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Research Article

Effect of Strength Reduction on Seismic Performance of the Steel Structures with Different Elevations

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Abstract: There have been considerable developments in techniques concerning seismic retrofitting of the structures in recent years which have been employed the same as the old ones. In this study, a new procedure with difference from common methods is proposed. The main objective of this procedure is to reduce simultaneously seismic requirements and maximum acceleration of the structure. Reducing seismic requirements of the structure, the lateral strength of the structure is decreased in the first step. Then, supplement damping devices are used to control the deformations caused by the first step. Fluid viscous damping devices are considered as inactive damping systems. Three moment steel frames with different elevation of 2, 4 and 7 stories were investigated using nonlinear static analysis (push over) and nonlinear dynamic analysis (time history). The results showed the reduction in base shear and decrease in acceleration induced on the structure as lateral strength. It is also concluded that, as the displacements are decreased by using damping devices, the performance of the structures has been improved significantly.

Keywords: Nonlinear dynamic analysis, seismic retrofitting, strength reduction, viscous damping

INTRODUCTION

A suitable design of a structure is expected to resist and show linear response under slight earthquake conditions while the level of damage can be acceptable under relatively major earthquake. This behavior may occur through formation of the plastic hinges so that seismic energy of the structure can be damped and hence, safety will be guaranteed. On the other hand, formation of the plastic hinges causes extensive displacements of the structures which as a result lead to disruption of the proper performance of the structure. In addition, it is of a great importance for the hospitals and fire stations to maintain their performance after heavy earthquakes. So, designing just based on life safety criteria seems not to be applicable for such structures. In this regard, these structures have to be designed strongly enough so that they can avoid too many displacements and too much amount of acceleration caused by intensive moment of the ground (Reinhorn and Cimellaro, 2006) In this study, a new method was employed to reduce acceleration, base shear and displacement of the structures all the same time. One of the researches done in a 4-story hospital in Buffalo, USA suggested a method of retrofitting in which structural behavior has been improved (Reinhorn, 1997). The results of the application of the new method on the structure with different elevations have been investigated. The improvement in seismic behavior of the structures is more pronounced in higher structures when using new method. Evaluating the new method, push over analysis was first applied and then the results were assessed by nonlinear dynamic analysis for further investigation. This method of retrofitting with the aim of displacement and acceleration reduction consists of two procedures. The first procedure involves weakening lateral strength of a structure by disconnecting frames or walls in a structure which is usually accompanied by displacement increase. The second procedure is to add damping devices to control and reduce deformations and displacements. The analysis of the structure for the different steps of the retrofitting procedure (original structure, weakened structure, weakened and damped structure) has been made through a spectral response approach. Such an analytical procedure, proposed by Reinhorn (1997) and Ramirez (2000) for low damped structures, has been specifically adapted in this study to be applied to highly damped structures. The proposed method leads to a simplified and effective evaluation of the structural response of damped structure under seismic excitation. Such method allows a quick evaluation of such complex retrofit. Damping devices are quite inexpensive and easy to insert in existing structures. Various damping devices with different mechanical properties and dissipation characteristics can be adopted

