Investigating the Performance Levels in Concrete Buildings Reinforced with the Braced Frame (Inverted V-CBF) and the Shear Wall through Non-linear Static Analysis (Push Over) with Plastic Hinges Formation Approach

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Abstract—**Using the design in extreme limit state, known as the design based on the performance, is one of the major advances in design and retrofitting the structures. In this design, the static analysis methods play special roles in which the non-linear static method (push over) is the main analysis method. The seismic demands of the structures are estimated by the performance point. The performance point in this method is the roof displacement which contains forces, displacements, and internal efforts. The current study aims at investigating three types of special concrete moment frame once reinforced with the steel braced frame (inverted V – CBF) and once with the shear wall by the regulations of ASCE7-10, ACI318-14, and AISC360-10 are analyzed with the Etabs. Moreover, the drift amount of the structures is compared after and before the reinforcement. Then the performance level and formation of the plastic hinges based on the reinforcement regulations of Fema-356, Fema- 440 and ATC40 in two earthquake risk levels of 1 (DBE) and earthquake risk level 2 (MPE) were compared by the SAP2000 software. Then, all models supplied the demanded performance levels after the retrofitting and finally their effects on the seismic behaviour of the structure or different heights are evaluated. According to the results, it is recommended to use the reinforcement with braced frame for the short-rise concrete frames and reinforcement with the shear wall for the mid-rise frames.**

Index Terms— **Reinforcement, Performance level, Nonlinear static analysis (push over), Plastic hinges.**

I. Introduction

Iran is one of the seismically active countries in the world in which the concrete buildings have poor performance. Accordingly, the issue of retrofitting has been of utmost importance due to the recent changes in the earthquake and building regulations. A considerable number of studies were conducted in the field of retrofitting the reinforced concrete structures that are reinforced with the bracings [1] as well as the shear wall [2]. Most the reinforcements are in form of linear static analysis and in the level 1 of earthquake risk. Therefore, considering the lack of comparative study based on the performance and non-linear analysis between these two reinforcement methods, the current study aims at investigating and comparing the seismic performance of these systems in retrofitting the reinforced concrete structure with regard to the height of the structure (done by non-linear static analysis). Using the design in Load and Resistant Factor Design (LRFD) modes (referred as design based on the performance) is one of the most important advances in designing and retrofitting the structures. The static analysis methods play a significant role in that the push over non-linear static method is used as the primary method for analysis. Moreover, the estimation of the seismic needs of structures in this method is done by the performance point, which is the roof displacement and all of the forces, displacements and internal efforts are calculated at this point. First, the study investigates the seismic behavior in three frame types of 3-6-9 in the moment concrete floor once with the steel braced frame and once with the shear wall based on the ACSE7 regulation via the Etabs2015 software. Besides, the relative displacement of the frames floors (Drift) is compared before and after the reinforcement. Second, the performance level and formation of the plastic hinge were evaluated based on the reinforcement value of ATC40, Fema -440, Fema -356, and in two earthquake risk levels of 1 and 2 along with non-linear analysis via SAP2000-17 software.

The purpose of the study is to evaluate the seismic behavior of the shear wall and concentric steel braced frame (cbf-inverted V) for the reinforced concrete structures with different heights and to do a behavioral comparison among them. In addition, the other aims are to:

1. Find an optimized system for retrofitting the reinforced concrete structures
2. Reduce the lateral displacement
3. Increase the strength and lateral stiffness sufficiently

II. Research Method

A. Definition of Performance Level

The performance level of a building is defined based on the performances of the structural and non-structural components based on the following clauses. It is abbreviated into one digit to indicate the performance of structural components and one

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letter for the performance of the non-structural component. The performance levels of the building are used in determining the goal of optimization. Moreover, the performance level indicates the vulnerability of the structural and non-structural components.

Operational Performance (OP) (A-1): a building that has OP in, if its structural components have the performance level of 1 and the non-structural component has the performance level of A.

Immediate Occupancy Performance (IO) (B-2): a building has IO performance level if its structural components have the performance level of 1 and the non-structural components have the performance level of B.

Life Safety Performance (LS) (C-3): a building has the Life Safety performance level, if its structural components have the performance level of 3 and the non-structural components have the performance level of C.

Collapse Prevention Performance (CP) (E-5): a building has collapse prevention performance level if its structural components have the level of 5. However, there is no restriction for the performance level of the non-structural components [3].

It is the seismic behavior level of the building, which is expressed by determining the maximum allowable defect of structural and non-structural components for a particular level of seismic vulnerability.

B. *Risk Level*

Risk level is the possibility of an earthquake with annual happening in the target time period (useful life of the building). Two types of risk level are defined in the risk level.

Risk level 1: in this level, the risk is determined based on the happening possibility percentage of 50 years that is equal to the return period of 475 years. The danger level is named as Design Basis Earthquake (DBE) in Iranian 2800 standard.

Risk level 2: this risk level is determined based on 2 percent of happening in the 50 years that is equal to the return period of 2475. The risk level 2 is named as Maximum Probable Earthquake (MPE) in Iranian 2800 standard.

C. *Types of Reinforcement*

Favorable Reinforcement: the goal of the base of reinforcement is expected to be achieved (performance level C-3) and also not collapsed through the earthquake with risk level 2 (performance level E-5).

Special reinforcement: special reinforcement has higher performance for the target buildings compared with the favorable reinforcement. Therefore, a higher level of performance for the building was considered on the same risk levels used in the favorable reinforcement or by maintaining the same performance level with favorable reinforcement, the higher risk level of the earthquake was considered.

