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PUSHOVER ANALYSIS OF REINFORCED CONCRETE BUILDING WITH VERTICAL SHEAR LINK STEEL BRACES

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Abstract: In recent decades, steel cross bracing has been used as a conventional method to retrofit concrete buildings. Most of the cases utilized concentric steel braces system. However, studies concerning the behavior of RC frames with eccentricity steel bracing are quite limited. In this research, three types of structures incorporating special moment frames, RC structure with invert V braces and RC structures with vertical link beams with different stories were modeled through SAP 2000 and analyzed by considering nonlinear static analysis (pushover). Results revealed that invert Y steel braces (vertical shear links) system is an alternative way to construct a ductile structure with great lateral stiffness. It was also found that the axial force in braces is controlled by the behavior of the vertical link beam.

Keywords: *RC, frame, bracing, vertical link beam, pushover analysis*

1.0 Introduction

The steel cross bracing system is a simple, cost-effective and efficient method to withstand lateral loading in multi-storey buildings. In recent decades, this system has been employed to retrofit old concrete buildings designed just for the purpose of resisting gravity loads. Yet, application of steel cross bracing in RC frame is not prevalent because of unknown behaviors of this system. Hence, more investigation needs to be done in this regard. There are a few studies about the behavior of RC frame incorporating steel cross bracing (Abou-Elfath and Ghoborah, 2000; Mazzolani, 2008; Maheri and Sahebi, 1997), most of which consider concentric steel brace system. While, study about the behavior of RC frame with eccentricity steel bracing is quite limited. Eccentrically braced frames (EBFs) are seismic lateral load resisting systems that comprise a ductile, energy dissipating portion in the beam elements, mentioned as the link beam (AISC, 2005). Different types of this system have been demonstrated in

Figure 1. This system (EBFs) is capable of meeting both important characters, including high lateral stiffness and high energy dissipation capacity, which are required parameters for seismic design of structures. The combination of eccentricity brace frame (EBFs) with RC frame is not common. It is due to the fact that the link beam which is an important part of (EBFs) system has been experiencing inelastic deformation during a major earthquake. Therefore, it is essential to deploy ductile material such as steel comprises the link beam. Furthermore, the link beam has been a segment of the main beam. Therefore, it is difficult to fabricate an RC frame with a vertical steel link beam. Last but not least, slab at the top of the horizontal link beam is susceptible to crashing after a major earthquake due to the large deformation of link beam (Symth *et al*., 2004; Adil and Esra, 2011; Richards, 2006).

In this research, RC frames with vertical steel link beams are analyzed through the nonlinear static method (pushover) and the results are compared to concrete moment frames and RC moment frames with invert V braces, as shown in Figure 2. This can be mentioned that the fabrication of RC frames with vertical link beams is easier than the construction of RC frames with horizontal link beams, especially in RC structure. Moreover, replacement of the vertical link beams after major earthquake is somehow more simple and cheaper than replacement of the horizontal link beams. In addition, implementing vertical links could be an alternative way to avoid the slab crashing during inelastic deformation of horizontal link beams.

2.0 Materials and Methods

2.1 Link Beam

The link beam generated through the diagonal brace is an especial segment of a beam in which at least at one end is connected to the end of the link rather than the beam-column joint, as shown in Figure 1. All inelastic activities are intended to be controlled through the ability of the links section. Links behave like fuses which can dissipate seismic input energy without reduction of strength and stiffness. In addition, implementing links leads to limiting the forces transferred to the adjacent columns, braces, and beam segments (Viswanath *et al*., 2010; Cengizhan and Murat, 2010). According to AICS, Equations to determine the length ranges and allowable link inelastic rotation angles have been developed for I sections as specified in AISC Seismic Provisions. (Eq.1) Short (Shear yielding) links; (Eq.2) Long (flexural yielding) links; (Eq.3) Intermediate length (combination of shear and flexural yielding) links (AISC, 2005) equations can be expressed as:

$$e < 1.6 \frac{Mp}{Vp}\gamma p = 0.08 \text{ radians} \qquad (1)$$

$$e > 2.6\frac{Mp}{Vp}\gamma p = 0.02 \text{ radians} \quad (2)$$

$$1.6\,\frac{Mp}{Vp} < e < 2.6\,\frac{Mp}{Vp} \quad (3)$$

2.2 Nonlinear Static Analysis

According to FEM356 the nonlinear static analysis shall be permitted for structures in which higher mode effects are not significant. In fact, if higher modes are important, a modal response spectrum analysis should be done for the structure using sufficient modes to capture 90% mass participation. Nevertheless, pushover analysis consists of increasing lateral loads representing inertia force in an earthquake until a structure achieves the target displacement (FEM356, 2000). The behavior of structure is obtained by force displacement curve that shows in Figure 3. Point A in this curve is the origin; the next point B is the yielding point after that BC represents the strain-hardening regions the point corresponding to the maximum force and DE is the post-failure capacity region. In addition, FEMA356 and ATC40 are divided BC line to the three performance levels, so, these points describe structure performance as the first point.

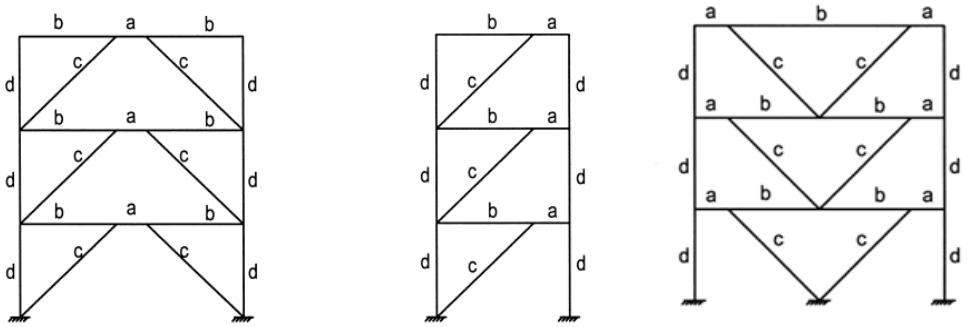

Figure 1: Examples of eccentrically braced frames. a :link , b: beam segment outside of link, c:brace, d: column.

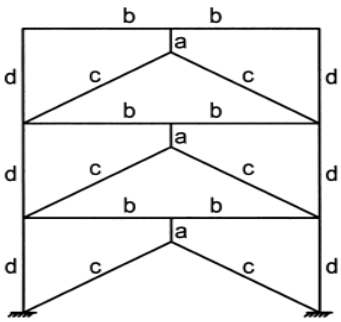

Figure 2: Vertical link beam. a :link , b: beam segment outside of link, c:brace, d: column.

