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Seismic Assessment and Strengthening of Intermediate Moment Resisting Concrete Frames

Meisam Safari Gorji [1], Masoud Taribakhsh[2] and Amirhossein Gandomi[3]
[1]*School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran*
[2]*Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran*
[3]*Department of Civil Engineering, Tafresh University, Tafresh, Iran*

Summary

The objective of this study was to investigate the seismic evaluation and strengthening of Intermediate Moment Resisting Concrete Frames (IMRCF) designed according to the Iranian concrete code of practice (ABA) and Iranian Seismic Code (Standard No. 2800).

This type of RC frames is excessively used in Iran while their vulnerability in earthquake prone area and their performance level is not clearly known for designers.

In this study, several intermediate moment resisting concrete frames have been selected and subjected to seismic evaluation according to the Iranian Guidelines for the Seismic Rehabilitation of Existing Buildings.

In this study, to determine the target point of frames, the Capacity Spectrum Method (CSM)has been used. CSM method works with capacity curves of the structural system. Such curves can be obtaining by means of static non-linear analysis (the so-called pushover analysis) that is for sure much less time-consuming than time-history analysis. The pushover analysis was performed using the SAP2000 computer program.

The results indicate that the frames having lesser spans are weak and some of structural elements are not able to fulfil the acceptance criteria given by the guidelines.

In the present paper to improve the seismic performance of such frames, one frame has been selected as a control frame and strengthened by adding different lateral load resisting systems.

The effects of proposed strengthening methods on performance of the frames have been investigated, pointing out the differences between the various strategies.

KEYWORDS: Seismic Assessment, Strengthening, Concrete Frame, Pushover Analysis, Capacity Spectrum Method

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1. INTRODUCTION

Moment frames have been widely used for seismic resisting systems due to their superior deformation and energy dissipation capacities. The evaluation of seismic safety of existing buildings is one of the matters that are being investigated by the researchers especially in countries of high seismic risk.

In recent years, efforts have begun to establish methods to evaluate the seismic safety of buildings to determine risks and to suggest strengthening of existing buildings. The seismic repair and/or strengthening philosophy generally consist of a) system behavior improvement and b) member repair/strengthening. Although these two general approaches can be applied separately in some cases, they generally are combined. In the system behavior improvement technique, the general philosophy is to introduce a new lateral load resisting system, which will increase the lateral strength and the lateral stiffness of the existing system, which is generally a non-ductile frame with inadequate lateral stiffness. Various techniques based on this principle have been developed and applied in the past.

Many researches have been directed to rehabilitation of RC frames with different strengthening methods. Bush et al. [1], Ghobarah & Abou Elfath [2], Masri & Goel [3], Tasnimi [4] and Negro & Verzeletti [5] conducted some experimental investigations on behaviour of RC frames strengthened with steel bracing system.Perera [6] and Mehrabi et al. [7] have evaluated the seismic performance of masonary-infilled RC frames. Younfei et al. [8] and Sugano [9] investigated the behaviour of RC frames strengthened using reinforced concrete infills.

In this study several intermediate moment resisting concrete frames (IMRCF) designed according to the Iranian concrete code of practice (ABA) and Iranian Seismic Code (Standard No. 2800) have been selected and subjected to seismic evaluation.

After assessing of the performance levels of the frames and the identification of their structural defects, different strengthening strategies have been proposed and investigated based on the both experimental and analytical researches.

To achieve the aim, one frame selected as a control frame and strengthened with the following methods: adding steel bracing, masonry infills and reinforced concrete infills. The performance of the strengthened frames obtained by nonlinear static analysis using SAP2000 program and compared with each other. Furthermore, the effects of each type of strengthening method on behaviour of frames have been investigated.

2. DESCRIPTION AND CASE STUDY

2.1. Assessment procedure

Assessing of seismic behavior of existing building can be faced according to main focuses, namely in terms of either maximum strength against the horizontal seismic actions and maximum ductility, consisting in the capability for plastic displacements. Seismic assessment of structures generally results in pointing out structural deficiencies related to a general lack of strength and ductility of both a certain number of members and the structural system as a whole.

To investigate the performance level of structure, it is necessary to specify the performance point on the capacity curves of the structural system. In this study, to determine the performance point of frames, the Capacity Spectrum Method (CSM) has been used. CSM method works with capacity curves of the structural system. Such curves can be obtaining by means of static non-linear analysis (the so-called pushover analysis) that is for sure much less time-consuming than time-history analysis. So, CSM has been widely adopted by Code of Standards, because it represents a reasonably adequate procedure for design and evaluation purposes. Software for determining capacity curves of structures by means of pushover analysis are no more confined to the academic framework, but is getting more and more popular between the practicing structural engineers.