D. *Nonlinear Static Analysis (Push Over)*

Push over analysis is a non-linear static analysis affected by the increasing lateral loads. The aim of this analysis is to estimate the expected behavior of a structural system by strength estimation, change in the required shape with a non-linear static analysis (considering the designed earthquake) and then comparing the required amounts with the available capacities in the target behavioral or functional levels. Besides, this estimation will be based on identifying the important behavioral parameters including the lateral displacement, relative change of the members' shape, the connections and so on.

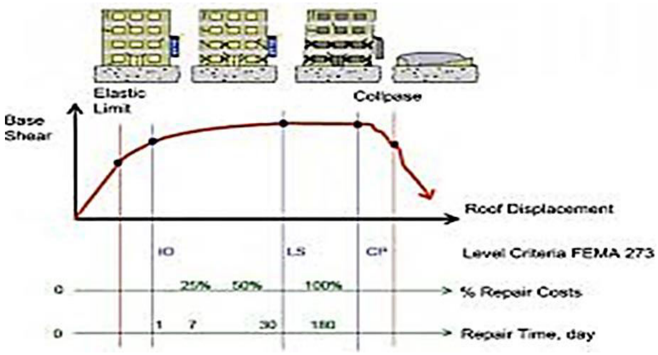


Fig.1 Load curve-displacement or pushover curve (FEMA-273) [4].

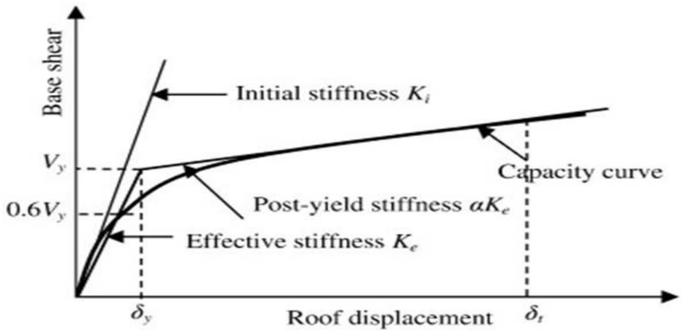


Fig. 2 Capacity curve (FEMA-356) [3].

E. *The Target Performance Point*

The target performance point is the intersection of the capacity spectrum curve and demand curve. In fact, the performance point is the stop point along the capacity curve of the structure. Moreover, it is the degree of the target displacement and the force similar to the target displacement. The structure demand is equal to the existing capacity at the performance point.

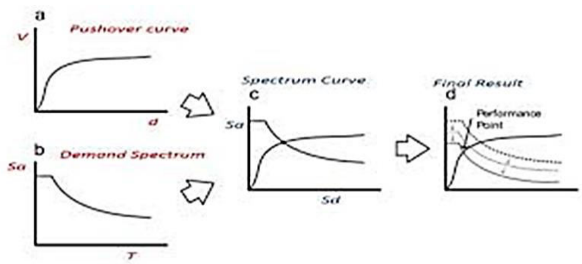


Fig 3. The mechanism of obtaining the target performance level at the performance point [5].

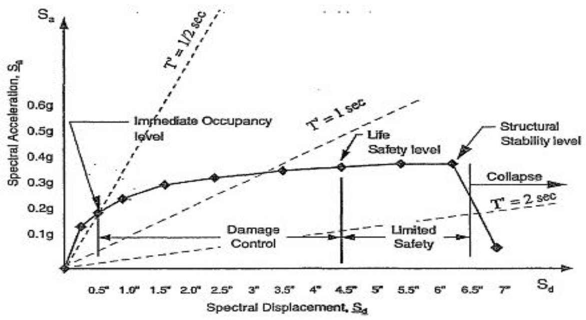


Fig. 4 Typical capacity spectrum (ATC- 40) [6]

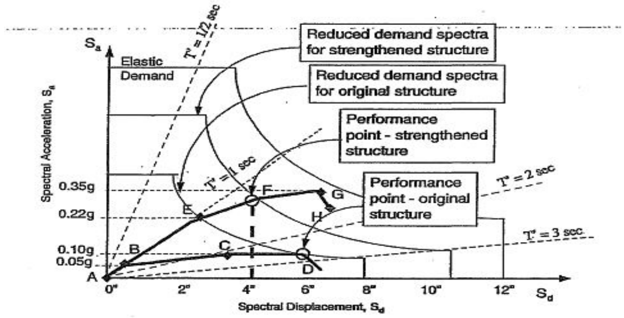
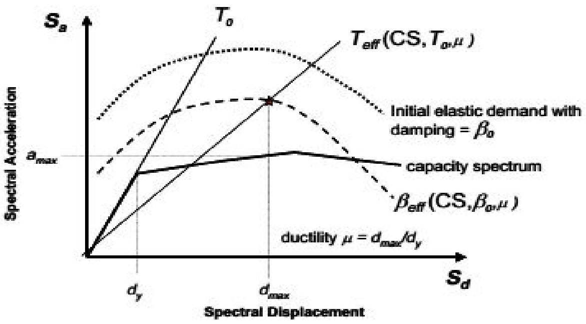


Fig. 5 Effect of system strengthening on performance (ATC -40) [6]



. Fig. 6 Equivalent linearization with capacity curve (capacity spectrum) – (FEMA -440) [5]

F. The Combination of Gravity Loading

In the combination of gravity and lateral loading, the upper and lower limit of the Quantum Gravity (QG) effects is obtained from the following equations (1), (2) [7]:

(1) $$Q_G = 1.1\,[\,Q_D + Q_L\,]$$

(2) $$Q_G = 0.9\,Q_D$$

In that Q_D is the dead quantum and Q_L is equal to 25 percent of the non-reduced live quantum, which should not be lower than the real live quantum available during the evaluation.

