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NONLINEAR SEISMIC BEHAVIOR OF RC FRAMES WITH RC BRACES !

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Abstract

Braced frames, besides other structural systems, such as moment resisting frames or shear walls, have been an effective and valuable method to enhance structures against lateral loads. In wind or seismic excitations, inclined elements react as truss web elements which would bear compression or tension stresses. This axial reaction results in less moments and therefore smaller sizes in beam and column sections with respect to members in similar moment resisting frame. However, low tensile strength of concrete material, made it a challenge to use in inclined members. In practice, there have been various methods to consider this defect such as disengagement of brace elements in tension or utilization of prestressed braces.

The purpose of this article is to study the nonlinear response of reinforced concrete frames which contain reinforced concrete braces as the major structural elements against earthquake loads. The advantages of nonlinear behavior in reinforced concrete elements and their adequate energy absorption in cyclic loading are taken into account. Also stiffness and strength degradation of structural members under cyclic loading is considered.

Two different braced frames with K and X braces are analyzed numerically for four, eight and twelve story buildings. This study focuses on evaluation of strength, stiffness, ductility and energy absorption of reinforced concrete braced frames and comparison with similar moment resisting frames and frames with shear wall. Results are plotted in diagrams and discussed extensively. According to this study it is concluded that besides effective lateral stiffness rising in reinforced concrete braced frames, there is a considerable amount of energy dissipation during earthquake loading.

Keywords: Concrete brace; seismic; energy dissipation; ductility; stiffness

1. Introduction

One of the most common methods to enhance lateral stiffness of frames is bracing with inclined members. Although this method is widely used in steel frames, its advantages made

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it practical in reinforced concrete frames. Considering low tensile strength in concrete, practical considerations such as prestressing brace members, disengagement of braces in tension and considering tensile strength of rebars are needed in reinforced concrete braces.

Desai [1] tested several RC members, under oscillating axial excitations, to predict hysteresis behavior of RC braces. Result showed that there is a continuous reduction in compression and tension stiffness due to more excitation loops. This reduction in stiffness is more considerable in tension caused by developing cracks in cross sections. He proposed a simple triangular hysteresis model which consists of 6 lines (0 to 5 in Figure 1). Figure 1 indicates the simple model in different loading stages.

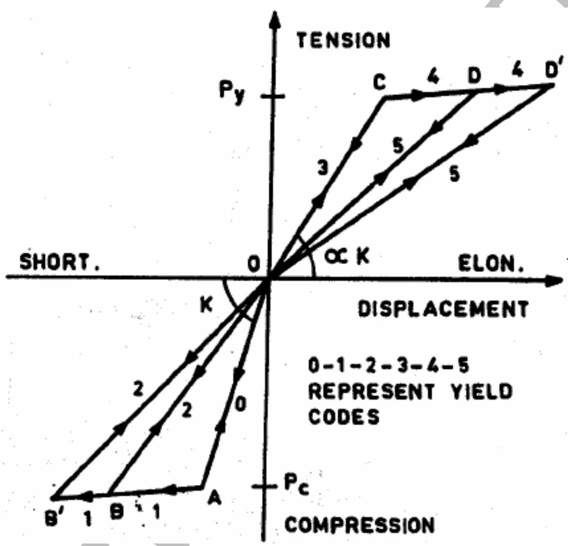


Figure 1. Desai simple triangular modeling in different loading stages

Desai *et al.* [1] also investigated dynamic response of RC braced frames numerically. In their study, tension stiffness of braces in upper and lower band assumed 1.0 and 0.5 times of the compression stiffness.

Iskhakov [2] determined optimal seismic response of RC frames with concrete braces assuming that braces were disconnected in tension. He declared fine energy absorption in braces due to nonlinear behavior of concrete materials in compression. Results indicate that using RC braces significantly reduce (over 50%) the seismic forces and relative displacements.

Xu and Niu [3] compared several braced frames with the same moment resisting frame and shear wall experimentally. In their models RC braces were bearing both compression and tension. According to their study, in braced frames, not only lateral resistance and stiffness enhanced, but also energy dissipation amount increased significantly. This observation was based on elasto–plastic behavior of braces and energy absorption in hysteresis loops. Also braced frames had slower stiffness degradation than shear wall and had the same stiffness degradation as moment resisting frame throughout the loading cycles.

Watanabe [4] in collaboration with Takenaka Corporation in 2002 used precast prestressed braces to strengthen a 4-story RC building against earthquake loads. Special connections with precompressed springs were used for installation. Hence, no tension imposed on precast braces.

In this study seismic response of RC frames with integrated RC braces is investigated focusing on their strength, stiffness, ductility and energy dissipation. Proposed models are analyzed with RAM-perform 3DS (ver.2.10) program [5].

2. Concrete Materials Modeling

Figure 2 indicates hysteresis behavior of concrete materials in compression. Unloading stiffness is equal to initial stiffness and energy dissipation amount modifies with reloading stiffness variation. Effect of maximum compression strain in concrete behavior during next loops is taken into account with Energy Dissipation Factor (EDF). If the EDF is 1.0, reloading occurs as shown in Figure 2(a). This is the maximum amount of energy dissipation. If the EDF is less than 1.0, reloading occurs as shown in Figure 2(b). If the EDF is zero, the unloading and reloading lines are the same and there is no dissipation. Tensile strength of concrete is neglected during analysis procedures.