2.2. Frames description used in this study

In order to investigate the performance of the buildings designed according to the Iranian Concrete Code, the following plan depicted in Fig. 1 was selected as the base plan. To investigate the performance of different stories, the design was carried out for 6, 8, 10 stories.

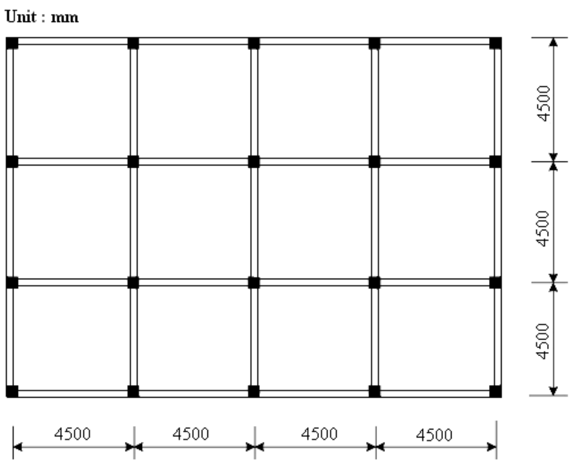

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Figure 1. Floor scheme of the considered structure

This is a B group structure (offices) and rectangular type plan with 18x13.5 m dimensions. The buildings have uniform storey height of 3.2m. The design was based on the Intermediate Moment Resisting Concrete Frames (IMRCF) and all the criteria regarding the Iranian Concrete Standard (ABA) and Iranian Seismic Code (Standard No. 2800) was taken into account. The mentioned buildings were designed in a region with relatively very high seismic probability. For purposes of the modeling, two critical frames presented in the plan in X (four bays) and Y (three bays) directions were selected as based frames to be studied. With respect to the above mentioned variables (number of stories and bays) 6 frames were selected for the analysis as given in Table 1.

Table 1. Different frames type evaluation studies

Frame type	A_1	A_2	A_3	A_4	A_5	A_6
No. of stories	6	8	10	6	8	10
No. of bays	3	3	3	4	4	4