G. The Target Displacement

The target displacement for the structure with rigid apertures should be estimated by considering the non-linear behavior of the structure. It can be calculated as an approximation method by the following equations (3), (4), (5) [3]:

(3) $$\delta_t = C_0\, C_1\, C_2\, S_a\, \frac{T_e^2}{4\pi^2}\, g$$

T_e is the effective fundamental period in the building based on equation (4):

(4) $$T_e = T_i \sqrt{\frac{K_i}{K_e}}$$

C_0 is the correction factor for connecting the spectrum displacement system with a degree of freedom to the roof displacement system of a few degrees of freedom that is equal to the following amounts:

a. First mode participation factor is obtained from the equation (5):

(5) $$C_0 = \varphi_{1,x}\, \frac{\sum_{i=1}^{n} w_i\, \varphi_{1,i}}{\sum_{i=1}^{n} w_i\, \varphi_{1,i}^2}$$

In that W_i and $\varphi_{I,i}$ are the effective seismic weight and the component of first modal form vector for the target length in I level. Moreover, $\varphi_{I,r}$ is the component of this vector in control point level.

b. The calculated participation factor is used by the form vector (corresponding with the structural deformation in the target displacement) instead of $\varphi_{I,i}$ and also the component of this vector is used in the control point level instead of $\varphi_{I,x}$.

c. The approximate amounts are obtained from the Table 1.

Table 1. The approximate amount of CO coefficient

	Shear buildings		Other buildings
Number of stories	Triangular load pattern	uniform load pattern	any load pattern
1	1.0	1	1
2	1.2	1.15	1.2
3	1.2	1.2	1.3
5	1.3	1.2	1.4
10+	1.3	1.2	1.5

C_1 is the correction factor for applying the inelastic displacement of the system and it is calculated by the equation (6):

(6) $$T_e \le 0.2 \longrightarrow C_1 = 1 + \frac{25(R_{u-1})}{a}$$

$$0.2 < T_e < 1 \longrightarrow C_1 = 1 + \frac{R_{u-1}}{a T_e^2}$$

$$T_e > 1 \longrightarrow c_1 = 1$$

R_u is the ratio of reactionary strength to the yield strength that is obtained from equation (7):

(7) $$R_u = \frac{S_a}{\frac{V_y}{W}}\, C_m$$

In this equation, S_a is the spectral acceleration per effective fundamental of Te. C_m is the effective mass factor in the first mode that can be calculated with Table 2 or the dynamic analysis.

Table 2. Cm coefficient amounts

No.of stories	Concrete moment frame	Concrete shear wall	Concrete pier-spandrel	Steel moment frame	Steel concentric braced frame	Steel incentive braced frame	other
1-2	1	1	1	1	1	1	1
3or more	0.9	0.8	0.8	0.9	0.9	0.9	1

C_2 is the correction coefficient for the reduced difficulty effects and the strength of the structural components of the displacement resulted from the cyclical decline and it is determined by equation (8):

(8) $$T< 0.7 \quad C_2=1+\frac{1}{800}\left(\frac{R_{u-1}}{T_e}\right)^2$$

$$T\geq 0.7 \quad c_1=1$$

III. The Model Definition

The non-linear static analysis on the special concrete moment frame and also the mixed system (moment frame with a convergent brace and concrete shear wall) was investigated in this study. The study compared and evaluated the special concrete moment frame system with non-linear static analysis. The considered answers for these structural systems are the maximum lateral displacement, relative floor displacement (drift), push over the graph and the formation of floor plastic hinge. To do this, three types of buildings with clinic use were investigated, including a 3-storey, 6-storey and 9-storey buildings.

IV. Discussion and Results

A. Investigating the Performance of the Reinforced Frames

Based on the analysis, most of the studied model did not achieve the favorable and special reinforcement, so there was no need for reinforcement. Therefore, most of the models are studies in two favorable and special reinforcements and the seismic performance is analyzed. Accordingly, each model is reinforced for comparison with two methods:

1. Reinforcements with concentric steel braced frame (inverted V),
2. Reinforcement with the concrete shear wall.

The studied models in this section are same as the initial models; however, the frames are reinforced once with the convergent steel bracing and once with the concrete shear wall. To do this, the reinforced concrete frames were modeled in Etabs2015 software and then the seismic loads are calculated based on the AISc360-10 [8], ASCE7 [9], and ACI-318-14 [10] regulations and applied to the frames. Then, the convergent steel bracing and concrete shear wall were added separately to the concrete frames. The cross-bracings and the thickness of the shear wall are determined in the way that the ratio of the tensions in the columns and braces is smaller than 1. Then through non-linear analysis to achieve a better distribution of plastic hinge (with SAP2000-17 software) and the higher performance level of their size and arrangement were edited.

B. The Evaluation of Seismic Performance in Models with Favorable and Special Reinforcement: The Reinforced Frames with Convergent Steel Bracing and Shear Wall Bracing in Risk Level 2 (MPE)

Due to the consideration of favorable and special reinforcement for the studied frames, the performance levels of collapse prevention and life safety should be supplied respectively to the risk level 2.

By investigating the Push-XG1 and Push-UXG1 loading in the frames (ex. for the 3-storey frame reinforced with the convergent bracing in the target displacement (Step11) indicated in Figure 2), a hinge was used in the life safety area and other hinges were formed in the previous area. Therefore, the considered frame should supply the favorable and special reinforcement conditions.