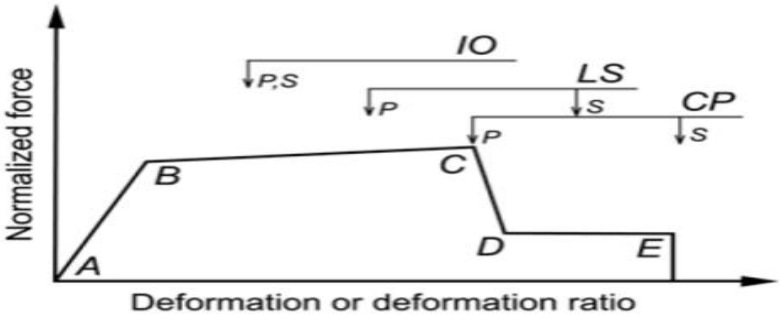

Figure3: Idealized force-deformation curve

3.0 Modeling

The SAP2000 V14 software is utilized to create a 2D model and carry out the nonlinear static analysis. Three types of structures with four, eight, and twelve stories are modeled and indicated short, moderate, and the tall building respectively to consider the effect of height on structure behaviour (SAP2000, 2006). Furthermore, each specimen included one special moment frame SMF, one moment frame with invert V steel brace, and moment fame with vertical link beam (invert Y) shown in Figure 4. In order to specify the samples, this can be mentioned that samples' story height is three meters. Moreover, the model is comprised of four bays each one five meters span. The earthquake loads to be applied to the frames are obtained in the UBC97 code. The study is performed in seismic zone III and while assuming SC as soil type. Distributed dead load on each beam on the floor is 12 KN/m and live load is 6 KN/m. All frames are assumed to be firmly fixed at the bottom, besides the soil–structure interaction is neglected. The last but not least, in order to study the effect of link beam in the behavior of structures, all beams and columns section is same in each specimen with identical story. Table 1 to

Table 4 illustrates dimensions of all beams, columns, braces, link beams and material properties used.