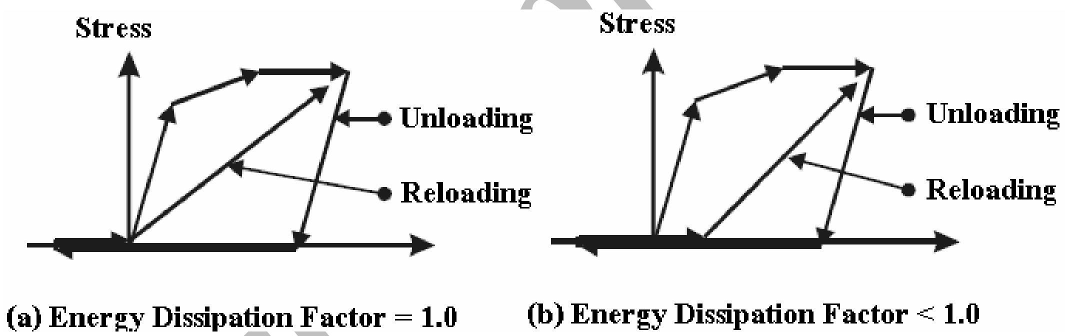


Figure 2. Concrete materials modeling in compression

3. Braced and Unbraced Frames

In order to investigate behavior of X and K braced frames and compare its response to moment resisting frame and shear wall frame system, three different frames with 4, 8 and 12 stories are modeled and analyzed numerically. Beams, columns, braces and shear walls are the same for every 4 stories (1-4, 5-8 and 9-12). X brace arrays are selected to be as similar as possible with K braces regarding to their equal length. In all cases, span length and story elevation are 4 and 3 meters, respectively.

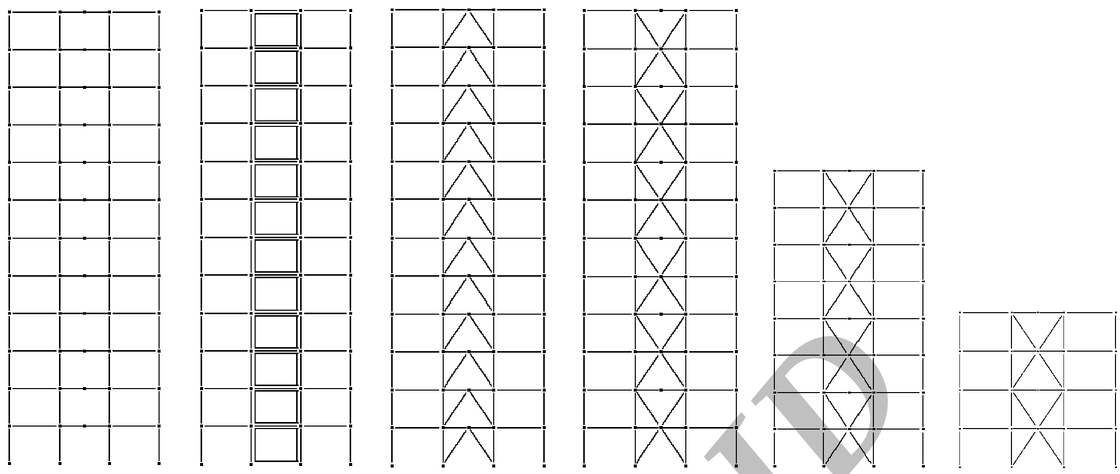


Figure 3. Four, eight and 12-story frames

Nonlinear compression behavior of concrete in first loading stage is displayed in Figure 4. Trilinear behavior is assumed before strength degradation stage which indicates more accurate stress-strain relationship.

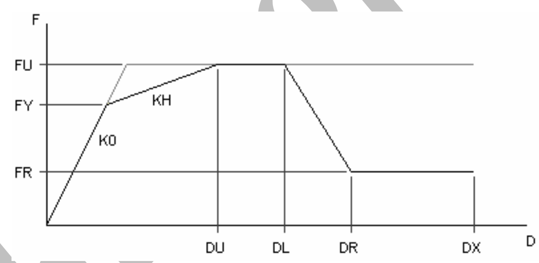


Figure 4. Nonlinear stress-strain relationship of concrete

Numerical parameters of Figure 4 are given in Table 1. Elastic modulus of concrete (E_c) is calculated by equation E_c=15100√FU. Tensile strength of concrete is neglected conservatively.

Table 1. Numerical values of concrete properties

E_c(kg/cm^2)	309460	**DU**	0.0025
KH/K0	0.192	**DX**	0.008
FY (kg/cm^2)	336	**DL**	0.003
FU(kg/cm^2)	420	**DR**	0.005
FR/FU	0.1		

Table 2. Assumed EDFs for different strains

Compressive strain	DY	DU	DL	DR	DX
Energy Dissipation Factor	1.0	0.8	0.5	0.2	0.1

Table 2 shows assumed EDF values for different stages in compression. In order to determine initial element sections, all cases were loaded as equivalent static loading [6] and designed according to reinforced concrete design code [7].

4. Reinforced Concrete Braces

In order to model RC braces accurately, element sections divided into several concrete and steel fibers. In this method total behavior of sections can be obtained from defined stress-strain curve of materials for each fiber. All RC braces are 25×25(cm^2) and their difference in stories is in longitudinal rebar percentage. Figure 5 indicates meshes for the four middle stories in 12-story frame. RC brace rebar percentages in four lower, middle and upper stories are 1.6, 3.3 and 4.9, respectively.

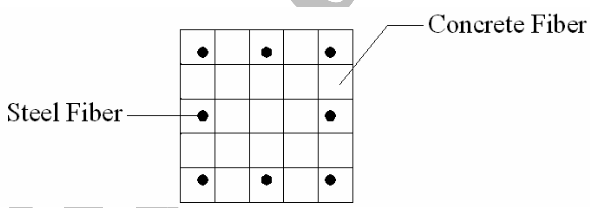


Figure 5. Section modeling of RC braces in the four middle stories of the 12-story frame

5. Ground Motion Records

To induce seismic loading on structures, three ground motion records have been selected according to FEMA-440 [8] and scaled according to FEMA-356 [9].