The capacity curve in the risk level 2 was indicated in the graph 1. The images of the formed hinges in other frames are indicated and all of the formed hinges are in the allowed range of special and favorable reinforcements and the capacity curve is indicated in other frames.

Fig.7 The plastic hinge formed in the 3-storey frame reinforced with the convergent steel bracing in risk level 2 (MPE).

Graph 1. The capacity spectrum curve in the 3-storey frame reinforced with the convergent steel bracing in risk level 2 (MPE).

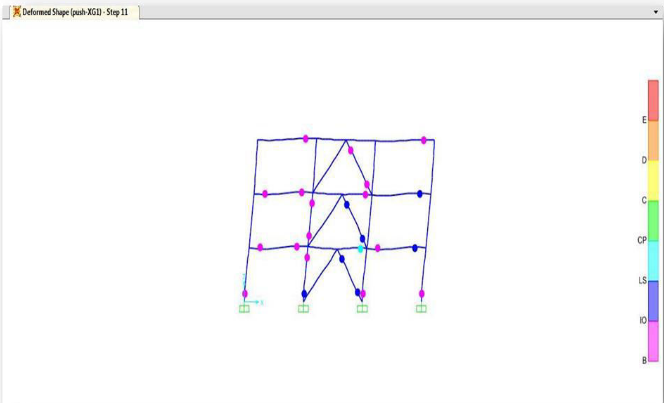
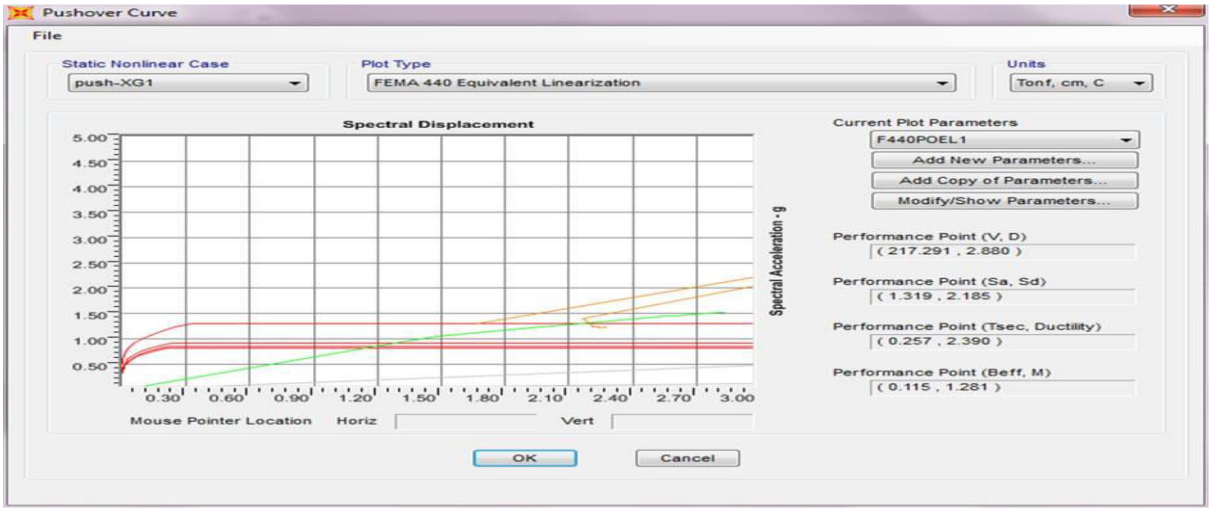


Fig. 7 Plastic joints formed in 3 floor frame improved by convergent steel bracing in risk level 2 (MPE)



Graph 1. Spectrum of capacity curve 3floor frame improved by convergent steel bracing in risk level 2 (MPE)

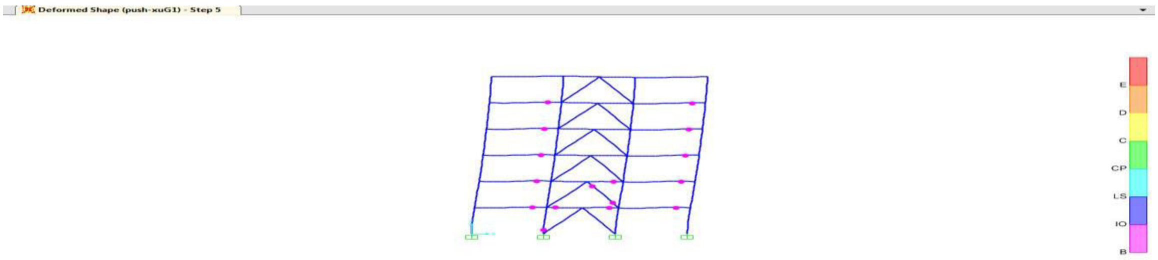
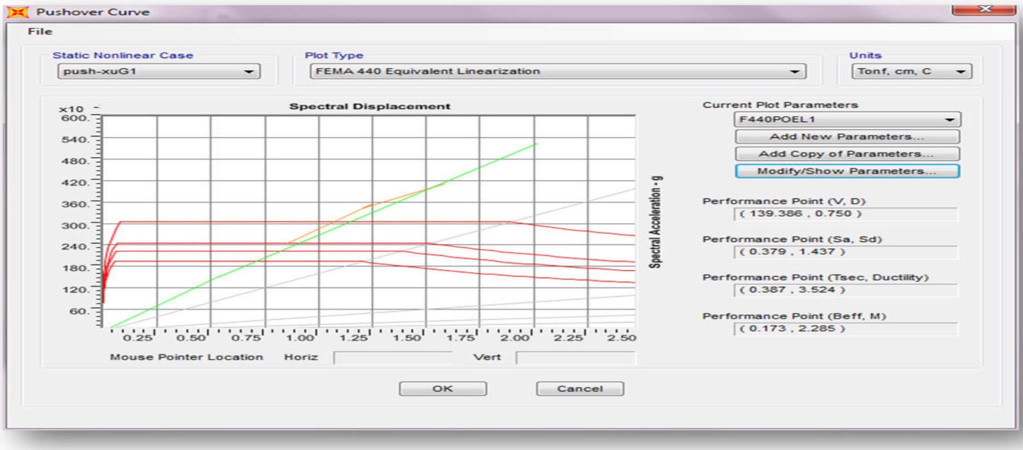