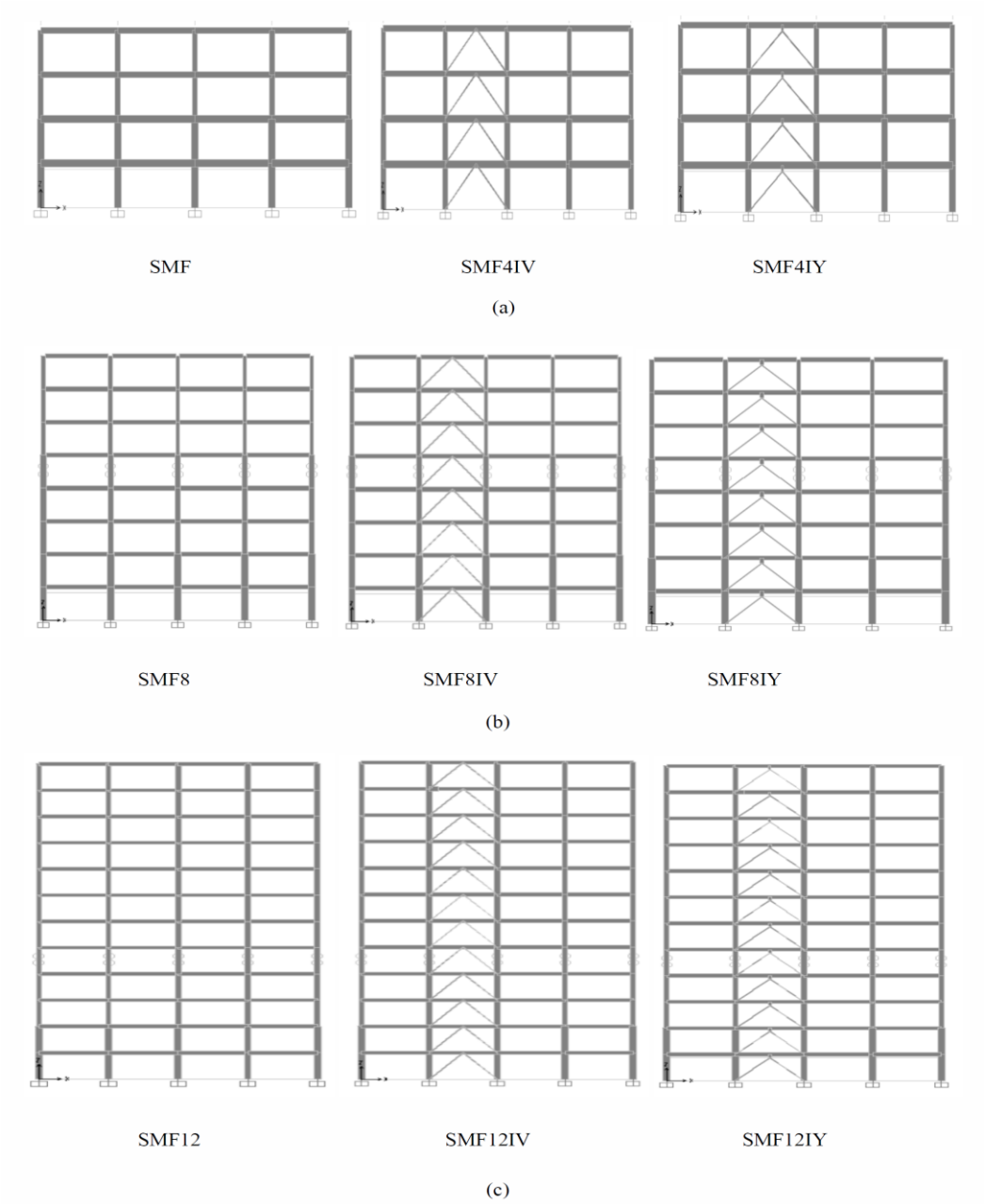

Figure 4: layout of specimens: (a) four stories, (b) eight stories, (c) twelve stories

Table 1: Sections properties for four story specimens

Specimen / Story	Column (mm)		Beam (mm)		Brace	Link beam
	1 &2	3&4	1&2	3&4	1-4	1-4
SMF4	450*450 12 ϕ16	350*350 8 ϕ16	500*300 3 ϕ14	400*300 3 ϕ14	-	-
SMF4IV	450*450 12 ϕ16	350*350 8 ϕ16	500*300 3 ϕ14	400*300 3 ϕ14	TUBO80*80 *8	-
SMF4IY	450*450 12 ϕ16	350*350 8 ϕ16	500*300 3 ϕ14	400*300 3 ϕ14	TUBO80*80 *8	IPE 140 (400 mm)

Table 2: Sections properties for eight story specimens

Specimen / Story	Column (mm)			Beam (mm)		Brace	Link beam
	1 &2	3&5	5&8	1&5	3&4	1-8	1-8
SMF8	500*500 12 ϕ16	400*400 8 ϕ16	300*300 10 ϕ14	400*300 4ϕ16	400*300 3ϕ16	-	-
SMF8IV	500*500 12 ϕ16	400*400 8 ϕ16	300*300 10 ϕ14	400*300 4 ϕ16	400*300 3 ϕ16	TUBO80*80 *8	-
SMF8IY	500*500 12 ϕ16	400*400 8 ϕ16	300*300 10 ϕ14	400*300 4 ϕ16	400*300 3 ϕ16	TUBO80*80 *8	IPE 200 (500 mm)

Table 3: Sections properties for twelve story specimens

Specimen / Story	Column (mm)			Beam (mm)		Brace	Link beam	
	1 &2	3&5	5&12	1&6	3&4	1-12	1-7	8-12
SMF12	500*500 12 ϕ20	400*400 12 ϕ16	400*400 10 ϕ16	400*30 0 4ϕ20	400*300 4ϕ18	-	-	
SMF12IV	500*500 12 ϕ20	400*400 12 ϕ16	400*400 10 ϕ16	400*30 0 4ϕ20	400*300 4ϕ18	TUBO80*80 *8	-	
SMF12IY	500*500 12 ϕ20	400*400 12 ϕ16	400*400 10 ϕ16	400*30 0 4ϕ20	400*300 4ϕ18	TUBO80*80 *8	IPE 220 (400 mm)	IPE16 0 (400 mm)

Table 4: Material properties

Material	Concrete (N/mm2)	Steel (N/mm2)	Rebar (N/mm2)
Young's modulus E	25000	200000	200000
Fc	28	-	-
Fy	-	245	420
Fu	-	370	600

4.0 Results and Discussion

4.1 Lateral Displacement

Table 5 shows the lateral displacement values for all specimens. It is observed that the lateral displacements are diminished the most for invert V bracing systems. In addition, the results indicate that invert Y bracing decreased lateral displacement near to 66%. While, invert V bracing reduced lateral displacements until 80%.