Table 3. Earthquake ground motions

Earthquake	Magnitude	Station	PGA (cm/s^2)
Loma Prieta	7.1	1652	239.4
Morgan Hill	6.1	57383	280.4
Northridge	6.8	24278	504.2

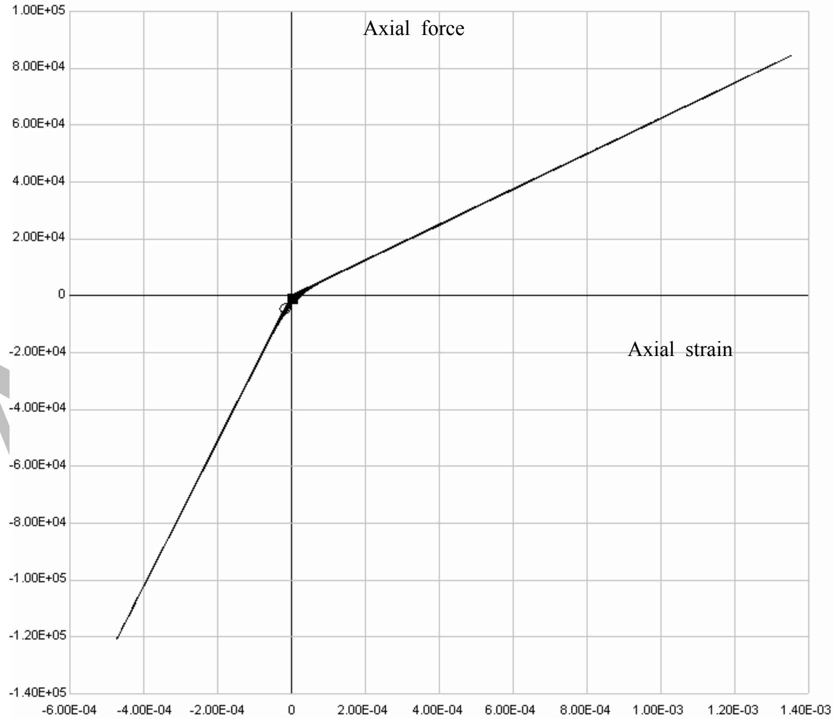
6. Nonlinear Dynamic Analysis

In this section, results from nonlinear dynamic analysis of braced frames, shear wall-frame system and moment resisting frames are presented. In order to prevent wide range of results and diagrams, in most cases, 12-story frames are discussed. Everywhere that height of structure affects its behavior, it is mentioned.

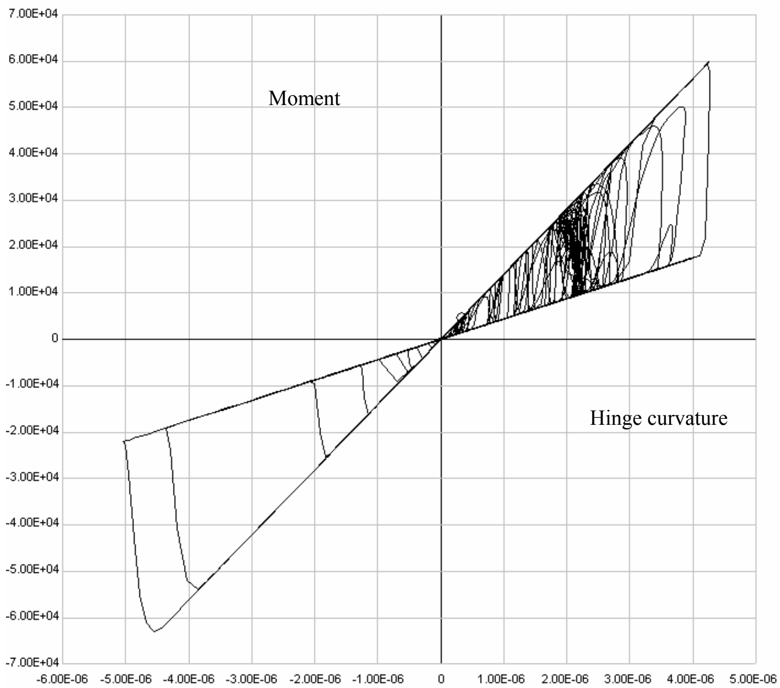
6.1 Structural elements hysteresis loops

Hysteresis loops of some members in 12-story frames are shown in Figure 6. The members are selected from second story and diagrams are related to "Loma Prieta" earthquake excitation. Braces are designed so that they do not enter to nonlinear stage due to axial stresses. As indicated in Figure 7, if they do so, low tensile stiffness of braces leads to unsuitable behavior. In that case, because of high strength of RC braces in compression, their compressive behavior remains elastic whereas longitudinal rebars go to plastic zone easily and may be ruptured in reality.