Fig. 8 Plastic joints formed in 6 floor frame improved by convergent steel bracing in risk level 2 (MPE)



Graph 2. Spectrum of capacity curve 6floor frame improved by convergent steel bracing in risk level 2 (MPE)

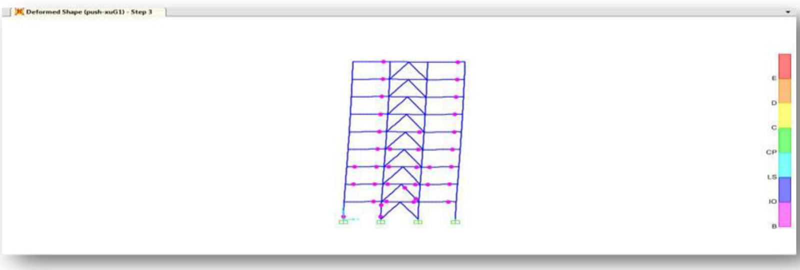
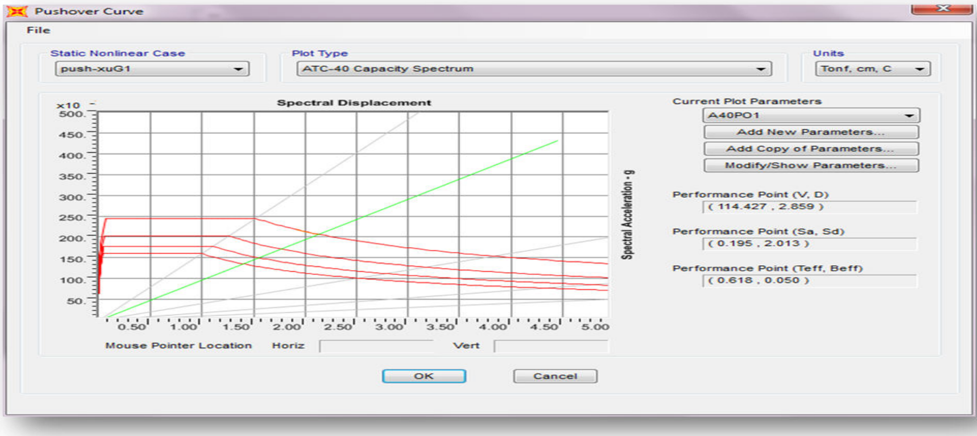


Fig. 9 Plastic joints formed in 9 floor frame improved by convergent steel bracing in risk level 2 (MPE)



Graph 3. Spectrum of capacity curve 9floor frame improved by convergent steel bracing in risk level 2 (MPE)

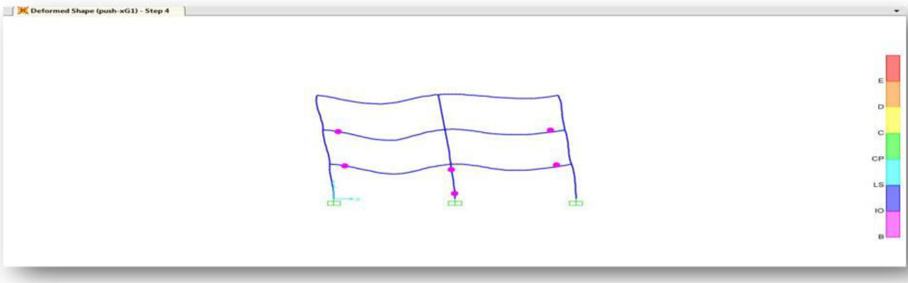
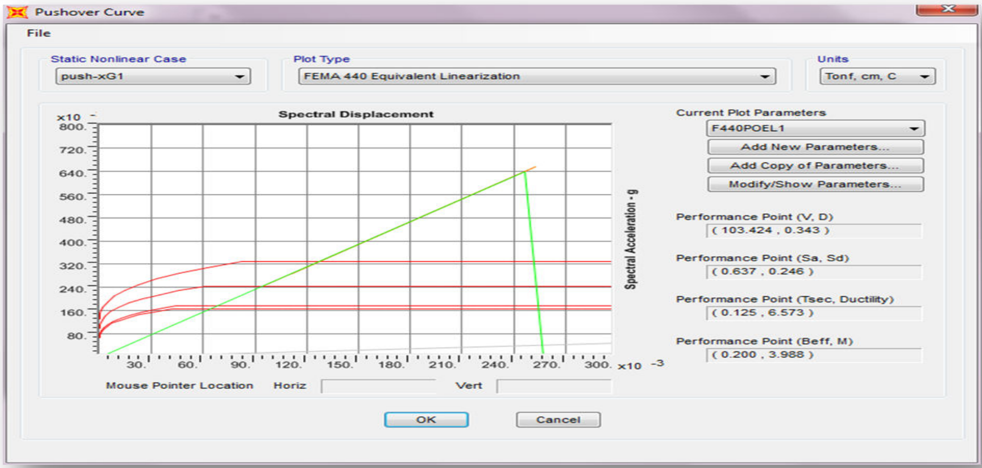