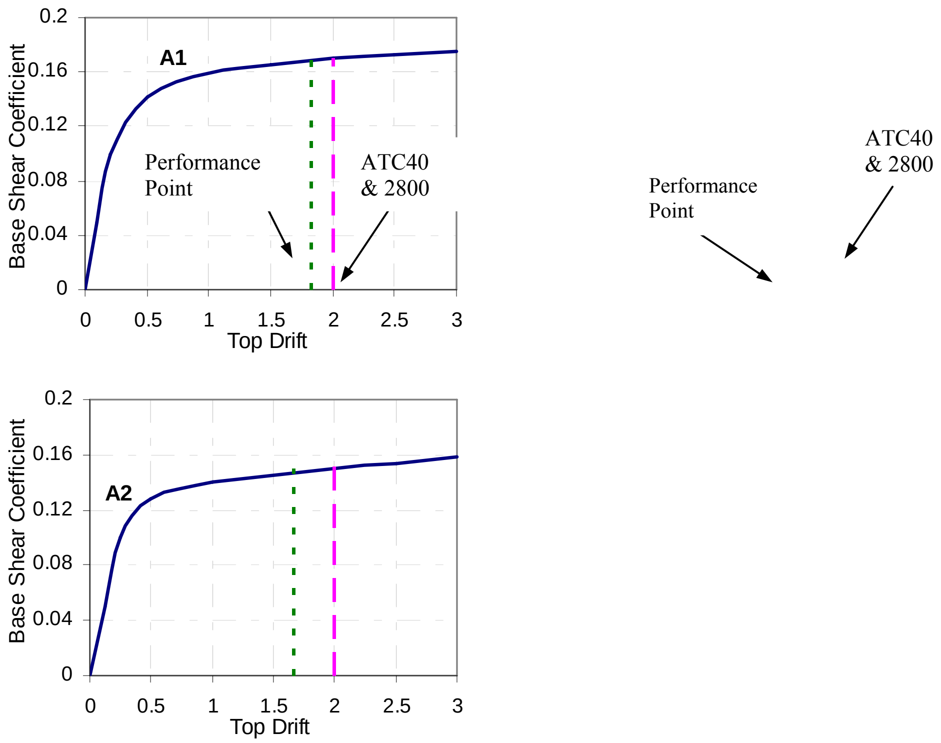
3. ANALYTICAL STUDY FOR EVALUATION OF FRAMES

3.1. Modeling of frames for pushover Analysis

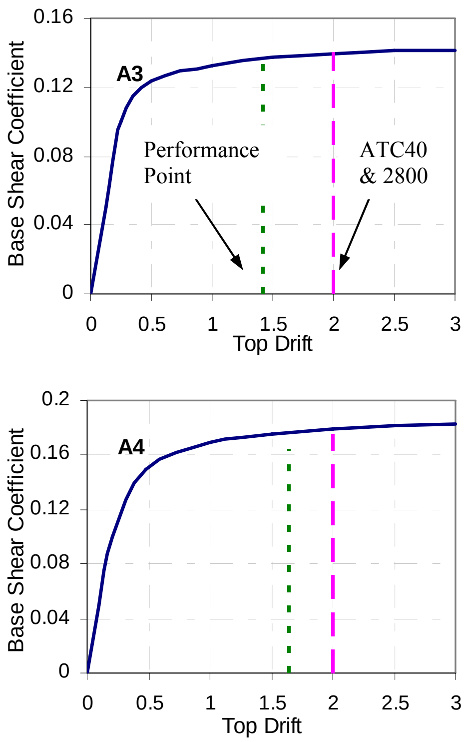
The SAP2000 static pushover analysis capabilities, which are fully integrated into the program, allow quick and easy implementation of the pushover procedures prescribed in the ATC-40 [12] and FEMA-273 [13] documents for both two and three-dimensional buildings. The criteria pertaining to the intermediate ductility has been considered in the modeling. The combination of critical loading has been considered for the gravity loads. The accuracy of a pushover analysis is also depends on using an appropriate distribution of the lateral loads. The lateral load distribution system was according to the Iranian guidelines for the seismic rehabilitation of existing buildings and the most critical state was chosen as a basis for the distribution of lateral loading. The P-Δ effect has also been taken into consideration in the modeling. In order to model nonlinear behavior in any structural element, a corresponding nonlinear hinge was assigned in the building model.

3.2. Analysis results

The resulting capacity curves for the frames are shown in Figure 2 and performance points have specified on these carves. All curves show similar features. They are linear initially but start to deviate from linearity when inelastic actions start to take place in the beams and later in the columns. When the frames are pushed well into the inelastic range, the capacity curves again become essentially linear, but with a much smaller slopes.



(a) (b)


0.16
0.12
0.08
0.04
0
Base Shear Coefficient
A3
Performance
Point
ATC40
& 2800
0
0.5
1
1.5
2
2.5
3
Top Drift
0.2
0.16
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Base Shear Coefficient
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0
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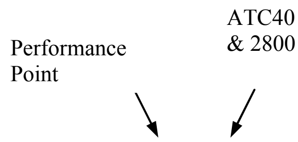
Top Drift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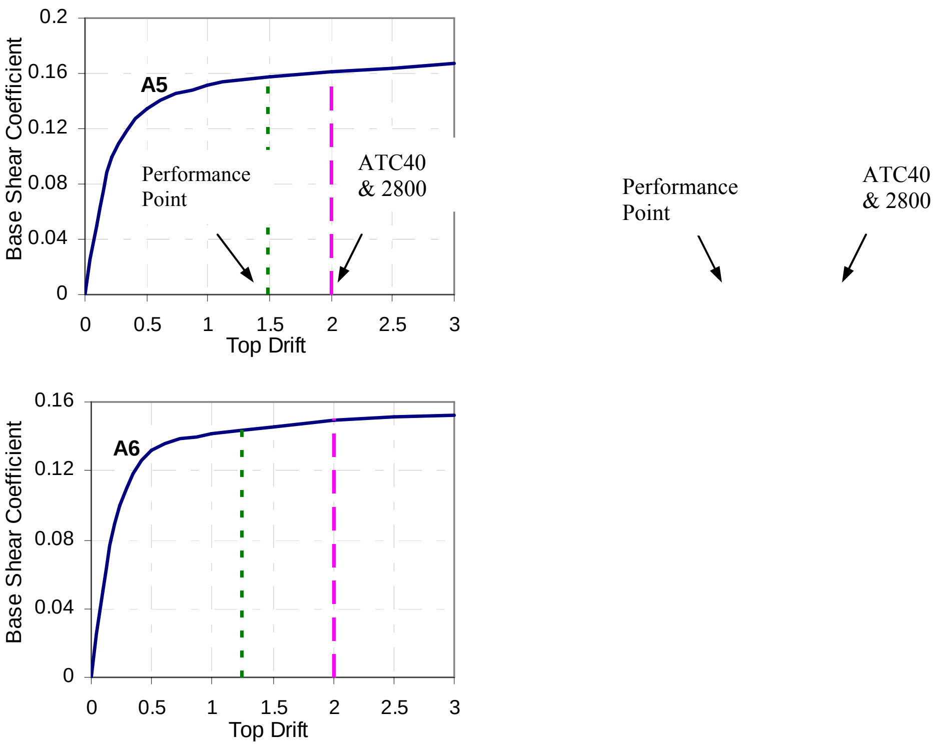
(c) (d)



