mass and stiffness irregularities.

Al-Ali and Krawinkler (1998) studied the seismic behavior of vertically irregular structures. They investigated different types of irregularities including mass, stiffness, strength, combined-stiffness-and-strength and combined-mass-and-stiffness irregularities along the height of structures. They analyzed them separately using the non-linear response history analysis (NL-RHA) method, and they showed that the effect of strength irregularity on seismic demands is, in general, much higher than that of mass or stiffness irregularity such that storey drifts and ductility demands are very sensitive to a small change in storey strength. For the cases with combined-strength-and-stiffness irregularity, the effect of strength irregularity on seismic responses is more significant than stiffness irregularity. Chintanapakdee and Chopra (2003, 2004) studied the seismic behavior of frames with strength, stiffness and combined-stiffness-and-strength irregularities over the height. They assumed a single-span 12-storey frame as reference regular structure and generated vertically irregular structures by applying two values of modification factors (MF=2 or 5) in four different locations along the height. One of the main goals of the research was applying modal pushover analysis (MPA) to vertically irregular structures. The results of their research showed that the MPA method is accurate enough in estimating the seismic demands of vertically irregular frames in which irregularity is in the middle or upper storey. The MPA procedure is less accurate in estimating the seismic demands of frames with strong or stiff-and-strong first story; soft, weak, or soft-and-weak lower half; stiff, strong, or stiff-and-strong lower half. (Fragiadakis *et al*. 2006) studied the effects of different types of irregularities along the height of a 9-storey steel frame using the incremental dynamic analysis (IDA). Based on their findings, they demonstrated that the effect of irregularity along the height on the seismic responses of a structure depends on the type of irregularity, the location (elevation) of irregularity and more significantly on the intensity of the earthquake. (Karavasilis *et al*. 2008) studied the inelastic seismic demands of plane steel moment resistant frames with vertical mass irregularity. (Le-Trung *et al*. 2010) studied the seismic behavior of vertically irregular buildings with three types of irregularities (mass, stiffness and strength) specified according to the IBC 2000 (ICC 2000).

On the other hand, the non-linear static analysis method based on pushover analysis is increasingly used for seismic evaluation and design verification of structures. Conventional pushover analysis method relies on the assumption that the response of a structure is controlled only by its fundamental mode. This assumption is not appropriate for irregular and tall building structures due to the contribution of higher vibration modes to the seismic responses. In order to overcome this deficiency, researchers suggested enhanced pushover analysis methods such as modal pushover analysis (MPA) (Chopra and Goel 2002), incremental response spectrum analysis (IRSA) (Aydinoglu 2003), upper-bound pushover analysis (Jan *et al*. 2004), adaptive modal combination procedure (Kalkan and Kunnath 2006), consecutive modal pushover (Poursha *et al*. 2009), story shear-based adaptive pushover procedure (shakeri *et al*. 2010), the extended N2 method (Kreslin and Fajfar 2011) and single-run multi-mode pushover procedure (Poursha and Amini 2015). Modal pushover analysis method (Chopra and Goel (2004), Reyes and Chopra 2011a, b), consecutive modal pushover (Poursha *et al*. 2011, 2014), adaptive modal pushover procedure (Shakeri *et al*. 2012), the N2 method (Kreslin and Fajfar 2012) and the upper-bound pushover method (Poursha and Talebi 2015) were extended to irregular in plan buildings considering the effect of higher modes in both plan and elevation. In this paper, the consecutive modal pushover (CMP) is applied for the seismic evaluation of vertically irregular medium-rise building frames in which the effect of higher modes is important. The purposes of this research are as follows: 1) investigating the effects of stiffness, strength, combined-stiffness-and-strength and mass irregularities along the height on the seismic demands of vertically irregular medium-rise moment resisting frames by considering the results of nonlinear response history analysis; 2) applying the CMP procedure for estimating the seismic demands of vertically irregular medium-rise frames with the above-mentioned types of irregularity and evaluating the accuracy of the CMP method. The modal pushover analysis (MPA) method is also performed for the purpose of comparison. Few studies have been conducted to assess the advantages and limitations of enhanced pushover analyses in the case of vertically irregular frames. It is worthwhile mentioning that no attention has been paid to seismic evaluation of vertically irregular frames with mass irregularity using enhanced pushover analyses in the previous investigations.

2. Reference regular frame

In order to investigate the effect of different types of irregularities along the height of building structures on the seismic responses and to study the applicability of the CMP procedure for seismic evaluation of these structures, a special steel moment resisting frame was assumed as reference structure. The reference structure was assumed to be a two-bay 10-storey frame. The bays are 5 m. The storey heights are equal to 3.2 m throughout the frame. The configuration of the frame is shown in Fig. 1. The dead and live loads were equal to 650 and 200 kg/m^2, respectively, on the floor area, assuming the loading width of 5 m. The seismic masses were assumed to be equal at all floor levels of the frame and to comprise the dead load plus 20% of the live load. The frame was assumed to be founded on stiff soil assigned to site class ‘I’ of the Iranian seismic code (Standard No. 2800-05), and located in the region of highest seismicity. The seismic effects were established according to Iranian seismic code and the frame was designed according to the allowable stress design (ASD) method (AISC 1989). The strong column and weak beam philosophy was used in the design of the special moment resistant frame. The fundamental period of vibration amounts to 1.68 sec for the reference regular frame. Details of the sections of the beams and columns for the reference regular frame are provided in Appendix A.

3. Vertically irregular frames

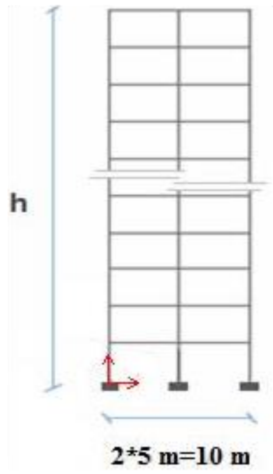

Fig. 1 Configuration of the 10-storey frame

In total, forty vertically irregular frames including four different types of irregularities in four different locations along the height were created by using a modification factor (MF). Four types of irregularities considered for the height-wise distribution of structural properties were as follows: stiffness irregularity (KM), strength irregularity (SM), combined-stiffness-and-strength irregularity (KM&SM), and mass irregularity (MM). Different vertically irregular frames were generated by changing the stiffness, strength, and mass of the reference regular frames. To create a frame with stiffness irregularity, the reference structure's storey stiffness is multiplied (for creating a stiff storey) or divided (for creating a soft storey) by a modification factor in four different locations. Also, to generate a frame with strength irregularity, the reference structure's storey strength is multiplied (for creating a strong storey) or divided (for creating a weak storey) by a modification factor in four different elevations. In order to generate a frame with combined-stiffness-and-strength irregularity along the height, the stiffness and strength of storey(s) of the reference regular structure are simultaneously multiplied or divided by a modification factor. Also, to create a frame with mass irregularity along the height, the mass of storey(s) of reference structure is multiplied or divided by a modification factor in four different locations. In order to generate stiffness, strength, and combined-stiffness-and-strength irregular frames, a modification factor of MF=2 was used. Also, modification factors, MF=2 and 4 were used for generating mass-irregular frames. The following cases describe various types of irregularities considered in this investigation: 1) weak and/or soft, and strong and/or stiff first storey, 2) first storey with heavy mass, 3) weak and/or soft, and strong and/or stiff middle storey, 4) middle storey with heavy mass, 5) weak and/or soft, and strong and/or stiff top storey, 6) top storey with heavy and light mass, 7) weak and/or soft, and strong and/or stiff lower half of frame, and 8) lower half storeys with heavy and light mass.