Fig. 10 Plastic joints formed in 3 floor frame improved by convergent shear wall in risk level 2 (MPE)



Graph 4. Spectrum of capacity curve 3floor frame improved by convergent shar wall in risk level 2 (MPE)

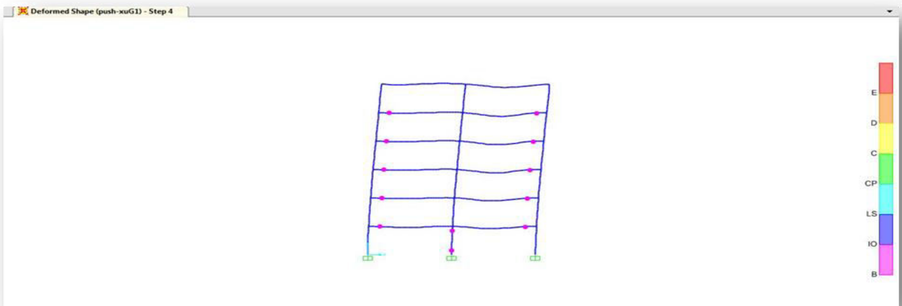
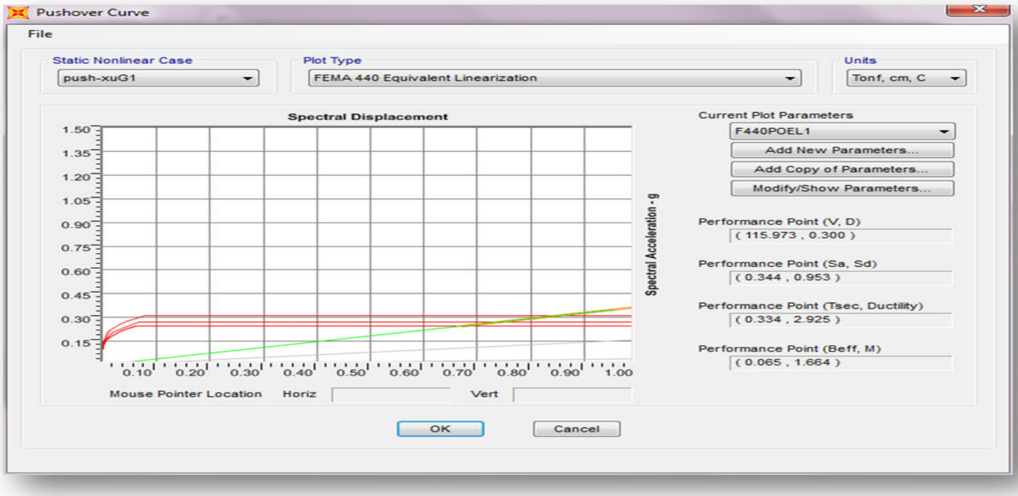


Fig. 11 Plastic joints formed in 6 floor frame improved by convergent shear wall in risk level 2 (MPE)



Graph 5. Spectrum of capacity curve 6floor frame improved by convergent shear wall in risk level 2 (MPE)

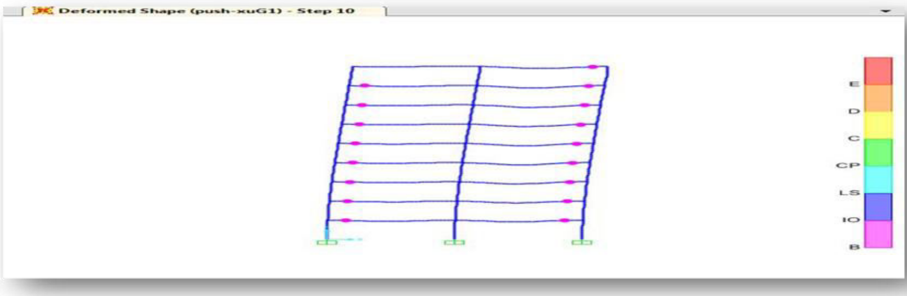
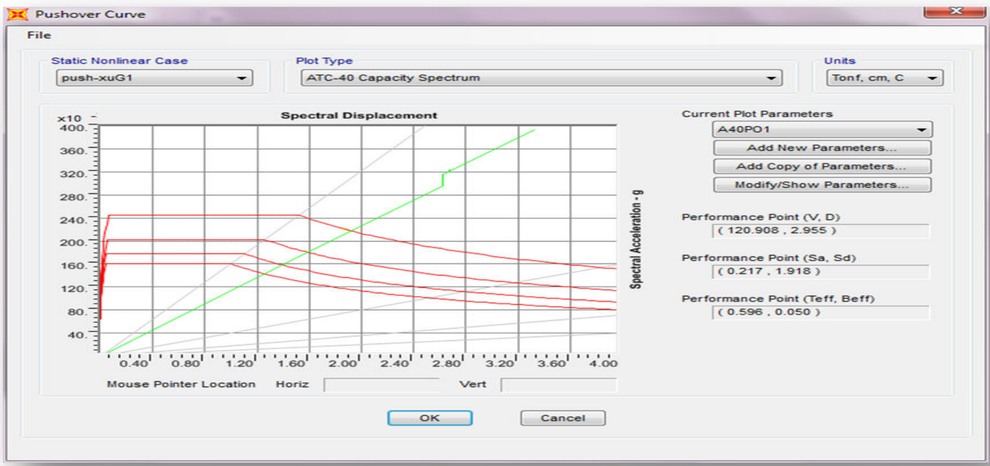
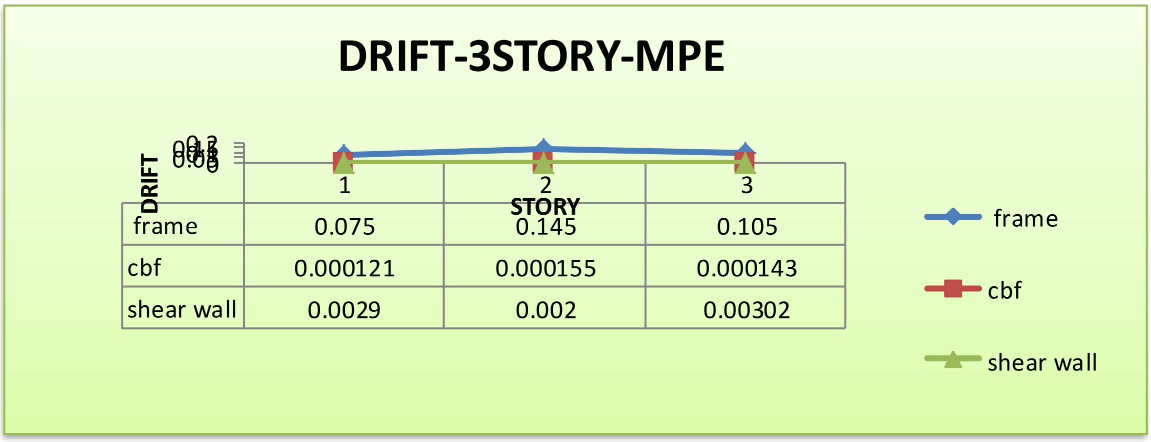