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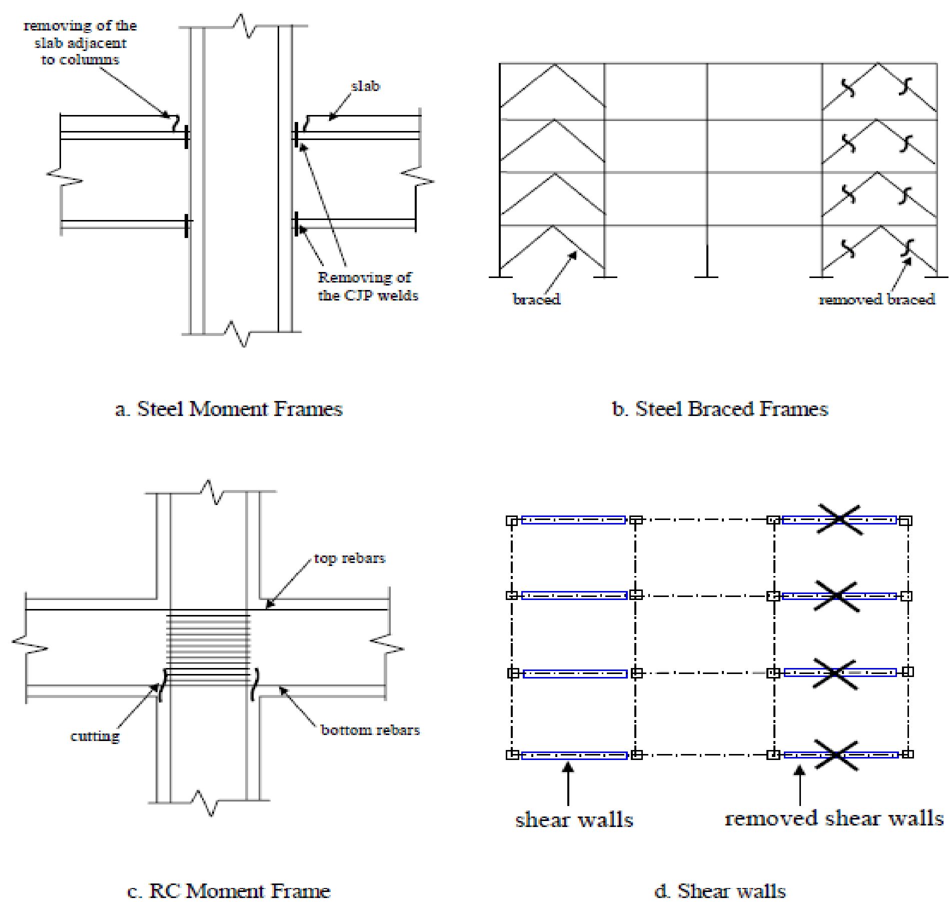
(Reinhorn *et al*., 1995; Constantinou *et al*., 1998). Depending on the dampers chosen, stiffness and strength of the structure might increase. In this study, viscous damping devices were used for the latter procedure. Viscous damping devices as energy dissipaters are considered not only as seismic separator systems for preventing extensive displacement, but also as tools for reduction in structural response to seismic, wind and storm forces (Douglas, 1996). The advantage of such damping devices is to enhance damping characteristic without any increase in strength and stiffness of the structure. Reducing strength of the structure in order to lower base shear in this method, it is better to utilize a damper which does not lead to increase the strength again. Hence, viscous damper is the best inactive damper in this regard (Hussain *et al*., 2006). This dissipater is applied to the structures after first step weakening. The study aims to investigate the effect of the application of this method on the structures with different stories. Also, effects on reduction of both displacement and acceleration have been studied.

MODELS AND ANALYSIS

In order to illustrate the applicability of the method, three models have been considered. These models include 4-span moment steel frames with 2, 4 and 7 stories. The study has been conducted in Shahrood University of Technology in 2011. The investigated cases are hypothetical hospital buildings located in Sari, Iran for which code of 519 and code 2800 were used for applying loads (dead and live) and seismic forces on the structure, respectively. Static analyses along with time history analysis were also performed using SAP 2000. For dynamic analysis, 7 spectra of Manjil, Naghan and Tabas, El Centro, Loma Prieta, Northridge and San Fernando were considered in which the first three of them were located in Iran (local) and others are global by using modal static and nonlinear dynamic analysis. Selected frames were investigated in three conditions including:

- The main structure
- Structure with weakened lateral strength
- Structure with weakened lateral strength with damper

The results of the analysis in three conditions are reported in the following. Besides, the effect of weakening and adding damping systems on structure and corresponding level of performance of the frames are considered.



a. Steel Moment Frames

b. Steel Braced Frames

c. RC Moment Frame

d. Shear walls

Fig. 1: Different methods of strength reduction

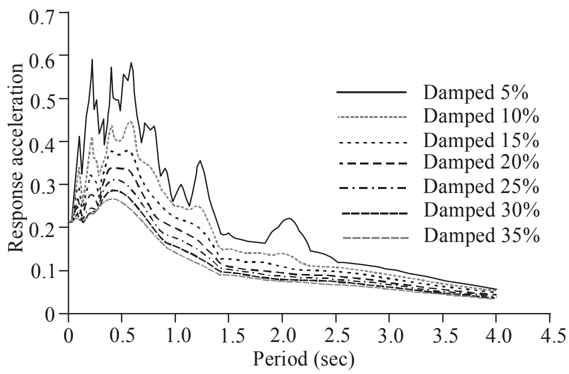


Fig. 2: Different damping conditions on El centro earthquake spectra with the scale of 0.35 g

Retrofitting process:

Main structure: The main structure is supposed to be retrofitted which is based on the preliminary design of the structure.

Structure with reduced strength: There are different methods to reduce strength in steel structures. Turning fixed joints into hinge ones, removing shear walls and removing in filled frames are the examples of such methods. Figure1 represents the proposed methods of reducing strength (Reinhorn *et al*., 2005). In this study, a fixed joint in a span turned into simple beam to column joint to reduce the strength of the moment frame. In practice, this is done by removing the upper plates below the fixed joint or by cutting the edges of the beam, thinning them and weakening the joints in tensed wing so that hinging behavior of this part can be obtained.