(e) (f)

Figure 2. Pushover (capacity) curves of the analyzed frames

3.3. Determining the performance points of the frames

According to the CSM, to estimate the performance point of frames, pushover curves resulted from the analyses, have been converted to capacity diagrams in A-D (Acceleration-Displacement) format. According to the chosen β (damping ratio 5%) and the behavior type (B), the CSM spectral reduction factors have been located from ATC-40 or Iranian Guidelines for the Seismic Rehabilitation of Existing Buildings. The demands have been recalculated by accounting the spectra reductions. Furthermore, the demand diagram and capacity diagram have been plotted together in A-D system and intersection point gave displacement demand. Table 2 shows the performance points of the frames resulted from the CSM.

Table 2. Performance points of the frames resulted from the CSM

Frame Type	δ_t in A-D system (mm)	δ_t (mm)	Top Drift
A1	254	352	1.85
A2	303	425	1.71
A3	308	454	1.45

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A4	231	330	1.69
A5	270	380	1.5
A6	276	402	1.28

3.4. Assessment of performance levels of structural elements

In order to evaluate the performance levels of structural elements of the frames, deformations and forces of each element (resulted from the pushover analysis) in performance points have been investigated. These results have been compared to limiting values for different performance levels according to the Iranian Guidelines for the Seismic Rehabilitation of Existing Buildings.

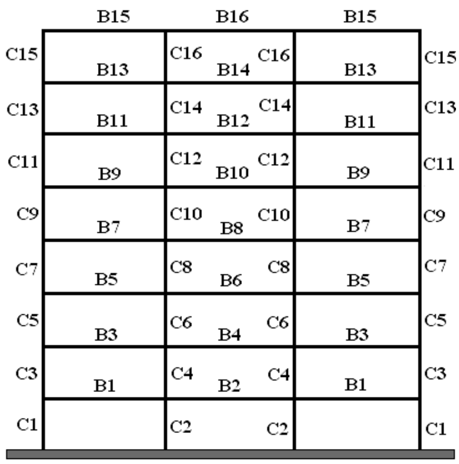

Figure 3. Different types of beams and columns in A2 frame.

Different types of beams and columns in A2 frame are shown in Fig. 3. Tables 3 and 4 show the performance levels of the beams and columns of A2 frame, respectively.

Tables 5 and 6 show the percentage of beams and columns existing in different performance levels for all of the frames.

Table 3. Evaluation of Performance levels of the beams in A2 frame.

Beam Type	$3.77\frac{V}{b_w d\sqrt{f_c}}$	Transverse bars	$\frac{\rho-\rho'}{\rho_{bal}}$	Acceptance Criteria IO	LS	CP	Rotation	Performance Level
B1	0.44	NC	0.07	0.0050	0.0100	0.0199	0.005	IO
B2	0.34	C	0.07	0.0099	0.0199	0.0249	0.004	IO
B3	0.45	NC	0.07	0.0050	0.0100	0.0199	0.013	LS-CP
B4	0.35	C	0.07	0.0099	0.0199	0.0249	0.011	IO-LS
B5	0.45	C	0.14	0.0099	0.0197	0.0249	0.021	IO-LS
B6	0.34	C	0.14	0.0099	0.0197	0.0249	0.018	IO-LS
B7	0.45	C	0.14	0.0099	0.0197	0.0249	0.0226	LS-CP

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B8	0.35	C	0.14	0.0099	0.0197	0.0249	0.0201	LS-CP
B9	0.42	C	0.14	0.0099	0.0197	0.0249	0.026	CP(OVER)
B10	0.33	C	0.14	0.0099	0.0197	0.0249	0.0235	LS-CP
B11	0.36	C	0.17	0.0098	0.0197	0.0248	0.025	CP(OVER)
B12	0.28	C	0.17	0.0098	0.0197	0.0248	0.0215	LS-CP
B13	0.32	C	0.21	0.0098	0.0196	0.0248	0.021	LS-CP
B14	0.24	C	0.21	0.0098	0.0196	0.0248	0.0198	LS-CP
B15	0.23	C	0.08	0.0099	0.0199	0.0249	0.014	IO-LS
B16	0.13	C	0.08	0.0099	0.0199	0.0249	0.003	IO

Table 4. Evaluation of Performance levels of the columns in A2 frame.