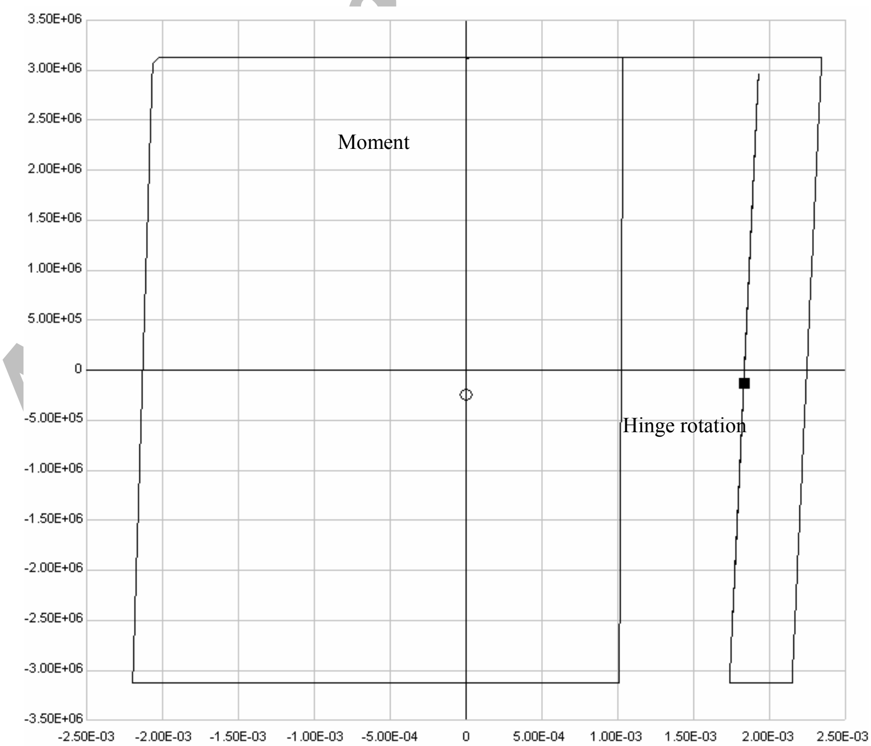
Figure 6 shows beams in moment resisting frames have the largest amount of energy absorption in comparison with other structural members (Figure 6(c)). K and X braces have no energy absorption in axial excitation and very small energy absorption in bending (Figure 6(a), 6(b), 6(d) and 6(e). In addition, shear wall elements in our sample models had small energy dissipation in bending behavior (Figure 6(f)).