It is noted that stiffness, strength, combined-stiffness-and-strength, and mass-irregular frames are denoted by KMh(*x*-*y*)**z*, SMh(*x*-*y*)**z*, KM&SMh(*x*-*y*)**z*, and MMh(*x*-*y*)**z*, respectively, in the paper. KM, SM, KM&SM and MM represent stiffness, strength, combined-stiffness-and-strength, and mass irregularities, respectively, *h* means total number of storeys, (*x*-*y*) implies storeys or floors in which modification is applied, and *z* indicates value of modification factor. For example, KM10(1-5)*0.5 specifies a 10-storey stiffness-irregular frame that stiffness of storeys 1 through 5 is multiplied by 0.5 (divided by 2).

3.1 Frames with stiffness irregularity

Frames with stiffness irregularity in a storey (storeys) along the height were defined by changing the stiffness of the columns in that storey (these storeys) and the beams that they support. For a meaningful comparison of seismic responses between the reference regular frame and stiffness-irregular frames, the period of the first mode, the yield base shear and damping properties were kept the same as the reference frame (Chintanapakdee and Chopra 2004). The period of the reference frame is influenced by multiplying or dividing the stiffness of one or more storeys by a modification factor. After applying the modification factor, the period of the first mode of a vertically irregular frame was kept the same as that of the reference regular frame. For this reason, the stiffnesses of all storeys were scaled identically. On the other hand, applying the modification factor to the stiffness of a storey changes slightly the yield base shear in comparison with the reference frame. In order to keep the yield base shear of an irregular frame the same as that of the reference frame, the strength of the whole structure was scaled uniformly after applying the modification factor. Also, Rayleigh damping matrix for vertically irregular structures is defined to maintain modal damping ratio equal to 5% for the first and third modes in 10-storey irregular frames, as for the regular frame. Fig. 2 shows ratio of storey stiffness and of storey strength for the stiffness-irregular frames to the corresponding property of the regular frame. It is noted that the results presented in the paper are only for MF=2 for brevity. Stiffness-irregular frames were also investigated for MF=4 that the relevant results are available in Reference (Ebrahimi 2011).

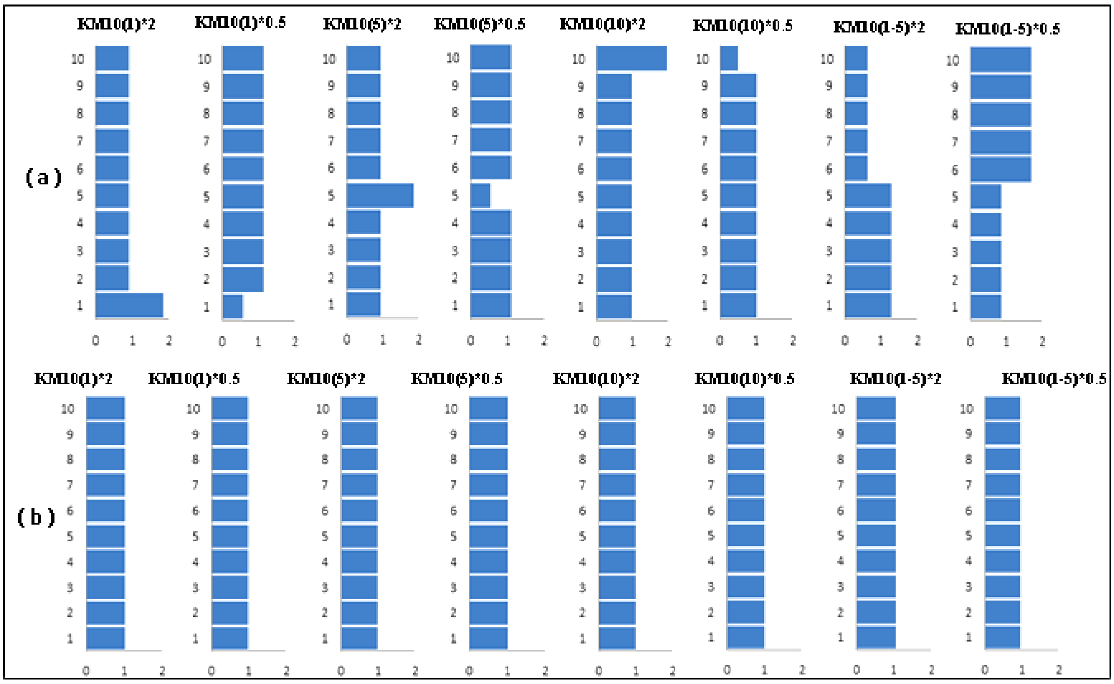

Fig. 2 Ratio of (a) storey stiffness and of (b) storey strength of the stiffness-irregular 10-storey frames to the corresponding properties of the reference regular frame for modification factor, MF=2

3.2 Frames with strength irregularity

In order to generate a frame with strength irregularity along the height in a particular storey (storeys), the strength of the beams at the top of the storey were multiplied or divided by MF=2. The columns were assumed to remain elastic. In a case where the strength irregularity occurs at the first storey or at the lower half storeys of the reference frame, the strengths of the columns of the first storey were also multiplied or divided by their respective modification factor. Like the cases with stiffness irregularity, the period of the first mode, the yield base shear and damping properties for strength-irregular frames were maintained the same as the reference regular frame. In strength-irregular structures, contrary to the stiffness irregularity, strength irregularity in a storey significantly affects the yield base shear of the structure. In order to keep the yield base shear of an irregular frame the same as that of the reference regular frame, the strength of the whole structure was scaled uniformly after applying the modification factor. It is noted that when a modification factor is applied to the strength of a storey with the aim of gaining strength-irregular frame, the period of the first mode of the strength-irregular frame will be equal to that of the reference regular frame because the stiffness of the irregular frame is the same as the reference frame.

For instance, the modification factors applied to the reference frame to create vertically irregular frames with stiffness and strength irregularities are individually given in Appendix B.

3.3 Frames with combined-stiffness-and-strength irregularity

In order to generate frames with combined-stiffness-and-strength irregularity along the height, the stiffness and strength of the storey (storeys) of the reference regular frame were simultaneously multiplied or divided by MF=2. In order to maintain the period of the first mode of an irregular frame equal to the period of the reference regular frame, after applying the modification factor in storey(s) in which irregularity is introduced, the stiffnesses of all storeys were scaled identically. Also, to retain the yield base shear equal to that of the reference regular frame, the strength of the whole structure was scaled uniformly.

3.4 Frames with mass irregularity

In order to generate frames with mass irregularity, the seismic mass of one storey (storeys) of the reference regular frame was multiplied or divided by MF=2 and MF=4. After applying the modification factor in storey(s) in which irregularity is introduced, the stiffnesses of all storeys with mass irregularity were scaled uniformly, again, to keep the fundamental period the same as that of the reference regular frame. Also, to retain the yield base shear equal to that of the reference regular frame, the strength of the whole structure was scaled uniformly. It is noted that damping matrix was defined as described before for stiffness-irregular frames.

4. Description of analyses

Herein, different analysis methods used in this investigation are described. The consecutive modal pushover (CMP) procedure uses single-stage and multi-stage pushover analyses for the 10-storey building frames. In the multi-stage pushover analysis, modal pushover analyses are performed continuously in a way that when a stage is completed, the next stage (next modal pushover analysis) begins with an initial structural condition (stress and displacement) which is the same as the condition at the end of the previous stage. At the end, the seismic responses are obtained by enveloping the peak responses derived from the single-stage and multi-stage pushover analyses. More details of the CMP procedure can be found in Reference (Poursha *et al*. 2009). In the modal pushover analysis (MPA) method, seismic responses were separately computed for each of the modal pushover analyses and combined using the appropriate modal combination scheme (Chopra and Goel 2002). To achieve a better accuracy in the MPA method, seismic responses were obtained by using three modes for the 10-storey frames.