Column Type	$3.77\frac{V}{b_w d\sqrt{f_c}}$	Transverse bars	$\frac{\rho}{A_g f_c}$	Acceptance Criteria			Rotation	Performance Level
				IO	LS	CP		
C1	0.39	C	0.13	0.0047	0.0146	0.0193	-0.002	IO
C2	0.57	NC	0.09	0.0050	0.0050	0.0060	-0.002	IO
C3	0.33	C	0.11	0.0049	0.0148	0.0197	-0.003	IO
C4	0.6	NC	0.09	0.0050	0.0050	0.0060	-0.003	IO
C5	0.42	C	0.11	0.0049	0.0148	0.0197	0.004	IO
C6	0.64	NC	0.10	0.0050	0.0050	0.0060	0.004	IO
C7	0.40	C	0.09	0.0050	0.0050	0.020	0.004	IO
C8	0.63	NC	0.08	0.0050	0.0150	0.006	0.005	IO
C9	0.46	C	0.09	0.0050	0.0150	0.020	0.004	IO
C10	0.66	C	0.08	0.0050	0.0150	0.020	0.004	IO
C11	0.35	C	0.07	0.0050	0.0150	0.020	-0.005	IO
C12	0.56	C	0.07	0.0050	0.0150	0.020	-0.005	IO
C13	0.39	C	0.04	0.0050	0.0150	0.020	-0.004	IO
C14	0.51	C	0.05	0.0050	0.0150	0.020	-0.006	IO-LS
C15	0.19	C	0.03	0.0050	0.0150	0.020	-0.004	IO
C16	0.32	C	0.03	0.0050	0.0150	0.020	-0.012	IO-LS

Table 5. Percentages of beams existing in different performance levels.

Performance level	Frame Types					
	A1	A2	A3	A4	A5	A6
IO	11.1%	16.66%	30%	29.17%	21.88%	47.5%
IO-LS	44.44%	25%	26.66%	41.67%	50%	17.5%
LS-CP	33.33%	41.6%	23.33%	29.17%	28.12%	32.5%
OVER CP	11.1%	16.66%	20%	0	0	2.5%

Table 6. Percentages of columns existing in different performance levels.

Performance level	Frame Types					
	A1	A2	A3	A4	A5	A6
IO	54.16%	87.5%	72.5%	83.33%	92.5%	74%
IO-LS	37.5%	12.5%	17.5%	13.33%	5%	16%
LS-CP	8.33%	0	7.5%	3.33%	2.5%	6%
OVER CP	0	0	2.5%	0	0	4%

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4. STRENGTHENING STRATEGIES

In order to investigate the effects of different strengthening methods, the A_2 frame is selected as a control frame. With respect to the performance levels of the structural elements of the selected frame, it is clear that this frame has some deficits regarding the lateral stiffness and as the deficits are distributed in many stories, the lateral strength and stiffness of the system should be improved. In this study, to improve the performance of the frame, different strengthening methods have been investigated as shown in Fig 4.

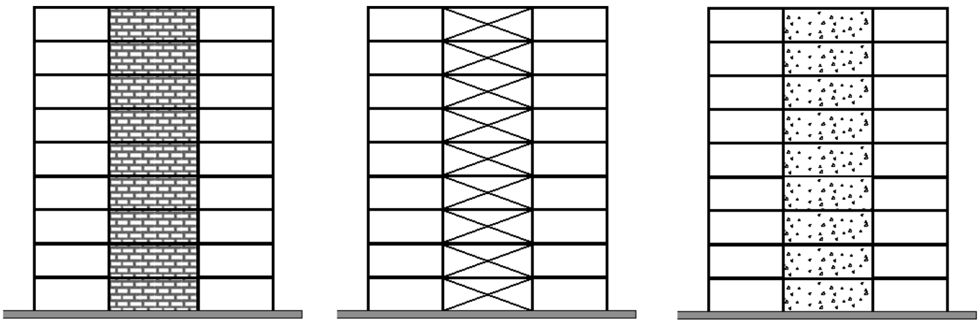

Figure 4. Added different lateral load resisting systems considered in this study. (a), (b) and (c) are masonry infills, steel bracing and reinforced concrete infills, respectively.