Fig. 12 Plastic joints formed in 9 floor frame improved by convergent shear wall in risk level 2 (MPE)



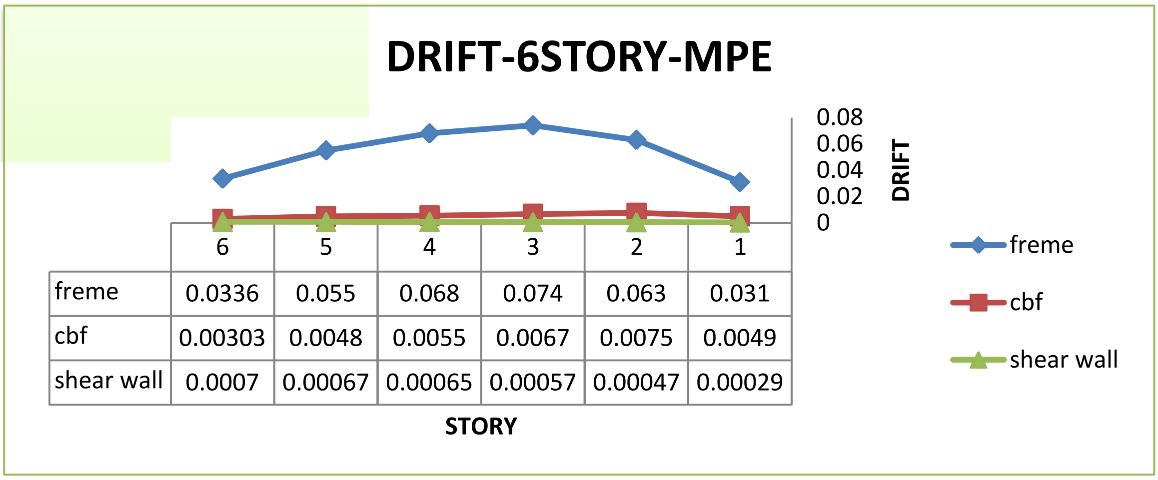
Graph 6. Spectrum of capacity curve 9floor frame improved by convergent share wall in risk level 2 (MPE)

A. Evaluation and Comparison of the Relative Displacement in Frames.



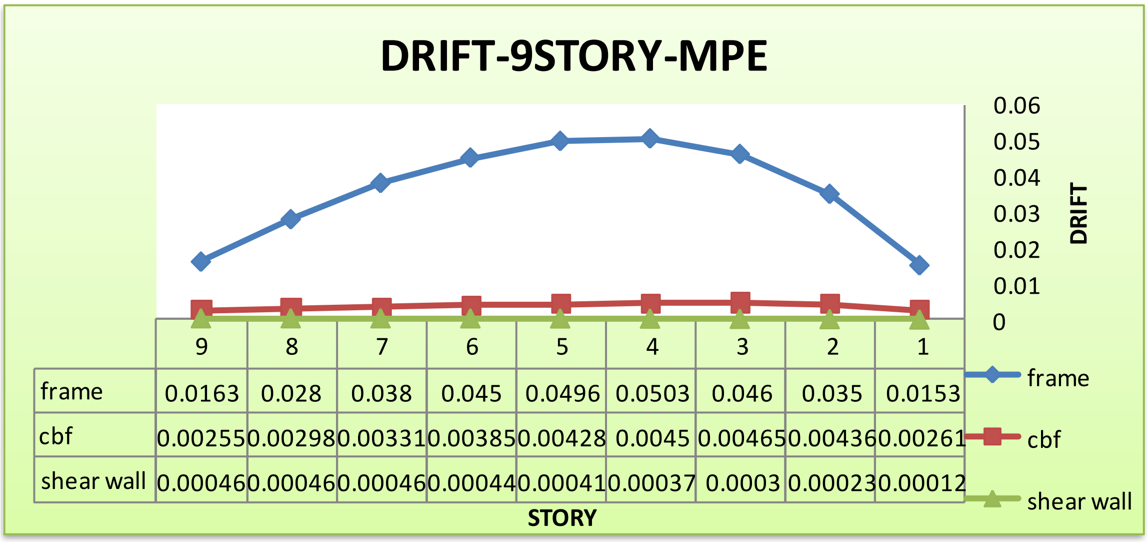
	1	2	3
frame	0.075	0.145	0.105
cbf	0.000121	0.000155	0.000143
shear wall	0.0029	0.002	0.00302