Structures with dampers and reduced strength: Considering the studied area, soil and acceleration base design, it is necessary to select a spectrum as a base design (Fajfar and Eeri, 2000). The El Centro earthquake was considered as a base design to determine the damping characteristic of the structure by using spectral response of this earthquake under different damping conditions. The effect of the damping of each structure as well as the frequency of the main structure can be estimated. Figure 2 presents different damping systems ranging from 5 to 35% which were performed on seismic spectra.

As seen, the values of the acceleration decreased with damping conditions of 10, 15, 20 and 25%, respectively. Acceleration between damping of 25 and 35% does not show significant decrease in all frequencies except frequencies varying from 0.3 to 0.8. As a result, increase in damping conditions higher than 25% does not have effect on acceleration reduction in the mentioned frequencies and seems economically unjustified.

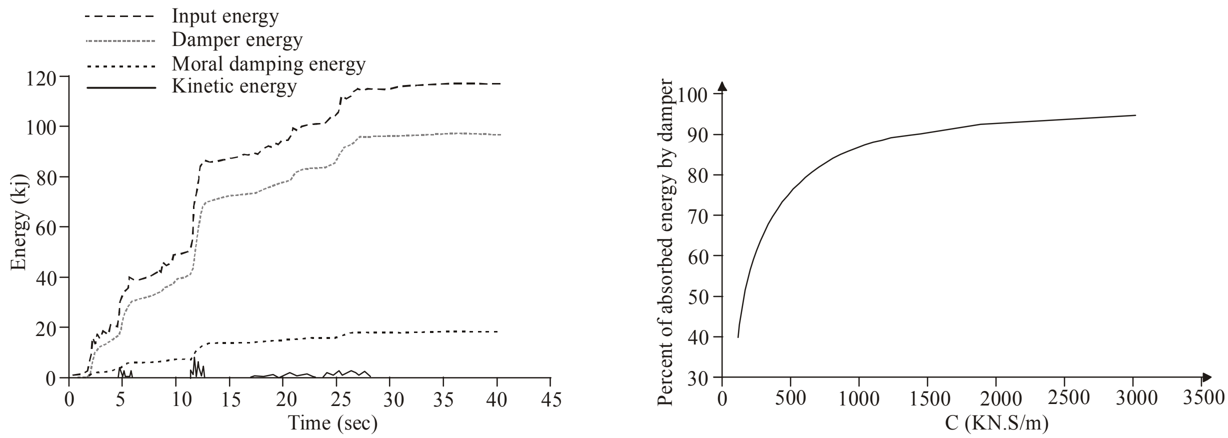
In this step, the viscous damper is added. These dampers are located in span with a hinge joint for all stories. Besides, all the damping coefficients are the same (for uniform distributions of damping). The required damper to absorb the maximum input energy forces induced by El Centro earthquake is determined by the absorbed energy curves. These curves are derived from total internal energy diagram of the structure for different damping coefficients. The vertical axis represents the percentage of the absorbed energy by damper. This value can be obtained by dividing the maximum absorbed energy by damper (damper energy) to maximum input energy at the end of the earthquake. These diagrams are shown in Fig. 3.

The percent of the absorbed energy by damper of 2-story structure was 82.86% for damping coefficient and 800 KN.s/m for absorbed energy which imply the absorption of the high amount of input energy by damper. Beyond this point, no considerable increase was observed. The value of 1700 KN.s/m was considered for a 4-story structure which is the equivalent of 85% of the input energy. For a 7-story structure, the values of 3500 KN.s/m and 84% were obtained for absorbed energy and damping coefficient, respectively. The effective viscous damping coefficients for 2, 4 and 7 stories were 26, 24 and 23% in respect.

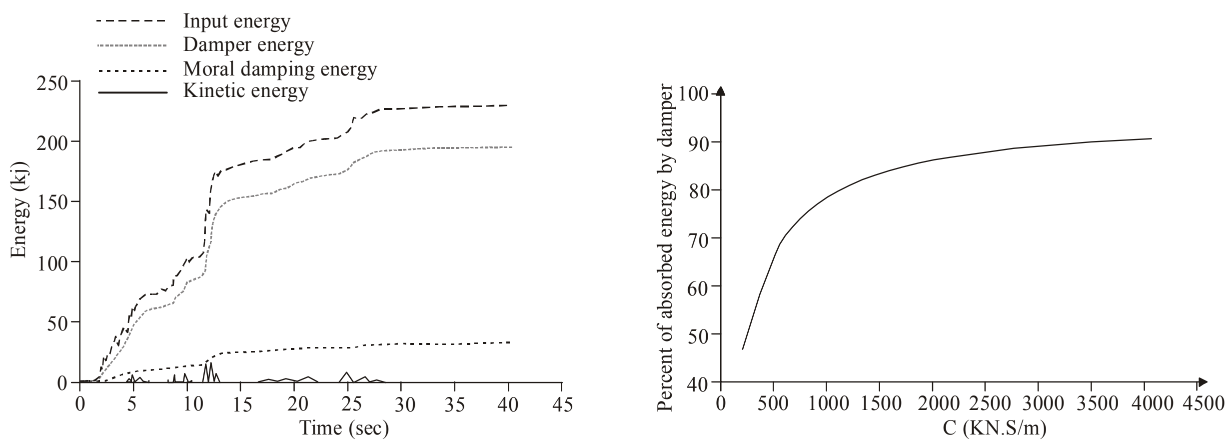
Spectra selection and scaling: The spectra with some specific features are selected for nonlinear dynamic analysis. These features include frequency content, spectral response and durability of the movement while earthquake so that the occurrence of the spectra is probable. The ground characteristic is another factor to be considered for spectral selection. Seven spectra were chosen in this study (Fig. 4) in which the corresponding responses were analyzed based on FEMA356 regulations and seismic retrofitting guidelines for moderate structures.