4.1. Steel Bracing System

In this part, the characteristics of the added steel bracings are such that the failure of the frame first occurs in bracings, then in beams and after that in columns. In order to add steel bracing system, 2U10 (channel section) was used for the first four stories and 2U8 was used for the last four stories. In order to model nonlinear behavior in any structural element, a corresponding nonlinear hinge was assigned in the frame models. PMM hinges at the columns, P hinges at the steel braces and moment hinges at the beams were assigned in the models according to modelling criteria of Iranian Guidelines for the Seismic Rehabilitation of Existing Buildings. The pushover curves of the control frame (A2) and strengthened frame with steel bracing are shown in Fig. 5. It can be observed that the strength and stiffness of the frame has well increased. The ductility of the strengthened frame in this case has decreased were compared to the control frame. The Analysis results show that first the braces buckled in compression and then hinges occurred in some braces and beams and ultimately the failure mechanism were transmitted to the columns. After

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evaluation of performance levels of the structural elements of the strengthened frame, it was observed that the steel bracing system was able to improve the performance of the frame significantly and provided Life Safety performance level intended by the code.

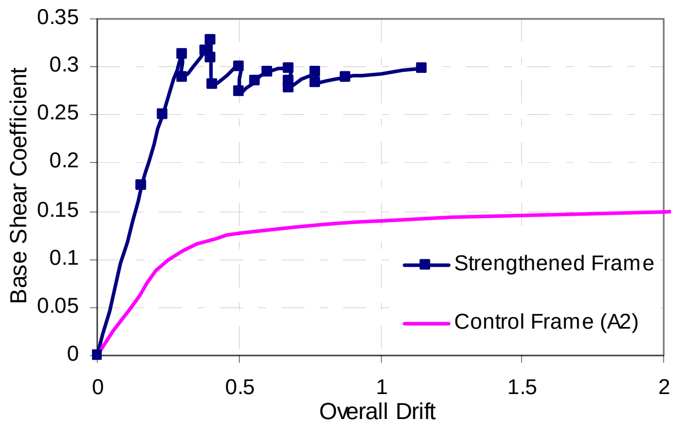

Figure 5. Pushover (Capacity) curves of the frames.

4.2. Shear wall

In this strengthening method, the reinforced concrete infills were added to the middle bay of the control frame. It was assumed that the added shear wall to the system interact completely with the frame beams and columns by stitching the reinforcements. In this case, it can be considered that the added shear wall and the two side columns work monolithically. Given that the shear wall in the frame are slender with wall height-to-length ratio well above 3 and therefore seismic response of the shear wall is expected to be dominated by flexure, as well as because modeling nonlinear behavior in SAP2000 pushover analysis is limited to frame elements, the shear walls were modeled as equivalent frame elements. According to the Iranian Concrete Code, the minimum values for thickness of the wall and reinforcement ratio are 0.15cm and 25%, respectively. Fig. 6 shows the pushover curves resulted from the analysis. It can be observed that the lateral strength of the system has been increased significantly. After determining the performance levels of the structural elements of the strengthened frame with the shear wall, it is concluded that all structural elements of the strengthened frame are in the Immediate Occupancy (IO) performance level. Adding the shear wall to the frame not only has met the performance level of Life Safety (LS), but also has increased the performance level of the frame and let the frame to lie in the Immediate Occupancy performance level.

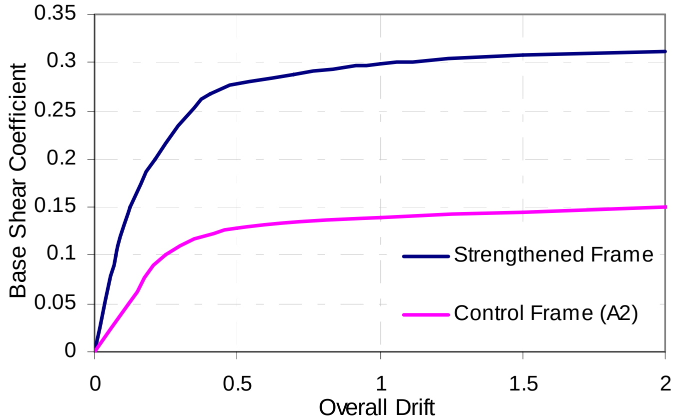

Figure 6. Pushover (Capacity) curves of the frames.