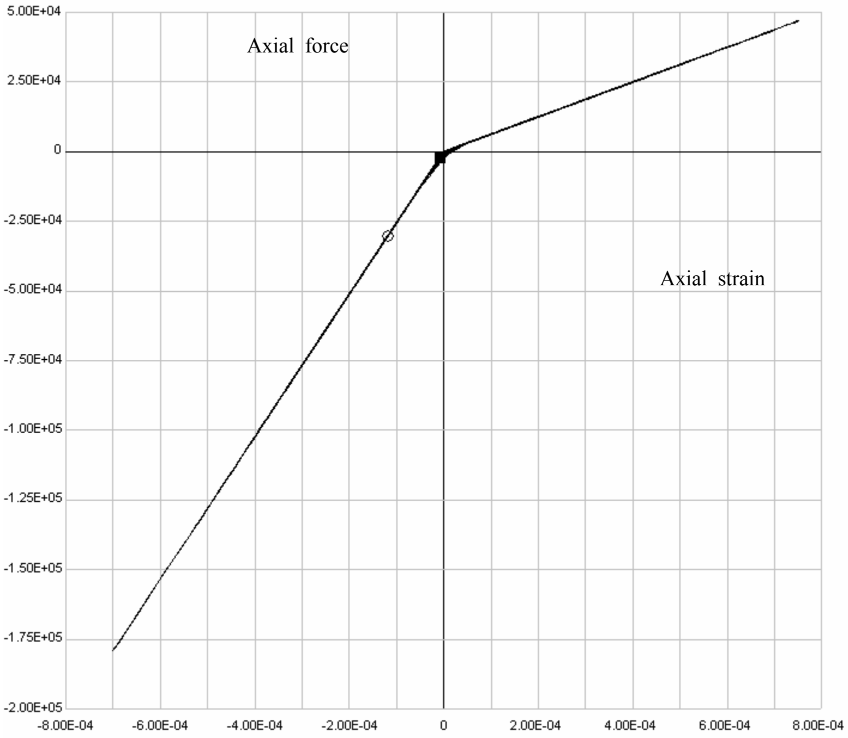
(a) Axial behavior of K braces



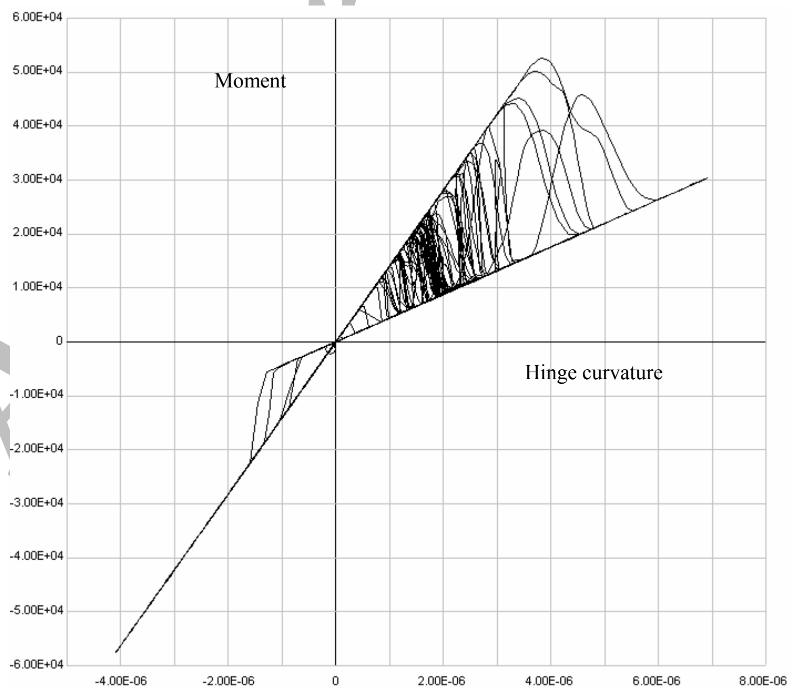
(b) Bending behavior of K braces



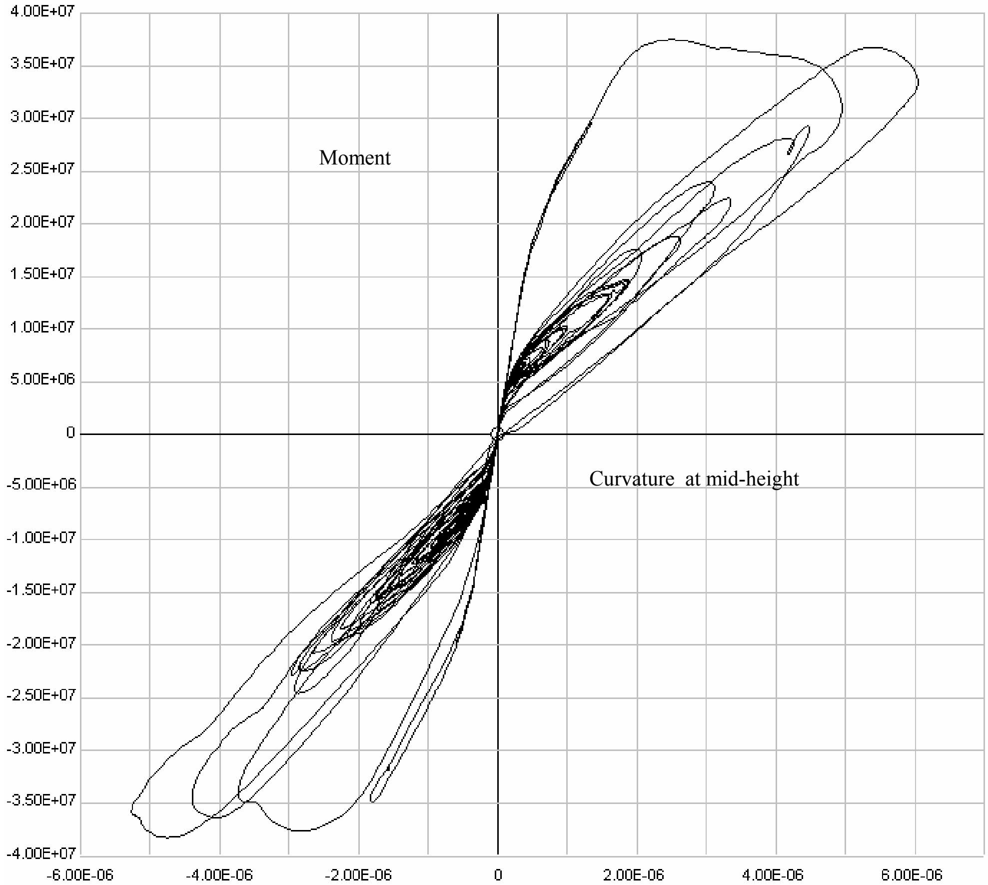
(c) Bending behavior of middle span beams



(d) Axial behavior of X braces



(e) Bending behavior of X braces



(f) Bnding behavior of shear wall.

Figure 6. Structural elements hysteresis loops in "Loma Prieta" earthquake

6.2 Story drifts

Maximum drifts of 12-story frames in different earthquakes are displayed in Figure 8. It is evident that drifts in braced frames are near to shear wall frame system and considerably less than moment resisting frame. Maximum drift for moment resisting frame in three different ground motions is in level 6. In that level, drifts of braced frames and shear wall included frame are less than 50% of drift in moment resisting frame.

Roof displacement time histories due to "Loma Prieta" earthquake record are presented in Figure 9. It shows that maximum roof displacements in braced frames are equal to shear wall frame system and about half of the moment resisting frame. There is not any major difference between two kind of braced frames roof displacement except that K braced frame has more monotonic waves after passing great shocks of the earthquake. In addition, there is a residual displacement equal to 15 centimeters in moment resisting frame.