Graph 7.The relative displacement curve of 3-storey frame before and after reinforcement



	6	5	4	3	2	1
freme	0.0336	0.055	0.068	0.074	0.063	0.031
cbf	0.00303	0.0048	0.0055	0.0067	0.0075	0.0049
shear wall	0.0007	0.00067	0.00065	0.00057	0.00047	0.00029

Graph 8.The relative displacement curve of 6-storey frame before and after reinforcement.



	9	8	7	6	5	4	3	2	1
frame	0.0163	0.028	0.038	0.045	0.0496	0.0503	0.046	0.035	0.0153
cbf	0.00255	0.00298	0.00331	0.00385	0.00428	0.0045	0.00465	0.00436	0.00261
shear wall	0.00046	0.00046	0.00046	0.00044	0.00041	0.00037	0.0003	0.00023	0.00012

Graph 9.The relative displacement curve of 9-storey frame before and after reinforcement.

The evaluation of concrete building performance reinforced with the steel braced frame (inverted V) and the shear wall was investigated with regard to the capacity spectrum curve. Therefore, the concrete frames were designed in different height levels with the seismic reinforcement instruction and through push over analysis. According to Table 3 and 4, the results are:

Table 3. Comparison of capacity spectrum in the reinforced frame of different floors in earthquake risk level 2

Target displacement / cm	Performance point /cm	Type of retrofit	upload	story
8.3	2.19	CBF	Push-XG1	3
8.3	0.25	WALL	Push-XG1	3
17.9	1.43	CBF	Push-UXG1	6
17.9	0.95	WALL	Push-UXG1	6
21.5	2.01	CBF	Push-UXG1	9
21.5	1.92	WALL	Push-UXG1	9

Table 4. The comparison of base shear in different frames before and after the reinforcement of earthquake risk level 2

story	upload	Type of retrofit	Performance point /cm	Target displacement / cm
3	Push-XG1	CBF	2.19	8.3
3	Push-XG1	WALL	0.25	8.3
6	Push-UXG1	CBF	1.43	17.9
6	Push-UXG1	WALL	0.95	17.9
9	Push-UXG1	CBF	2.01	21.5
9	Push-UXG1	WALL	1.92	21.5

V. Conclusion

According to the hypothesis in the study such as the use of restricted frames in number of openings, floors and the special reinforcement performance level in the earthquake risk level 2 (MPE), the following results are obtained:

1. The improvement of reinforced concrete frames by steel braced frames has led to the increase in strength and difficulty of the structure and decrease in the floor displacement. This also affects the moment load in the columns and decreased the tensions.

2. The buckling of bracings in most of the floors especially the pressure bracings happens before the target displacement. Moreover, the performance level of stretching hinges is better than the pressure bracings.

3. According to the results, all models are promoted in performance level after the retrofitting with steel braced frame and shear wall bracing. This promotion is the outcome of the displacement control in reinforced concrete frame.

4. Creating bracing and shear wall in the structure led to the increase in the difficulty of structure, reduction in the fundamental period of the structure and also increased in the base shear of the structure. Due to the appropriate structural behavior in the dual system, the braced frame and shear wall system in the performance level of all models were promoted.

5. The relative deformation amounts of the floors for the concrete buildings with the steel braced frame and shear wall decreased because of the advantage of using a dual system of the moment and braced frames interaction. The defunct sudden deformations and structure system acts more integrated. The reason is the increase of difficulty and lateral strength of the structure because in the moment's frames of the lower floors, the relative floor displacement is higher and on the higher floors, the displacement is lower. The bracing systems act in the opposite.

6. Considering the obtained results from the reinforced concrete frames, which are short-rise and reinforced with the steel braced frames (inverted V – CBF) have better seismic performance than the reinforcement with the shear wall. Because the short shear walls are stronger in the moments, but they are weaker in the shearing. Therefore, the shearing behavior overcomes these walls and the level capacity is decreased by formation of the shear hinge in the wall. Accordingly, it is recommended to use the steel braced frames for reinforcement in the short-rise buildings.

7. For improving the reinforced concrete frames with the steel braced frame (inverted V – CBF), the increase in the floors results in the increase of the incoming forces, in needing for an increase in the cross section and in adding more bracing to supply the performance level of the structure. Therefore, the shear wall is effective in the reinforcement of structures with a high number of floors.

8. The shear wall reinforcement is recommended to be used in the mid-rise reinforced concrete frames, due to better performance level distribution of hinges compared with the reinforcement with steel braced frame.

9. The reinforcement operation is focused on more restricted points in the mid-rise and high-rise concrete frames reinforced with the shear wall and need less demolition compared with the frame reinforced with the steel braced frame.

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