4.3. Masonry Infills (MI)

The third strategy for strengthening of the frame in this study was added masonry infills. There is strong evidence that masonry infills enhance the lateral strength of framed building structures under severe earthquake loads and have been successfully used to strengthen the existing moment-resisting frames in some countries. In order to use masonry infills and regarding the diversity of using these materials as well as different characteristics of them, the results of laboratory tests of Tasnimie et al. [4] was used. It should be noted that because the axial load effects in providing the cohesive bond is not high, this effects has been ignored according to Iranian Guidelines for the Seismic Rehabilitation of Existing Buildings. Hence, only the cohesive bond of masonry has been taken into account. According to the Iranian Guidelines, Behavior of frame with masonry infills was modeled with a diagonally braced frame model in which the columns act as vertical chords, the beams act as horizontal ties, and the infill is modeled using the equivalent compression strut analogy. Characteristics of the equivalent compression strut are shown in Table 8. The combined behavior of MI-RC frames is such that the total seismic design force is resisted in proportion to the lateral stiffnesses of the RC frame and MI walls at all story levels. The analysis results show that plastic hinges were formed almost in all beams and compressive strut. The failure mechanism occurred in beams concurrently with the compressive strut. Thus introduction of Masonry infills in RC frames changes the lateral-load transfer mechanism of the structure from predominant frame action to predominant truss action. Results show that by placing masonry wall in building, the lateral strength of the system have been increased and the performance level of the structural elements of the frame have been improved. Fig. 7 shows the pushover curves resulted from the analysis.

Table7. Characteristics of the equivalent compression strut.

Story	T_{inf} (cm)	λ	a (cm)	Ani (cm^2)	F_{vie} ($\frac{kg}{cm^2}$)	Q_{CE} (kg)
1	20	0.0137	76.7	9325	2.17	20200
2	20	0.0137	76.7	9325	2.17	20200
3	20	0.0121	79.75	9225	2.17	19980
4	20	0.0121	79.75	9225	2.17	19980
5	25	0.0114	80.6	11400	2.17	24700
6	25	0.0114	80.6	11400	2.17	24700
7	30	0.0109	80.25	13525	2.17	29320
8	30	0.0109	80.25	13525	2.17	29320

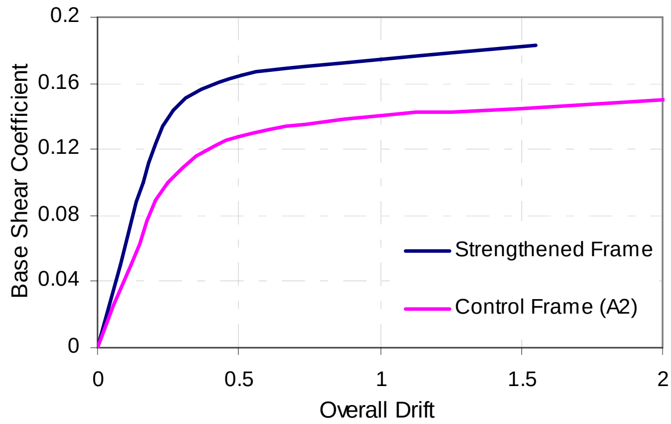

Figure 7. Pushover (Capacity) curves of the frames.

4.3. Comparison between Different Strengthening Methods

CSM spectral reduction factors and target points of the frames are shown in Table 8. Fig. 8 shows the pushover curves resulted from the analyses for different type of strengthened frame. By comparing the curves it can be observed that by adding steel bracings the most increase in the lateral strength of the system was achieved and after that the shear wall, masonry infills had the most effects on the lateral strength of the system, respectively.

Table 8. CSM spectral reduction factors and performance points of the frames

Frame type	K	β_{eff}	β_0	SRV	SRA	δ_t in A-D system (mm)	δ_t (mm)	Top drift
Control (A2)	0.7	37.68	46.8	0.56	0.44	303	425	1.71%
Strengthened with	0.77	22.28	22.32	0.60	0.52	86.2	120	0.50%

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steel bracing								
Strengthened with shear wall	0.77	22.88	23.21	0.62	0.50	95.7	142	0.62%
Strengthened with masonry infills	0.73	30.68	36	0.56	0.44	230	291.5	1.18%

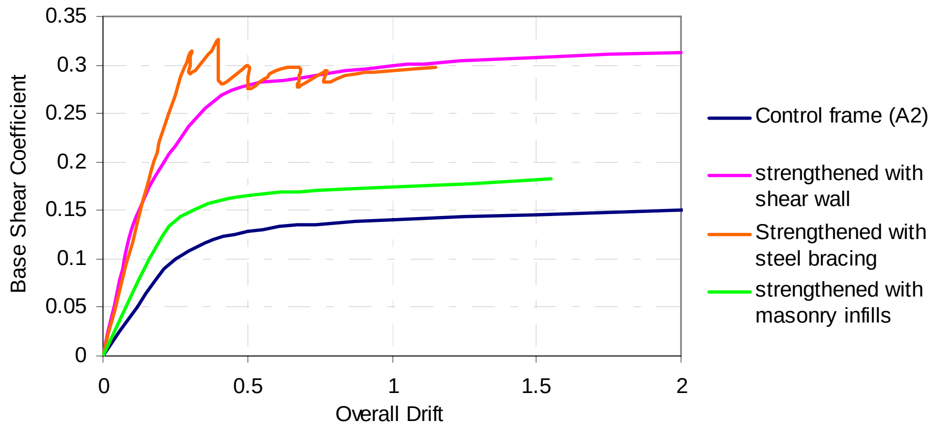

Figure 8. Comparison of pushover curves before and after the strengthening

5. CONCLUSIONS

This article presents an analytical investigation of the effects of different strengthening methods on the seismic performance of the Intermediate Moment Resisting Concrete Frames (IMRCF) using rational displacement-based analytical method (nonlinear static pushover analysis) based on realistic and efficient computational models of the structural components. On the basis of results, the following conclusions can be drawn:

Assessment of the performance levels of the frames structural elements according to the Iranian guidelines, shows that some of the beams and columns were seismically deficient in terms of life safety.

The frames including four spans have a better performance as compared with the frames having three spans.

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Comparison between the three strengthening strategies, shows that the most increase in the lateral strength were related to using steel bracing system.

With regards to the performance levels of the structural elements in strengthened frames, the best strengthening system was adding shear wall.

By utilizing reinforced concrete infills to strengthen the frame, the performance level of the frame has been improved significantly. In this case, the Immediate Occupancy (IO) performance level was reached and the relative displacement corresponding to the performance point decreased significantly owing to the increase in lateral stiffness of the strengthened frame.

In the strengthened frame with steel bracing system, the compressive bracings buckle rapidly. In order to prevent the buckling of braces, if stronger braces were used, the failure mechanism may transferred to columns and beams owing to the increase in axial load of columns as well as the increase in shear forces of beams and columns. In this case study, in order to improve the performance level up to the Immediate Occupancy, only adding bracing is not sufficient but also some of the structural element should be strengthened along with adding steel bracings to resist the increase of forces in these structural elements.

The analyses results show that ordinary masonry infills can increase the lateral strength of the frames and improve the performance level of the system to some extent.

References

1. Bush, T., Jons, E., Jirsa, J., Behavior of RC Frame Strengthening Using Structural Steel Bracing, *Journal of Structural Engineering*, 1991, Vol. 117, No. 4, April 1991, pp. 1115-1126.
2. Ghobarah, A., Abouelfath, H., Rehabilitation of a Reinforced Concrete Frame using Eccentric Steel Bracing, *Journal of Engineering Structures*, Vol. 23, No. 7, July 2001, pp. 745-755.
3. Masry, A. C., Subhash, C. G., Seismic Design and Testing of an RC Slab-Column Frame Strengthened by Steel Bracing, *Journal of Earthquake Spectra*, Vol. 12, No. 4, November 1996, pp. 645-666.
4. Tasnimi A. A., Strengthening of Reinforced Concrete Frames Using Steel Bracing, *Building and Housing Research Center, research report*, September 2000, Tehran, Iran.
5. Negro, P., Verzeletti, G., Effect of Infills on the Global Behevior of R/C Frames: Energy Considerations Pseudo-Dynamic Tests, *Earthquake Engineering & Structural Dynamics*, 1996, Vol. 25, No. 8, pp. 753-773.
6. Prera, R., Performance evaluation of masonry-infilled RC frames under cyclic loading based on damage mechanics, *Journal of Engineering Structures*, Vol. 27, No. 8, July 2005, pp. 1278-1288.
7. Mehrabi, A. B., Shing, P. B., Schller M. P., Noland, J. L., Experimental Evaluation of Masonry-Infilled RC Frames, *Journal of Structural Engineering*, 1996, No. 3, pp. 228-237.

ISSN 1582-3024

8. Yunfei, H., Yufeng, C., Changs, S., Bainian, H., The Experimental Study of a two-Bay Tree Story Reinforced Concrete Frame Under Cyclic Loading, *Proceeding of the Eight Symposium on Earthquake Engineering*, 1986, Roorkee, India.
9. Sugano, S., Seismic Strengthening of Existing Reinforced Concrete Building in Japan, International Institute of Seismology and Earthquake Engineering Building Research Institute Ministry of Construction, 1992.
10. Mohele, J. P., State of Research on Seismic Retrofit of Concrete Building Structures in US, *Pacific Earthquake Engineering Research Center*, University of California Berkeley, 2000.
11. Iranian Guidelines for the Seismic Rehabilitation of Existing Buildings, *International Institute of Earthquake Engineering and Seismology*, 2002, Tehran, Iran.
12. ATC-40, "Seismic Evaluation and Retrofit of Concrete Buildings", *Applied Technology Council,* 1996.
13. FEMA-273, "Seismic Rehabilitation Guidelines", *Federal Emergency Management Agency*, September 1996.