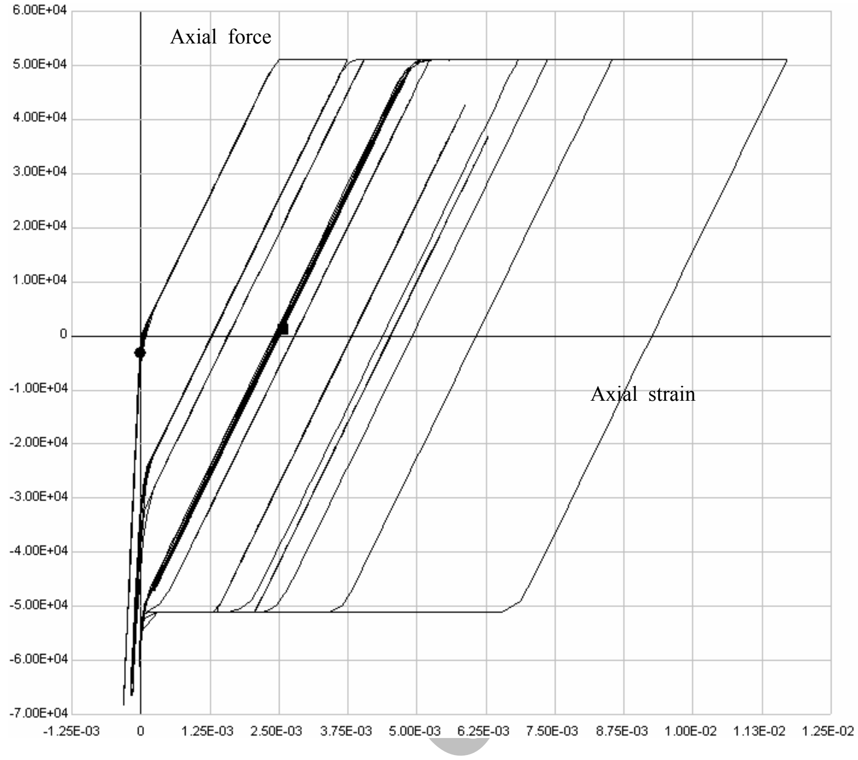
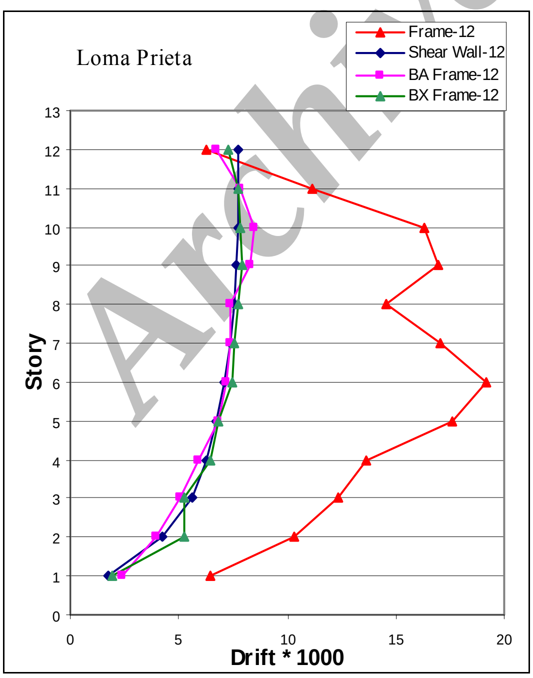
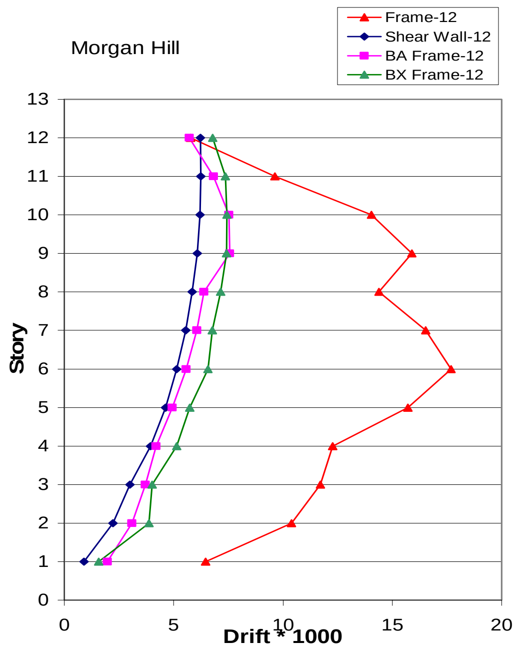


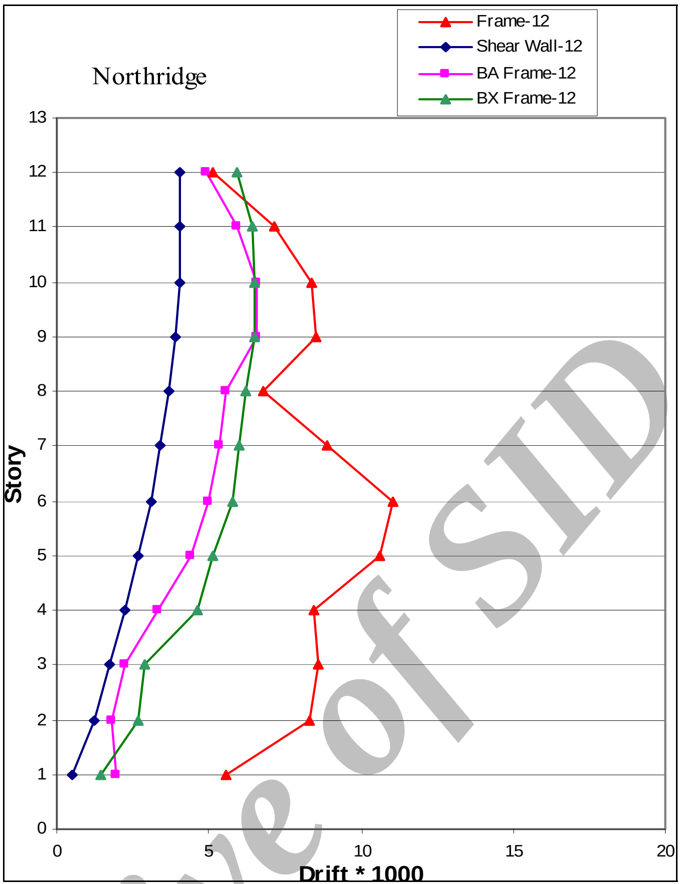
Figure 7. A brace hysteresis loop in nonlinear stage



(a) Loma Prieta



(B) Morgan Hill



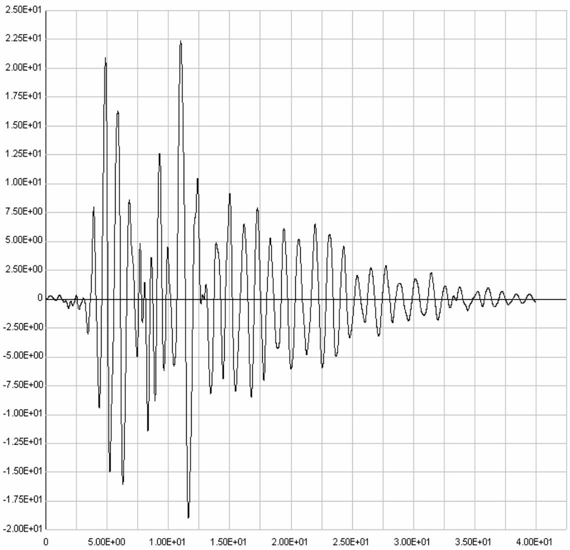
(c) Northridge

Figure 8. Maximum story drifts in 12-story frames under different ground motions, 6.3 roof displacement time histories