4.2 Nonlinear Static Analysis Results

Ductility is one of the important parameters in seismic design. Structures with ductile behavior can absorb earthquake energy during major earthquakes. Table 6 and Figure 5 show, respectively the ductility factors for all specimens and lateral load–roof displacement curves derived from a push over analysis of all specimens. Pushover curve shows that invert V bracing is capable of enhancing lateral stiffness rapidly in all specimens besides diminishing ductility of structure. In fact, after buckling in braces during a major earthquake, all or some parts of the structure are collapsed. In addition to invert V bracing, Invert Y bracing boosts lateral stiffness as well. But this type of structural system has a ductile behavior which is actually between moment frame and invert V bracing system. It is due to the fact that first plastic hinges occur on link beam; consequently, axial force that transfers to the braces is controlled by the link beam. In other words, the behavior of link beam prevents from buckling of braces. Figure 6 illustrates that first plastic hinges happen on beams in SMF4 specimen, while SMF4IV first plastic hinges appear on brace at second story due to compressive forces. Moreover, first plastic hinges for SMF8IV and SMF12IV happen to the braces at the second and third story.

According to Figure 6 (d), Vertical shear links distribute first plastic hinges from second to fifth stories for specimen SMF12IY. However, based on nonlinear static analysis, SMF4 specimen reaches to IO (immediate occupancy) performance point when shear force is around 0.064W, which W represents the weight of building while this value is increased to 0.49W for SMF4IV. Furthermore, the structure incorporating invert Y steel

braces reaches to the performance point by value of shear force near to 0.23W. Table 7 indicates the amount of shear force in different levels of performance point. This result shows that the value of the shear force of IO level to C level is closer together while height of structure increasing. However, these values could be changed when assigned larger IPE section for vertical the link beam. Moreover, the results from the pushover analyses demonstrate that the SMF4 provides a lateral yield load of around 0.15W and an ultimate lateral load of 0.35 W, where W represents the weight of the structure. Both yield load and ultimate lateral load are increased to 0.4W and 0.7W respectively by the virtue of implementing the inverted V brace to strengthen the SMF4. This can be inferred from the capacity curves of the invert Y brace system that the yield load reaches to 0.26W and ultimate load reaches to 0.5W.

Table 5: Roof displacement refer static earthquake force (UBC)

Specimen	Four story			Eight story			Twelve story		
Type	SMF4	SMF4IV	SMF4IY	SMF8	SMF8IV	SMF8IY	SMF12	SMF12IV	SMF 12IY
Displacement (mm)	19.44	3.98	6.54	71.34	11.49	24.15	137.67	34.73	44.74

Table 6: System ductility factor for all specimens

Specimen	SMF4	SMF4IY	SMFIV	SMF8	SMF8IY	SMF8IV	SMF12	SMF12IY	SMF12IV
μ	3.2	3.022	1.95	7.4	5.7	3	2.75	2.20	1.3

Table 7: Proportion between performance point and shear force

Performance point	SMF4	SMF4IV	SMF4IY	SMF8	SMF8IV	SMF8IY	SMF12	SMF12IV	SMF12IY
IO	0.064 W	0.49W	0.23W	0.045 W	0.19W	0.197W	0.114W	0.089W	0.11W
LS	0.33W	0.74W	0.45W	0.09W	0.19W	0.22W	0.12W	0.18W	0.126W
C	0.36W	0.75W	0.5W	0.1W	0.20W	0.25W	0.13W	0.19W	0.132W