In order to demonstrate the accuracy of the enhanced pushover analysis methods, the results derived from the CMP and MPA were compared to those from nonlinear response history analysis (NL-RHA). Seven far-field ground motion records including 1999 Chi-Chi, 1999 Duzce, 1984 Morgan Hill, 1994 Northridge, 1986 N Palm Springs, 1980 Victoria, and 1987 Whittier Narrows earthquakes were used in NL-RHA The characteristics of far-field ground motion records, which were used in the NL-RHA, are given in Table 1. Also, the soil at the site corresponds to NEHRP site class B. In order to ensure that regular and vertically irregular frames deform into inelastic range under the influence of the selected ground motion records, peak ground acceleration (PGA) of the records was scaled to 0.7 g. Nonlinear response history analyses were performed using the implicit Wilson-θ numerical integration method in which parameter θ was assumed to have a value of 1.4. In order to define the Rayleigh damping matrix in the NL-RHA, a damping ratio of 5% was considered for the first and third modes of vibration in the 10-storey frames. The seismic responses for the NL-RHA were determined as the mean of the maximum values obtained for the seven ground motion records. P-Δ effects were included in all analyses. It is noted that all nonlinear static and dynamic analyses were performed using SAP2000 software (Computers and Structures Incorporated, 2004). The nonlinear behaviour of the frames was assumed to occur in hinges at the ends of the beams and columns. Hinges based on bending moments were defined for beams, whereas hinges based on the interaction of the axial forces and bending moments were assigned to column members. The hinge properties were specified according to FEMA-356 (BSSC 2000).

5. Assessment of the effects of different types of irregularities on the seismic response of structures

Seismic responses of irregular frames derived from the NL-RHA method are shown in Figs. 3 and 4. The effects of four types of irregularities (stiffness, strength, combined-stiffness-and-strength and mass irregularities) on the seismic responses of building frames can be seen in these figures.

For a better understanding of the effects of irregularities in different locations along the height, each of the locations mentioned earlier is separately studied.

5.1 The effects of irregularities along the height on the storey drifts

As can be seen in Fig. 3, the effect of combined-stiffness-and-strength irregularity on storey drifts is more significant than that of strength irregularity in vertically irregular frames, and that strength irregularity influences seismic responses more significantly than stiffness irregularity. The results are in good agreement with those obtained by Krawinkler and Al-Ali (1998),

Table 1 List of the ground motions used

Number	Name	Record/Component	Station	PGA (g)	Distance (Km)	Time(Sec)
1	Chi-Chi,Taiwan	CHICHI/TCU045-N	TCU045	0.512	24.06	90
2	Duzce, Turkey	DUZCE/1061-E	1061Lamont 1061	0.134	15.6	42.5
3	Morgan Hill	MORGAN/SJB-UP	1377 San Juan	0.052	30.3	28
4	Northridge	NORTHR/BLD090	LA-Baldwin Hills	0.239	31.3	40
5	N. palm Springs	PALMSPR/JOS090	22170 Joshua Tree	0.065	29.8	25
6	Victoria, Mexico	VICT/CPE045	6604 Cerro Prieto	0.621	34.8	25
7	Whittier Narrows	WHITTIER/A-GLE180	Mt Gleason Ave	0.089	27.5	35
8	Livermore	LIVERMOR/A-ANT270	67070 Antioch	0.051	20.3	40
9	Whittier Narrows	WHITTIER/A-SEC295	90048 Santa Monica	0.034	32.6	24

Chintanapakdee and Chopra (2004).

Reducing the strength of a storey causes the storey to deform considerably into the nonlinear region; hence, drift of the storey, in which irregularity has been introduced, substantially increases. Also, the story drift increases to a lesser extent at adjacent storeys. On the other hand, reducing the stiffness of a storey causes its drift to moderately increase compared to the regular reference frame. For example, as can be seen in Fig. 3 (cases KM10(1)*0.5, SM10(1)*0.5 and SM&KM10(1)*0.5), simultaneously reducing the stiffness and strength of the first storey in the 10-storey frame increases the first storey drift by up to 3.11 times that of the regular reference frame. The increase of the first storey drift in the case of strength and stiffness irregularities is 2.81 and 1.49 times that of the regular reference frame, respectively. Also, simultaneously reducing the stiffness and strength of the middle storey (SM&KM10(5)*0.5) increases the storey drift by up to 40%, whereas the storey drift increases by up to about 24.2% and 18.7% for strength and stiffness irregularities (cases KM10(5)*0.5, SM10(5)*0.5), respectively.

According to Fig. 3 (cases KM10(1-5)*0.5 and SM10(1-5)*0.5), decreasing the strength of the lower half of the reference regular frame does not significantly influence storey drifts, and the effect of stiffness irregularity is larger than strength irregularity in this case. As mentioned earlier, in order to have a meaningful comparison of seismic responses between regular and irregular frames, the yield base shear of irregular frames was maintained equal to that of the regular frame. To this purpose, after applying a modification factor to the stiffness, strength or mass of the reference regular frame, the strength of the whole structure was scaled uniformly to maintain the same yield base shear as for the reference frame. After applying the reduction factor to the strength of the lower half storeys, the yield base shear significantly decreased. To maintain the yield base shear as described above, the strength of the whole structure was multiplied by 1.98 for the 10-storey frame. As a result, the strength of the lower half storeys will be almost equal to the strength of the corresponding regular frame, and the strength of the upper half will be two times that of the reference regular frame. It should be noted that the distribution of stiffness along the height in strength-irregular frames is similar to that of the corresponding regular frame. Also, the yield base shear changes moderately with reducing the stiffness of the lower half storeys, and in order to maintain the same yield base shear as for the reference regular frame, strength of the stiffness-irregular frames will remain almost unchanged. As can be seen in Fig. 2, the height-wise distribution of strength in the case KM10(1-5)*0.5 is almost similar to that of the corresponding reference regular frame, whereas the height-wise distribution of stiffness is different from the reference regular frame. In the case SM10(1-5)*0.5, storey drifts are almost similar to those of the regular frame at the lower half, since all storey strengths were scaled uniformly to keep the yield base shear of the irregular frame the same as that of the reference regular frame.

The increase of strength in one or several storeys of the regular frame prevents the structure from deforming well into the nonlinear range and storey drifts experience a slight change as compared to the reference regular frame. On the other hand, the increase of stiffness in the lower half storeys influences storey drifts of the upper storeys more significantly than the increase of strength. As is apparent from Fig. 3, increasing or decreasing the stiffness and strength at the lower half storeys not only relatively influences drifts at the lower storeys but also has a considerable effect on the upper storey drifts. The figure demonstrates that increasing or decreasing the stiffness or strength at the middle or top storey influences only drift of the storey in which irregularity has been introduced, and that adjacent storeys are only slightly influenced by this kind of irregularity.

Fig. 3 illustrates that the mass irregularity at the first or middle floor does not have a significant effect on storey drifts of mass-irregular frames compared to the reference frame, whereas mass irregularity at the top or lower half floors significantly influences storey drifts. The figure demonstrates that storey drifts decrease moderately to severely at the storeys below the top storey with increasing the mass at the top of the 10-storey frame.

5.2 The effects of irregularities along the height on the plastic hinge rotations

As can be seen in Fig. 4, simultaneous change of the stiffness and strength influences plastic hinge rotations more substantially than the change of only strength. Also, strength irregularity influences plastic hinge rotations more significantly than stiffness irregularity. Reducing the strength of a storey causes the storey to considerably deform into the nonlinear range; hence, plastic hinge rotations substantially increase. The figure provides evidence that the increase of strength of a storey leads to a significant decrease of plastic hinge rotation in that storey, while the stiffness change has a smaller effect on plastic hinge rotations than the strength change. Fig. 4 demonstrates that increase or decrease of strength in the first storey not only influences the plastic hinge rotation in the irregular storey but also influences plastic rotations of other storeys. A similar trend is obtained for decrease of strength at the lower half storeys. However, decreasing or increasing the strength in the middle or top storey only influences plastic hinge rotations of the irregular storey where the strength modification factor has been applied.