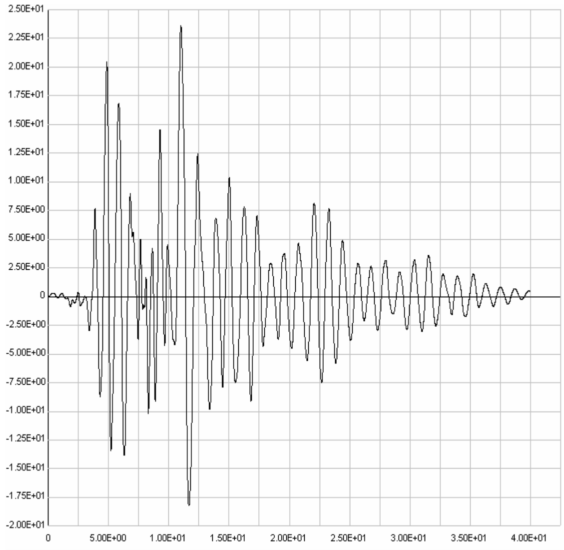
6.4 Energy dissipation

Dissipated energy in structures due to earthquake excitations are generally divided into strain energy of structural members, viscous damping by stiffness and viscous damping by mass. In addition, total dissipated energy is equal to input earthquake energy and has direct relation to lateral stiffness of structure. Table 4 indicates amount of input energy and dissipated energy during three ground motion records. It can be concluded from Table 4 that stiffness viscous damping has the greatest values of dissipated energy for all frames. After that, nonlinear strain energy and mass viscous damping are next major energy dissipaters. Table 4 shows that K and X braced frames have desirable amount of nonlinear strain energy with respect to moment resisting frame and shear wall included frame.

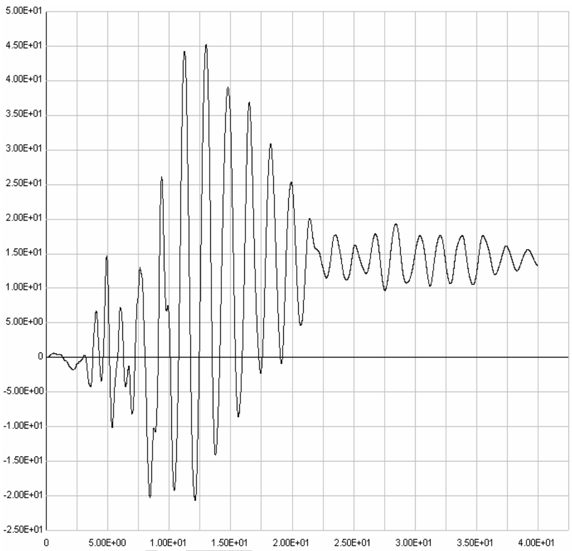
Further studies on element behavior showed that good amount of nonlinear strain energy in braced frame is due to energy absorption in members, especially middle span beams in K braced frame and adjacent columns in X braced frame.



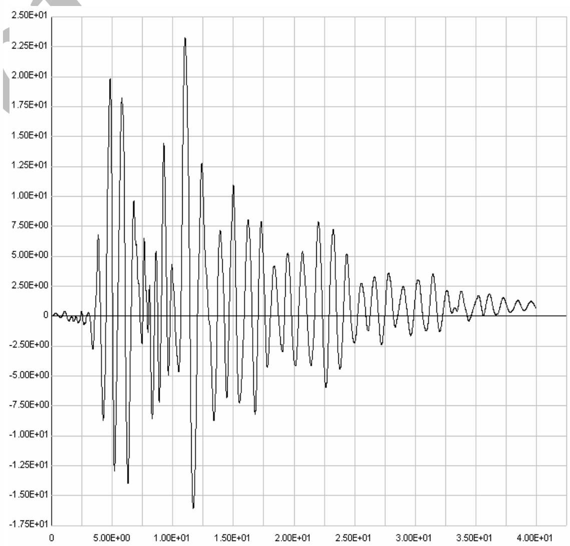
(a) K braced frame



(b) X braced frame



(c) Moment resisting frame



(d) Shear wall included frame

Figure 9. Roof displacement of 12-story frames in "Loma Prieta"

6.5 Demand-capacity ratio and performance level

Two structural features, maximum Demand-Capacity Ratio (DCR) and ultimate performance level of structure, according to FEMA-356 [9] are used to describe damage in each frame. Table 5 indicates those parameters for 4, 8 and 12-story frames. Performance levels which are labeled by "1", "3" and "5" are Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) respectively. Not considered performance level is indicated by "6".

Table 4. Input earthquake energy and different damping methods in 12-story frames

	Loma Prieta				Morgan Hill				Northridge			
Frame Model	**BA**	**BX**	**SW**	**MR**	**BA**	**BX**	**SW**	**MR**	**BA**	**BX**	**SW**	**MR**
Input Energy (ton.m)	52.15	59.59	50.59	85.07	59.15	60.46	43.84	34.07	58.98	55.17	51.51	39.35
Nonlinear Strain Energy %	28.0	25.5	28.5	30.0	40.8	37.3	39.5	30.4	29.2	30.8	30.1	17.8
Stiffness Viscous Damping %	54.6	60.3	53.9	57.9	44.2	49.1	44.6	55.0	52.1	53.1	51.0	65.7
Mass Viscous Damping %	16.0	13.0	16.3	11.3	13.5	11.9	14.3	12.4	17.4	14.6	17.7	14.7

In 4-story frames, shear wall system has a very fine behavior with respect to moment resisting and braced frames. X braced frame acts more effective than K braced frame in all ground motions. As it is obvious from Table 5, even though moment resisting frames are designed with latest edition of conventional codes [6,7], the 4-story moment resisting frame with an average performance level above 5, does not have acceptable seismic behavior. Shear wall system and X braced frame have the best performance level in these three earthquakes.