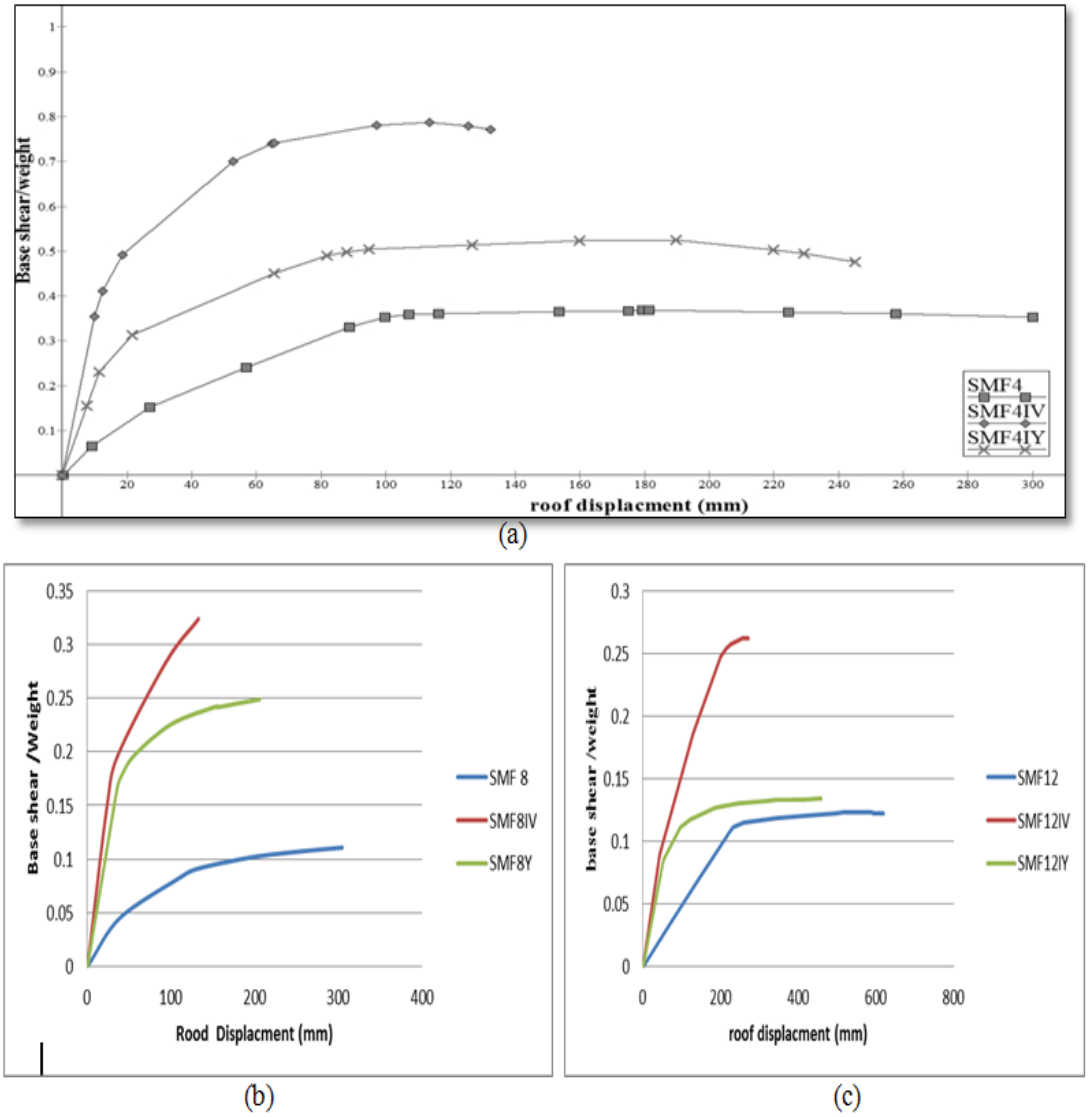

Figure 5: Pushover curve (a) four story specimens, (b) eight story specimens, (c) twelve story specimens.