According to Fig. 4, the increase of the mass at the top storey causes a large amount of force to be applied in that storey and causes the storey to considerably deform into the nonlinear region. Then, plastic hinge rotation at the top storey increases in comparison with the reference regular frame. The larger the amount of modification factor in the top storey, the greater the plastic hinge rotation becomes. However, reducing the mass at the top storey results in a smaller plastic hinge rotation. It should be noted that mass irregularity at the top storey influences plastic rotations of the hinges in other storeys in addition to the top storey. Also, the figure illustrates that the change of the mass at the lower half storeys influences considerably plastic rotations at the lower half and at the upper storeys as well. Fig. 4 shows that plastic hinge rotations are not greatly influenced by mass irregularity in the first and middle storeys (see cases MM10(1)*2 and MM10(5)*2).

In this study, we investigated the effects of different types of irregularities on floor displacements as well. For brevity and also because they are not appropriate for indicating structural damage, they are not presented in this paper.

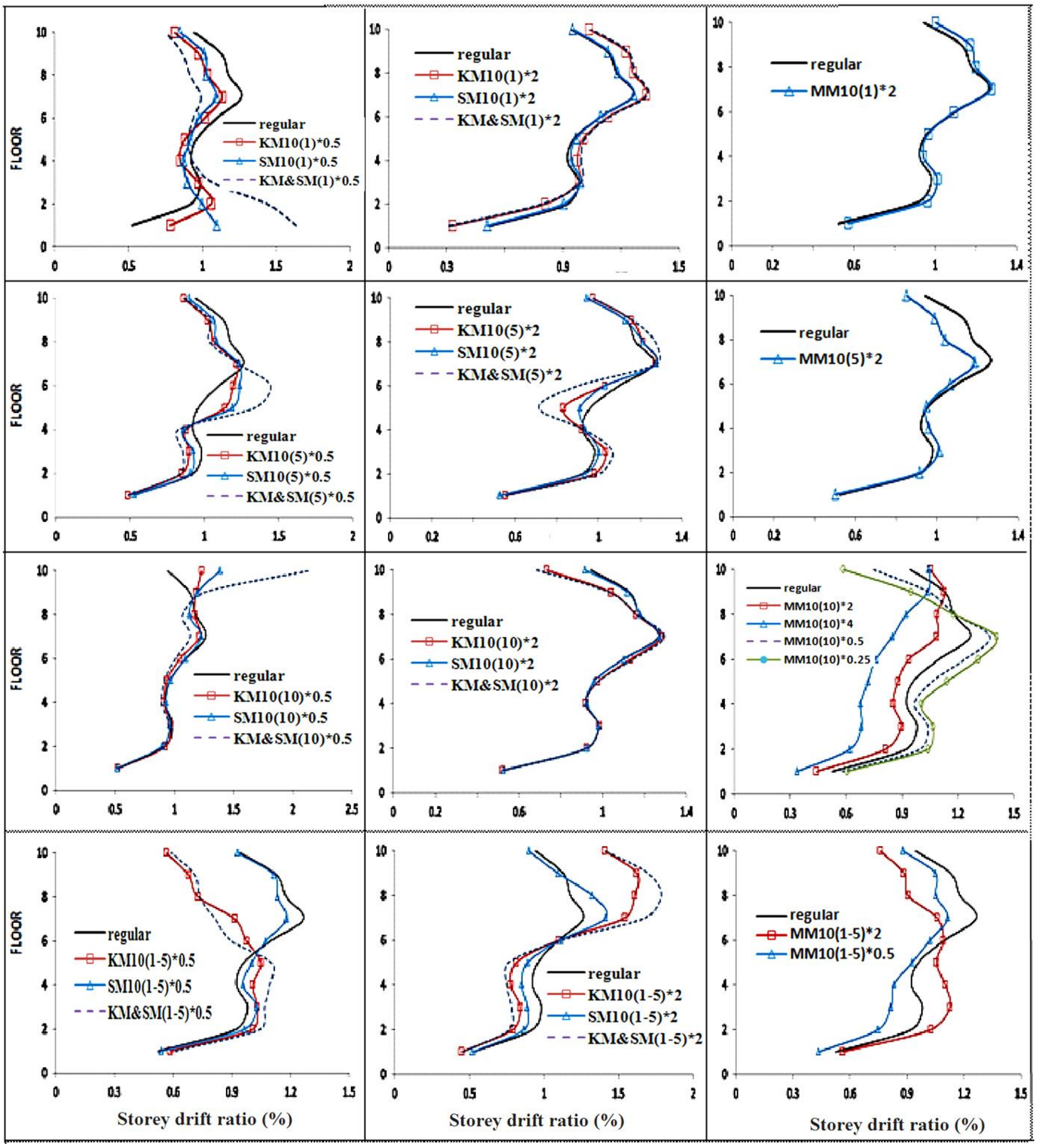

Fig. 3 Storey drift ratios (%) determined by NL-RHA for the stiffness, strength, combined-stiffness-and-strength and mass irregular 10-storey frames denoted by *KM*, *SM*, *KM&SM* and MM, respectively, with modification factor, MF=2