In 8-story frames maximum DCRs for two kinds of braced frames are almost the same and some higher than moment resisting frame and shear wall system. Again, shear wall system has the best seismic behavior during selected ground motions. All 4 systems have acceptable performance level except K braced frame in Morgan Hill earthquake.

In 12-story frames, moment resisting frame has the best seismic behavior and the lowest DCR and performance level. Similar to 4-story models, X braced frame has better seismic behavior with respect to K braced frame. The DCR and performance level for X braced frame and shear wall system are almost the same.

For better comparison, maximum DCRs are plotted in Figure 10. It can be concluded that X braced frames have a suitable seismic behavior with respect to other systems especially in less high buildings. It means that this system can be used instead of shear wall system especially in cases that we are not allowed to fill some spans regarding architectural aspects.

Table 5. Demand-capacity ratios and performance levels

Model	Maximum DCR			Max	Performance Level			Max
	LP	NR	MH		LP	NR	MH	
Frame-04	2.06	2.65	4.43	4.43	5	5	6	6
Shear Wall-04	1.33	0.12	0.32	1.33	3	1	1	3
BA Frame-04	5.16	2.01	2.12	5.16	5	3	3	5
BX Frame-04	1.73	1.15	1.46	1.73	3	3	3	3
Frame-08	0.79	1.67	1.92	1.92	1	3	3	3
Shear Wall-08	1.62	1.45	1.41	1.62	3	3	3	3
BA Frame-08	1.66	1.47	2.50	2.50	3	3	5	5
BX Frame-08	1.29	2.58	2.30	2.58	3	3	3	3
Frame-12	1.82	1.22	1.53	1.82	3	3	3	3
Shear Wall-12	1.30	2.35	2.27	2.35	3	5	5	5
BA Frame-12	1.21	1.93	3.55	3.55	3	3	6	6
BX Frame-12	1.35	1.98	2.47	2.47	3	3	5	5

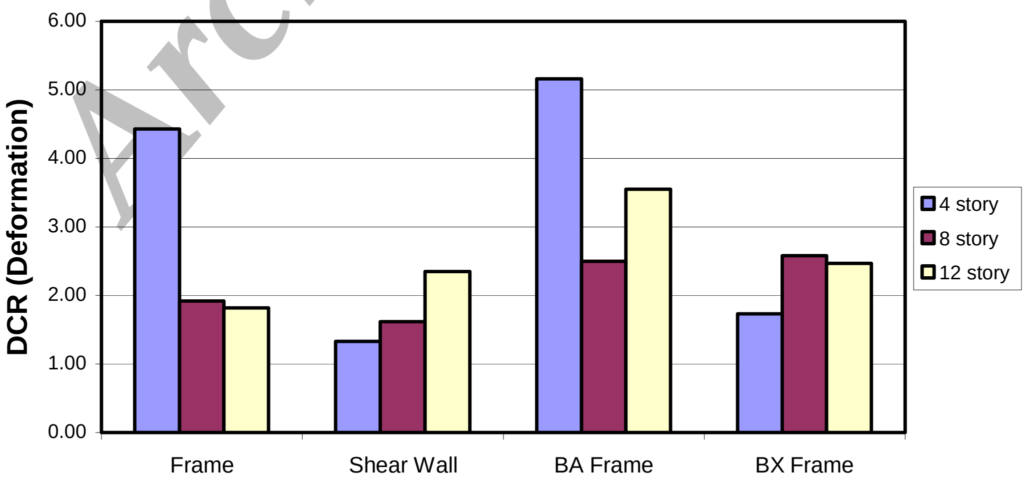


Figure 10. Maximum DCRs for structural members

7. Conclusion

The main purpose of this study was to compare reinforced concrete frames with reinforced concrete (RC) braces, moment resisting frame and frame with shear walls. Even though RC braces are designed to be linear during earthquake excitations, two different kind of braced frames showed adequate energy absorption. Also, nonlinear strain energy in structural members is about 30% of total input energy in braced frames.

Maximum drift of braced frames in different stories are near to shear wall and significantly less than moment resisting frame. Maximum roof displacement of braced frames in “Loma Prieta” is equal to frame with shear wall and about 50% less than moment resisting frame. During “Morgan Hill” and “Northridge”, maximum roof displacement is almost equal for all frames.

In this study, maximum demand-capacity ratio and ultimate performance level are selected to show behavior and damage of different frames. Frames analysis results declared acceptable behavior of RC frames with reinforced concrete braces in X pattern. In short buildings, they can act as shear wall system according to their fine energy absorption and stiffness. This may help to solve architectural problems due to using shear walls in some spans.

Terminology

BA	K braced frame
BX	X braced frame
DY	Strain at yielding point
DL	Strain at ductile limit
DR	Strain at minimum residual point
DU	Strain at ultimate strength point
DX	Strain at maximum deformation
Ec	Elastic modulus of concrete (kg/cm^2)
EDF	Energy Dissipation Factor
K0	Initial stiffness (kg/cm^2)
KH	Hardening stiffness (kg/cm^2)
FR	Residual strength (kg/cm^2)
FU	Ultimate strength (kg/cm^2)
FY	Yielding strength (kg/cm^2)
MR	Moment resisting frame
PG	Pick Ground Acceleration (cm/s^2)
A	
SW	Shear wall included frame

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