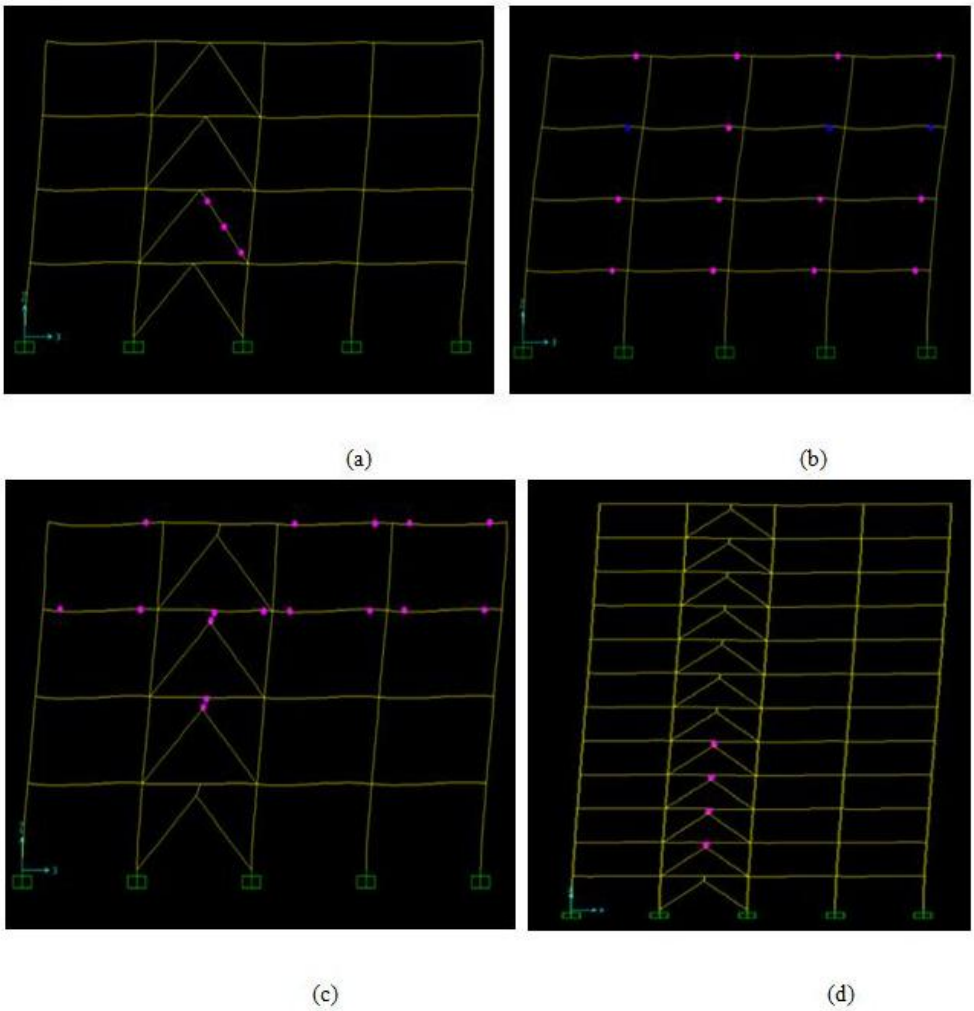

Figure 6: First plastic hinges (a) SMV4IV, (b) SMF4, (c) SMF4IY (d) SMF4IY.

5.0 Conclusion

Taking everything into consideration, this research represents a nonlinear static analysis of a special moment frame R/C Building before and after applying eccentric steel braces which are accompanied by the vertical link beam and the invert V concentric steel brace. The result indicates that invert Y steel brace system is an alternative way to construct ductile structures with greater lateral stiffness. Moreover, the fabrication of eccentric steel brace with vertical shear link is much easier than construction with horizontal shear

link in RC frame. Eventually, this system could be employed to retrofit old concrete buildings and to prevent from crashed slab concrete.

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