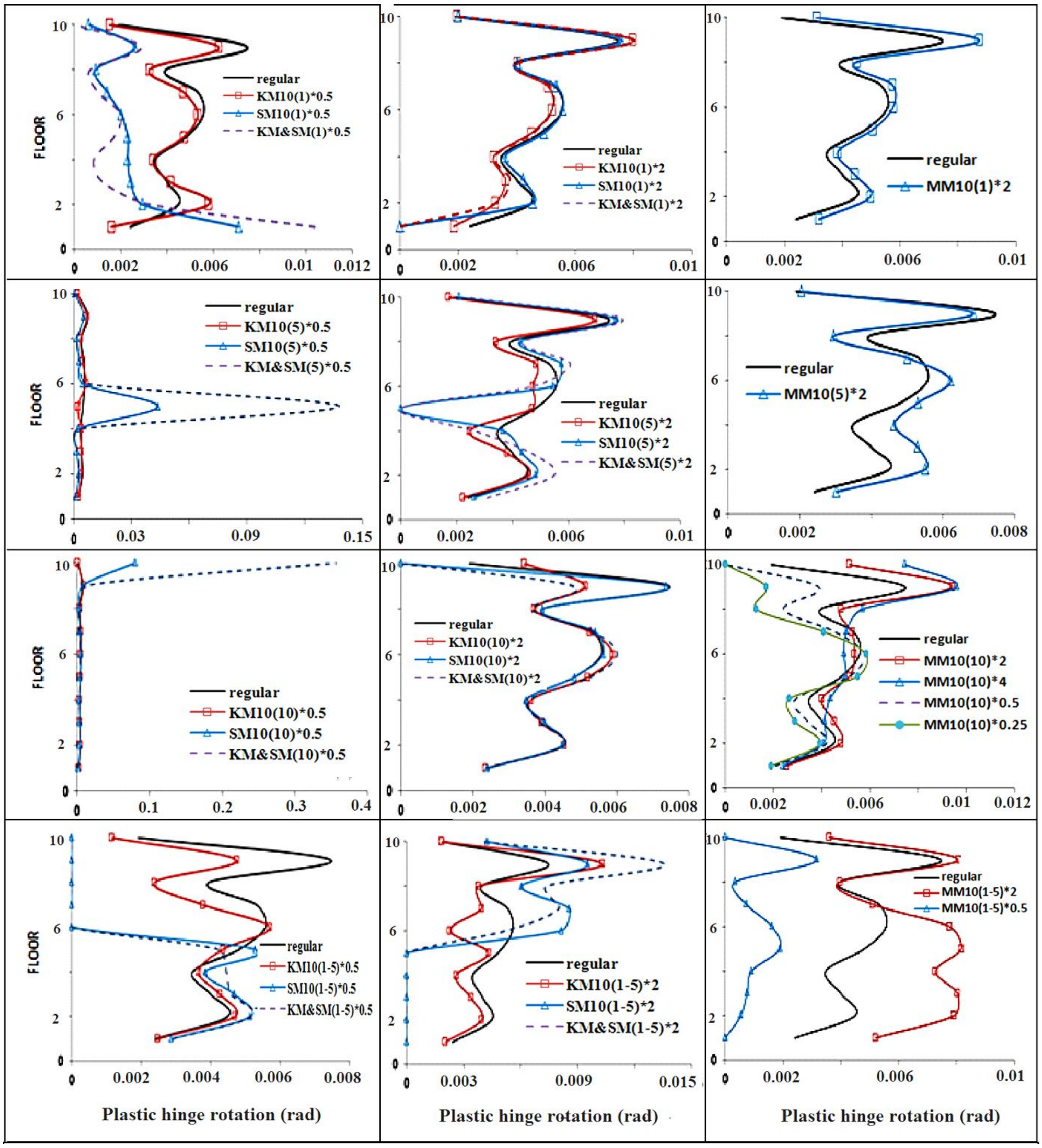

Fig. 4 Plastic hinge rotations (rad) obtained by NL-RHA for the stiffness, strength, combined-stiffness-and-strength and mass-irregular 10-storey frames denoted by *KM*, *SM*, *KM&SM* and MM, respectively, with modification factor, MF=2

6. Evaluation of the accuracy of the MPA and CMP methods in estimating the seismic responses of vertically irregular frames

We proceed to evaluate the accuracy of the MPA and CMP methods in estimating the seismic responses of vertically irregular building frames. To perform the CMP procedure for the 10-storey frames, a two-stage pushover analysis was used in addition to the single-stage pushover analysis. Multi-stage pushover analyses can take the effect of higher modes into consideration in the CMP procedure.

Fig. 5 demonstrates that when stiffness irregularity occurs in the middle or top storey (cases KM10(5)*0.5, KM10(5)*2, KM10(10)*0.5 and KM10(10)*2), the MPA and CMP methods produce good results of storey drifts but the MPA is unable to accurately estimate plastic rotation of hinges. For the irregular frames mentioned above, plastic hinge rotations obtained by the MPA are greatly underestimated in most of the storeys. Plastic rotations derived from the CMP are more accurate than the MPA method, as compared to the NL-RHA. The improvement in the estimates of plastic rotations obtained by the CMP results from consecutive implementation of modal pushover analyses in the multi-stage pushover analysis that causes plastic rotations to be accumulated at the mid and upper floor levels during different stages of the multi-stage pushover analysis, whereas the MPA procedure estimates the total response quantities by combining the individual peak responses obtained separately for each mode.

According to Fig. 5, both CMP and MPA provide acceptable and fairly accurate estimates of storey drifts in frames with stiffness irregularity at the lower half in which the stiffness is reduced (case KM10(1-5)*0.5). The CMP gives more accurate results of plastic hinge rotations than the MPA. If the stiffness is increased at the lower half (case KM10(1-5)*2), storey drifts obtained by the CMP and MPA methods are almost similar at the lower storeys, but the results derived from the CMP and MPA at the upper storeys are relatively overestimated and underestimated, respectively.

Fig. 6 shows that when strength is reduced at the first, middle or top storey (cases SM10(1)*0.5, SM10(5)*0.5 and SM10(10)*0.5 introducing vertically irregular frames with a weak storey), the irregular frame enters considerably into the nonlinear range; hence, plastic hinge rotation increases substantially in the storey where strength has been reduced. In this case, plastic rotation of the hinges for the weak storey, predicted by the CMP and MPA methods, may be noticeably underestimated as compared to NL-RHA. However, in this case, the CMP provides generally better estimates of plastic hinge rotations than the MPA in other storeys. As can be seen from Fig. 6, the CMP procedure may produce a reliable estimate of storey drifts especially at the middle to upper storeys of the strength-irregular frames with a weak storey (sometimes the results may be relatively overestimated), whereas storey drifts gained by the MPA method are generally more accurate at the lower storeys. Fig. 6 illustrates that although the CMP provides better estimates of storey drifts compared with the MPA for the case SM10(10)*0.5, both the CMP and MPA methods underestimate storey drifts at the middle and upper storeys. Fig. 6 demonstrates that the CMP procedure gives a good estimate of storey drifts and plastic hinge rotations at the middle to upper storeys for vertically irregular frames in which strength of the lower half has been increased, whereas the MPA produces better results at the lower half storeys.

Combined-stiffness-strength irregularity with reduction factor, applied only in one storey, results in a considerable nonlinear deformation in the storey where irregularity has been introduced. Both CMP and MPA methods are not accurate enough in estimating storey drift of the soft-and-weak storey for the case KM&SM10(10)*0.5 in which stiffness and strength have been simultaneously reduced at the top storey. As is apparent from Fig. 7 (cases KM&SM10(5)*0.5 and KM&SM10(10)*0.5), the CMP and MPA methods greatly underestimate plastic hinge rotation in the soft-and-weak storey located at the middle or top of the frame. As can be seen in Fig. 7, storey drifts obtained by the CMP and MPA methods are accurate enough for the frames with stiff-and-strong storey(s) (cases KM&SM10(1)*2, KM&SM10(5)*2, KM&SM10(10)*2, and KM&SM10(1-5)*2). A considerable improvement has been gained by the CMP procedure in computing plastic hinge rotations for vertically irregular frames with stiff-and-strong storey(s). The CMP procedure computes plastic hinge rotations more accurately than the MPA especially at the middle to upper levels.

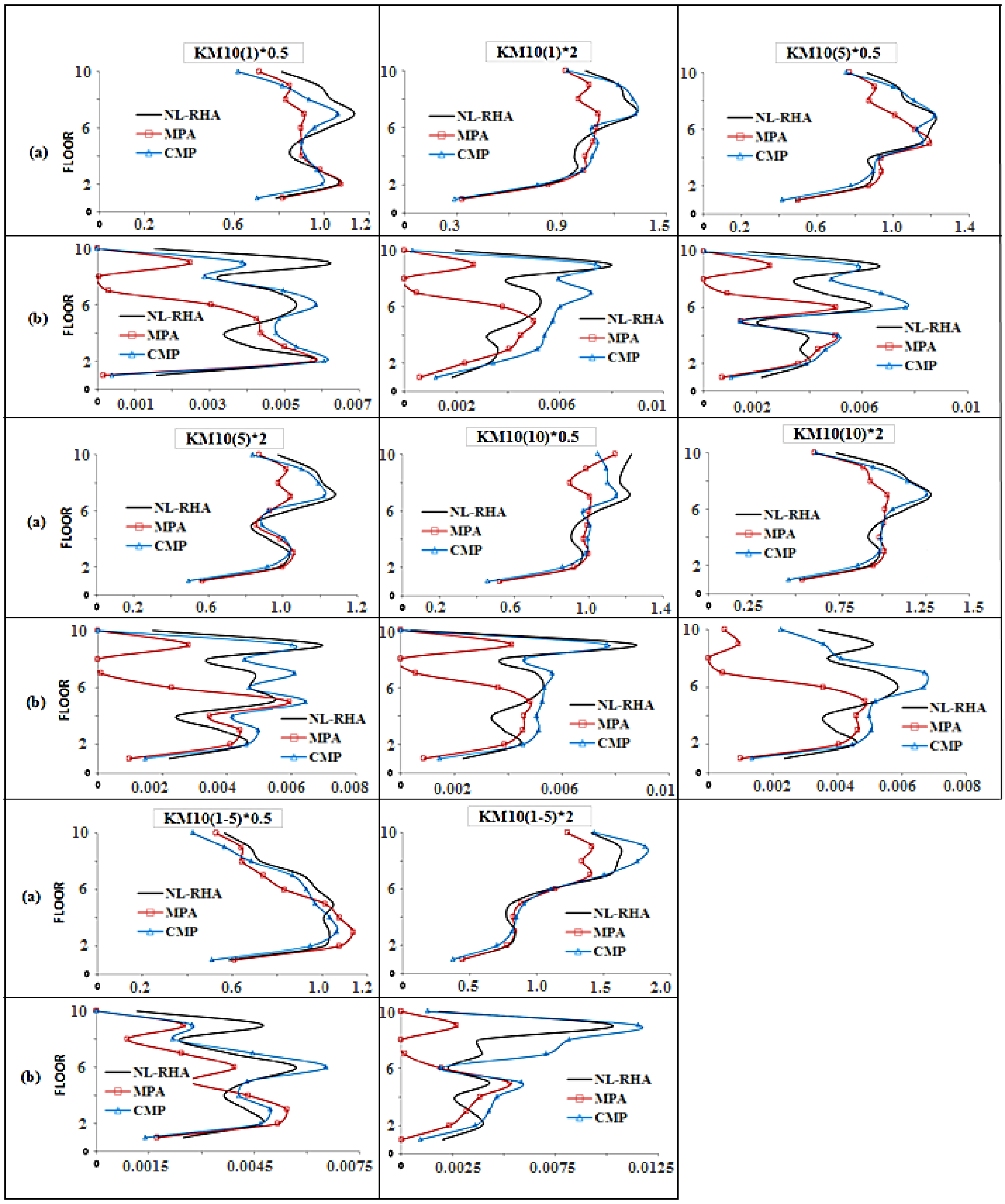

Fig. 5 Seismic responses obtained by the MPA, CMP and NL-RHA for the stiffness-irregular 10-storey frames: (a) storey drift ratios (%); and (b) plastic hinge rotations (rad)

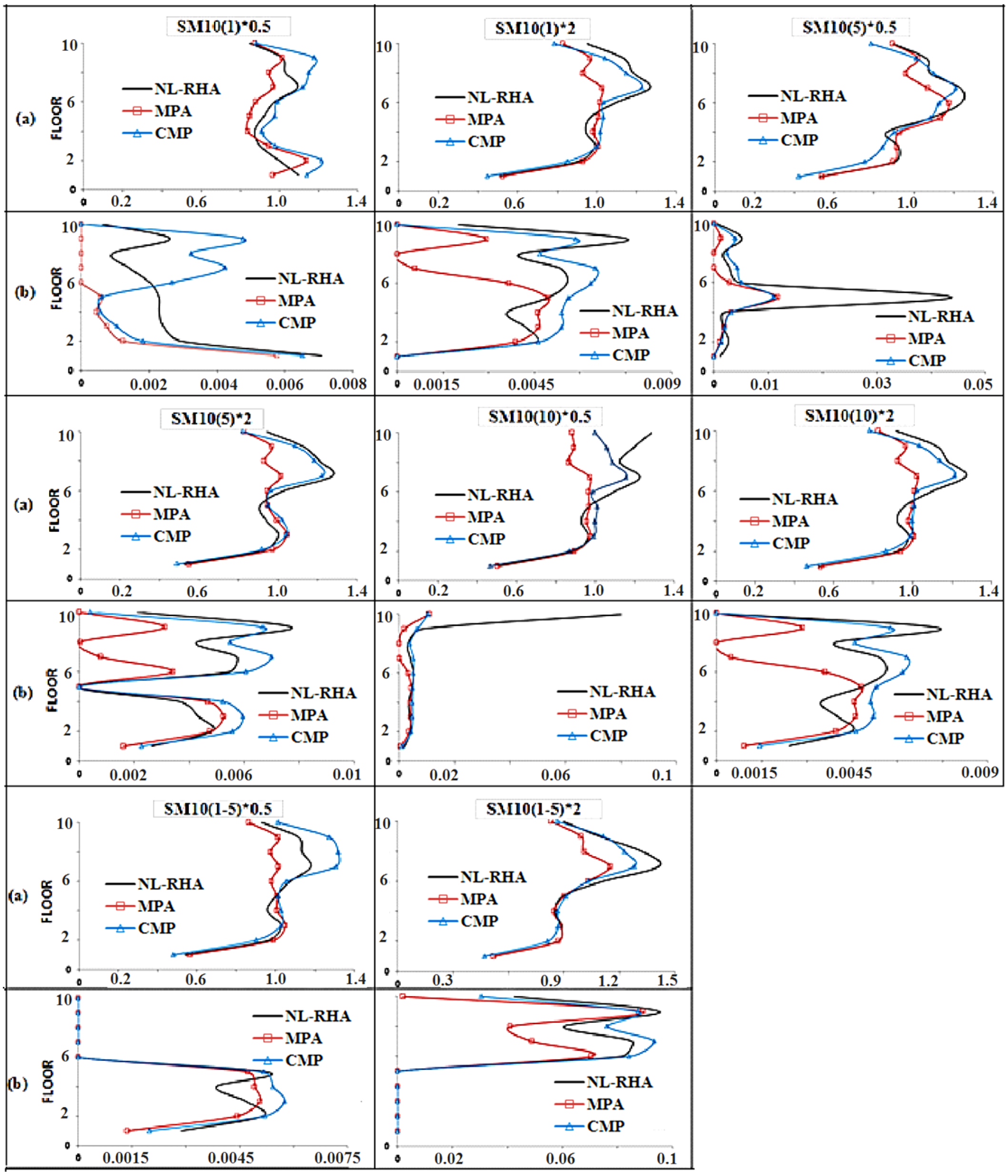

Fig. 6 Seismic responses obtained by the MPA, CMP and NL-RHA for the strength-irregular 10-storey frames: (a) storey drift ratios (%); and (b) plastic hinge rotations (rad)

Fig. 8 clearly illustrates that the CMP and MPA procedures provide good estimates of storey drifts for mass-irregular frames in which the seismic mass has been increased or decreased. The figure demonstrates that the estimates of storey drifts resulting from the CMP procedure are more accurate than those obtained from the MPA procedure in some cases and in some other cases the MPA gives better estimates than the CMP. The CMP procedure generally computes storey drifts more accurately than the MPA at the upper storeys of mass-irregular frames in which the seismic mass has been increased at the top floor level (cases MM10(10)*2 and MM10(10)*4), while the MPA may give better predictions at the lower storeys. Plastic hinge rotations obtained by the CMP are, in general, much more accurate than the MPA for mass-irregular frames. For vertically irregular frames with reduced mass at the lower half (case MM10(1-5)*0.5), the CMP procedure overestimates plastic hinge rotations at the upper storeys as compared to the NL-RHA, whereas plastic rotations derived from the MPA are equal to zero at these storeys.

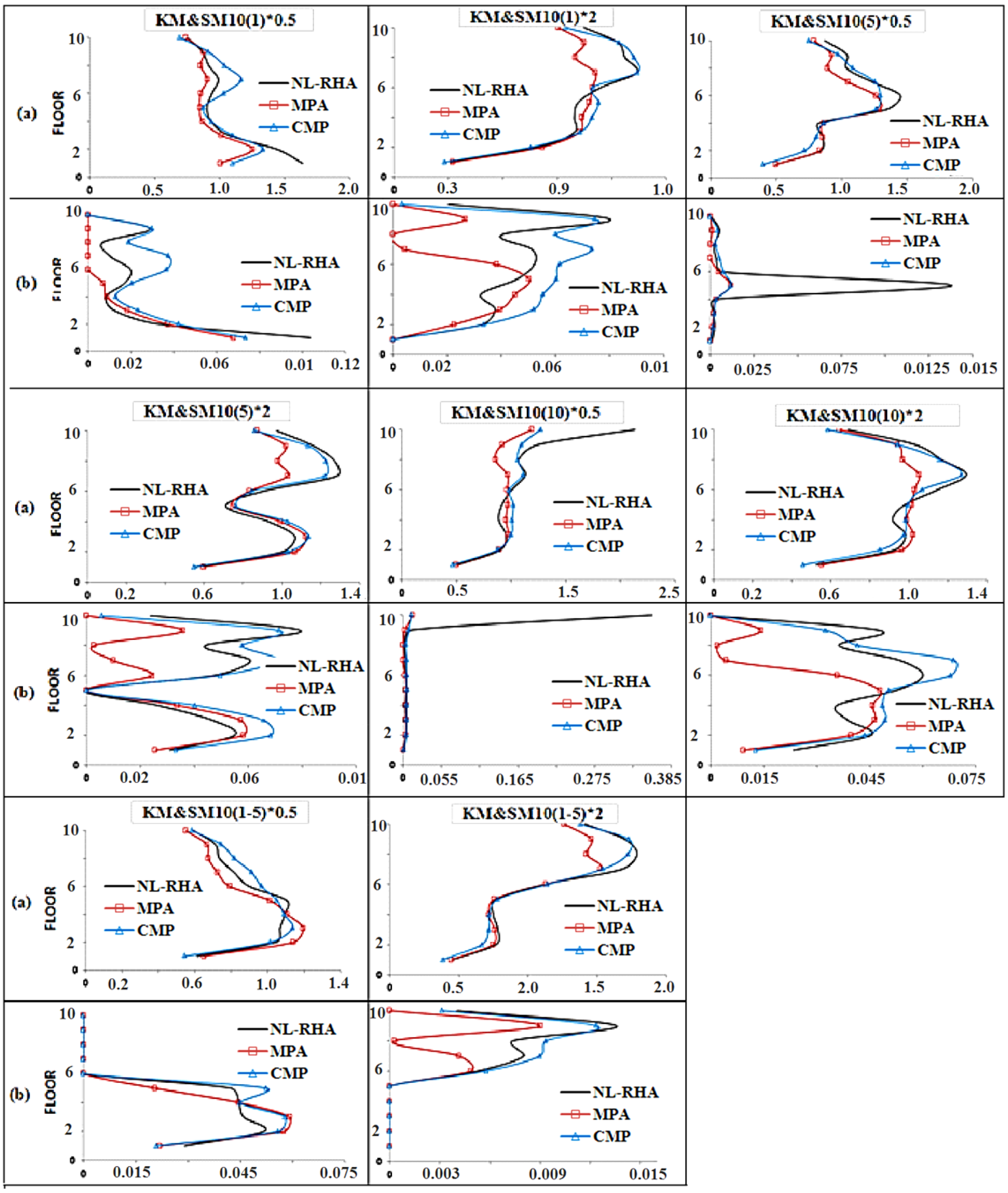

Fig. 7 Seismic responses obtained by the MPA, CMP and NL-RHA for the combined-stiffness-and-strength-irregular 10-storey frames: (a) storey drift ratios (%); and (b) plastic hinge rotations (rad)

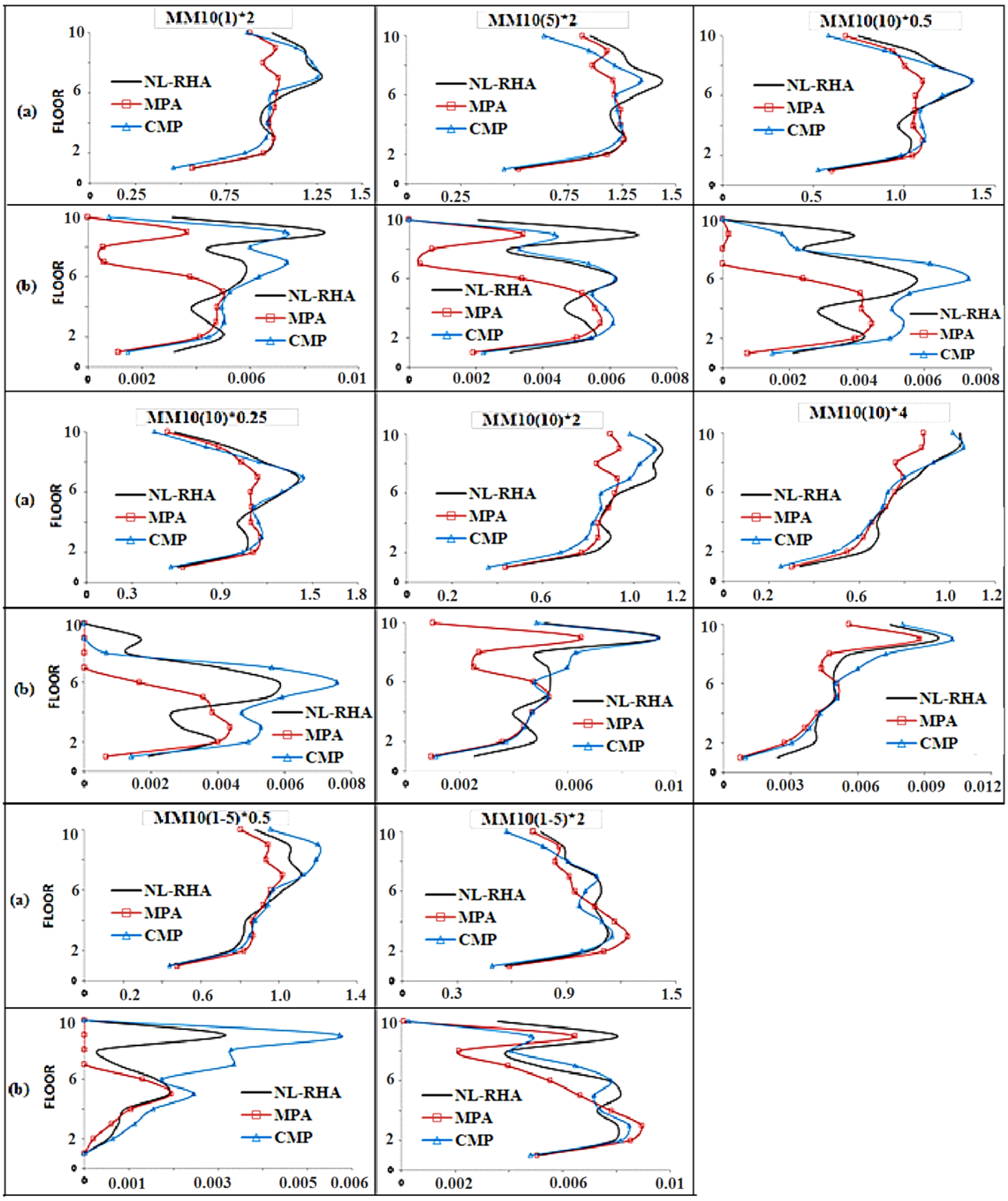

Fig. 8 Seismic responses obtained by the MPA, CMP and NL-RHA for the mass-irregular 10-storey frames: (a) storey drift ratios (%); and (b) plastic hinge rotations (rad)

7. Conclusions

In the paper, the effects of four types of irregularity including stiffness, strength, combined-stiffness-strength and mass irregularities along the height of building frames on the seismic responses were first studied using nonlinear response history analysis. Secondly, the CMP and MPA methods were applied to different types of vertically-irregular frames and accuracy of the methods in seismic evaluation of the frames was investigated. The following conclusions are drawn based on the models considered in this investigation:

• The effect of combined-stiffness-and-strength irregularity along the height on the seismic responses is more significant than that of strength irregularity. Also, strength irregularity is more crucial than stiffness irregularity.

• Decreasing the strength of a storey (storeys) causes the structure to considerably deform into the nonlinear range; hence, the seismic response of the weak storey, in which the irregularity has been introduced, substantially increases. The effect of strength reduction (weak storey) on the seismic responses is more significant than the stiffness reduction (soft storey). Increasing the strength in one or several storeys of the frame prevents the structure from deforming well into the nonlinear range and storey drifts experience a slight change as compared to the reference regular frame.

• Stiffness, strength and combined-stiffness-and-strength irregularities in the first and lower half storeys, not only affect the seismic demands of the irregular storey(s) but also affect those of other storeys. Also, these types of irregularities in the middle or top storey affect the seismic demands of that storey and other (especially adjacent) storeys. The effect of these types of irregularities in the first and lower half storeys on the seismic responses of the upper storeys is noticeably more than that in the middle and top storeys on the seismic responses of the lower storeys.

• Mass irregularity at the first or middle storey does not have a significant effect on the seismic responses of the irregular storey or other storeys as compared to the reference frame, whereas mass irregularity at the top or lower half storeys not only significantly influences seismic responses of the irregular storey(s) but also has a considerable effect on the seismic responses of other storeys. Increasing the mass at the top storey causes a large amount of force to be applied in that storey and causes the story to considerably deform into the nonlinear region. Then, plastic rotation of the hinges at the top storey increases in comparison with the reference frame.

• Storey drifts obtained by the CMP and MPA procedures are accurate enough for vertically irregular frames. The CMP procedure may generally produce an accurate estimate of storey drifts particularly at the middle to upper storeys (the results may be sometimes relatively overestimated), whereas storey drifts derived from the MPA method are generally more accurate at the lower storeys.

• An improvement has been, in general, gained by the CMP procedure in computing plastic hinge rotations especially at the middle and upper floor levels of the vertically irregular frames studied in the paper. Plastic rotations derived from the CMP are generally more accurate than those from the MPA at the aforementioned floor levels. The methods may be, however, less accurate especially in estimating plastic hinge rotations of irregular storeys of vertically irregular frames in which irregularity has been generated by reducing the strength or simultaneously reducing the stiffness and strength at the middle and top storeys.

• In the case of strength and combined-stiffness-and-strength irregular frames, for which a reduction factor has been applied only in one storey, a considerable nonlinear deformation is obtained at the storey in which the irregularity has been introduced. Both the CMP and MPA methods noticeably underestimate plastic hinge rotation in the storey where the irregularity has been generated. For the aforementioned irregular frames, the CMP procedure gives a better estimate of plastic hinge rotations at other floor levels. Also, an improvement has been achieved by the CMP in computing plastic hinge rotations for vertically irregular frames with stiff and strong storey(s).

• The CMP and MPA procedures provide a good estimate of storey drifts for vertically mass-irregular frames in which the seismic mass has been increased or decreased. Plastic hinge rotations obtained by the CMP are, in general, much more accurate than the MPA for mass-irregular frames. For vertically irregular frames with the reduced mass at the lower half storeys, the CMP procedure overestimates plastic hinge rotations at the upper storeys as compared to the NL-RHA, whereas plastic rotations derived from the MPA are equal to zero at the upper storeys.

To generalize the conclusions for vertically irregular frames, it is needed to study realistic vertically irregular frames in practice that typically involve differences in storey height (at the lower storeys) or setbacks at the upper storeys.

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Appendix A: Details of the members of the analytical reference frame

As shown in Fig. A1, the sections of beams and columns of the reference regular frame are considered to be of the plate girder and box type, respectively. Tables A1-A3 give details of the sections and members of the reference frame.

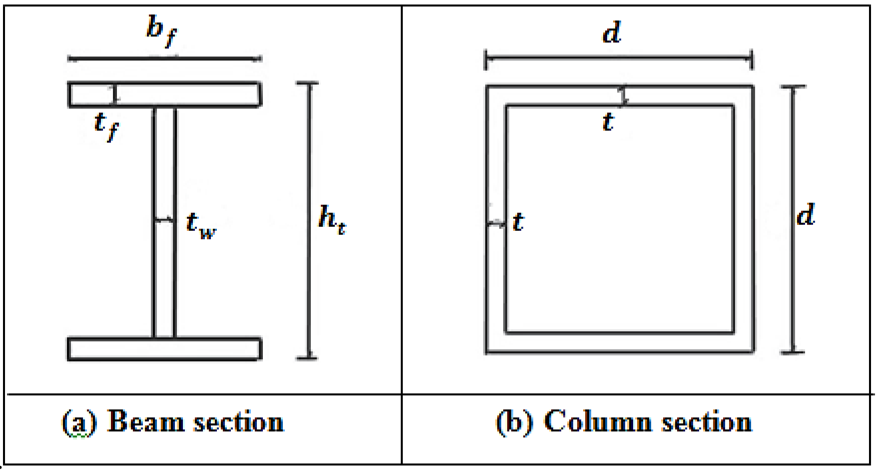

Fig. A1 Sections of the beams and columns

Table A1 Details of the sections of columns

Section	*d* (cm)	*t* (cm)
C_1	45	3
C_2	40	2.5
C_3	35	2.5
C_4	30	2

Table A2 Details of the sections of beams

Section	h_t(cm)	b_f(cm)	t_f(cm)	t_w(cm)
B_1	45	22.5	2	1
B_2	40	22.5	2	1
B_3	35	22.5	2	0.8
B_4	30	20	1.5	0.8

Table A3 Sections of the members of the reference regular frame

Buildings	Storyes	Beams	Columns
10 Storey	1-4	B_2	C_3
	5-6	B_3	C_3
	7-8	B_3	C_4
	9-10	B_4	C_4

Appendix B: Details of modification factors to create vertically irregular frames

Modification factors applied to the stiffness and strength of the reference regular frame to create vertically irregular frames are denoted by MF_k and MF_S. In the tables, T_{1reg} and T_{1irreg} are the fundamental period of the reference regular and vertically irregular frames, respectively. $V_{y\,reg}$ and $V_{y\,irreg}$ are the yield base shear of the reference regular and vertically irregular frames, respectively.

Table B1 The modification factors applied to the reference frame to create frames with stiffness irregularity

Structure	$T_{1\,reg}(sec)$	$T_{1\,irreg}(sec)$	MF_K	$V_{y\,reg}(ton)$	$V_{y\,irreg}(ton)$	MF_S
KM10(1)*2	1.624	1.682	0.922	57.07	55.83	1.025
KM10(1)*0.5	1.78	1.682	1.135	57.07	57.63	0.99
KM10(5)*2	1.627	1.682	0.926	57.07	56.75	1.006
KM10(5)*0.5	1.755	1.682	1.103	57.07	56.4	1.01
KM10(10)*2	1.676	1.682	0.993	57.07	57.22	0.9976
KM10(10)*0.5	1.6875	1.682	1.0068	57.07	56.86	1.004
KM10(1-5)*2	1.4	1.682	0.643	57.07	54.71	1.048
KM10(1-5)*0.5	2.133	1.682	1.7	57.07	58.65	0.9765

Table B2 The modification factors applied to the reference frame to create frames with strength irregularity

Structure	$T_{1\,reg}(sec)$	$T_{1\,irreg}(sec)$	MF_K	$V_{y\,reg}(ton)$	$V_{y\,irreg}(ton)$	MF_S
SM10(1)*2	1.682	1.682	1	57.07	57.12	0.998
SM10(1)*0.5	1.682	1.682	1	57.07	48.3	1.3
SM10(5)*2	1.682	1.682	1	57.07	58.02	0.982
SM10(5)*0.5	1.682	1.682	1	57.07	51.03	1.14
SM10(10)*2	1.682	1.682	1	57.07	57.06	1
SM10(10)*0.5	1.682	1.682	1	57.07	55.6	1.024
SM10(1-5)*2	1.682	1.682	1	57.07	64.945	0.838
SM10(1-5)*0.5	1.682	1.682	1	57.07	33.83	1.98