RESULTS

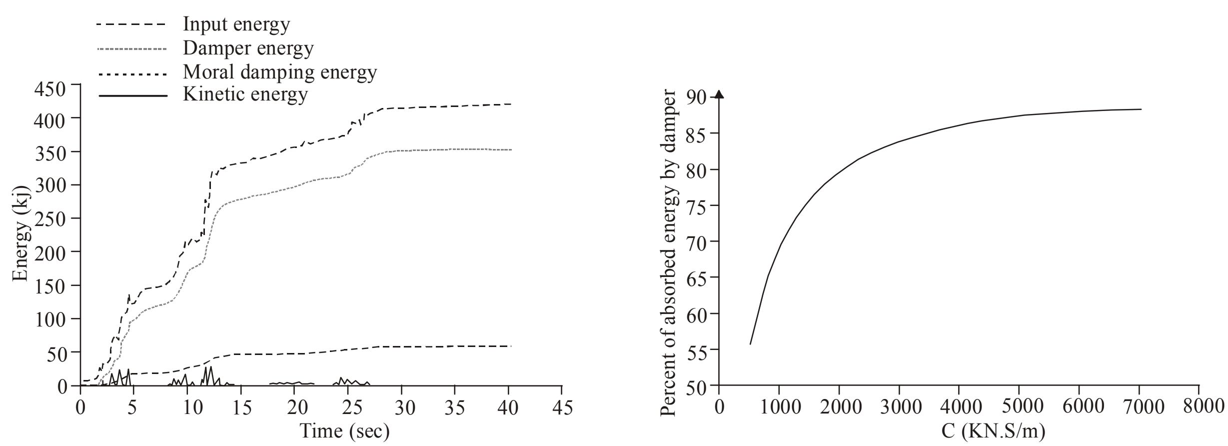
Results of nonlinear static analysis: In nonlinear static analysis, the lateral loadings are applied to evaluate the structure capacity in large displacements. According to Fig. 5, the corresponding curve of 2-story structure lowers and base shear decreases as the strength of the structure decreases. For example, the corresponding values of the base shear for 10 cm displacement were 440 and 418 KN for original and weakened structure, respectively. The difference is about 5% which increases in nonlinear area. It should



(a) 2-story



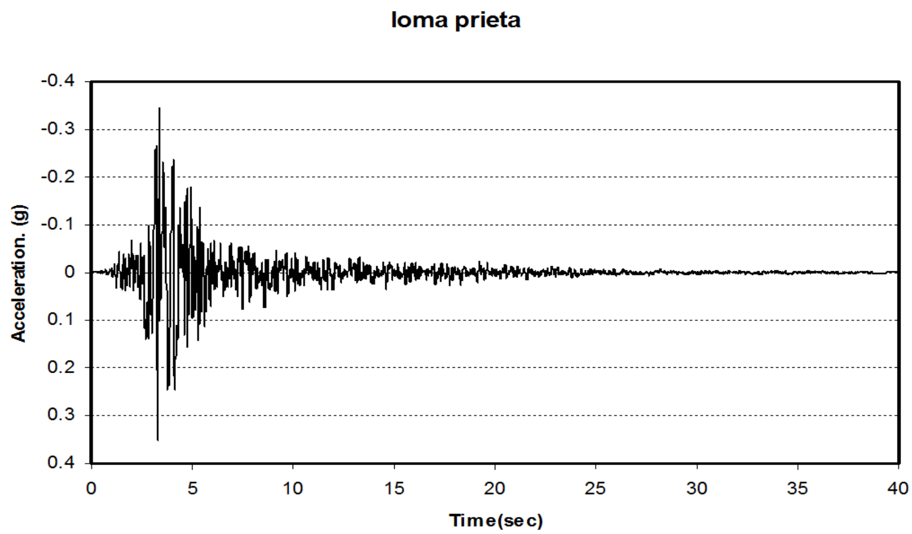
(b) 4-story

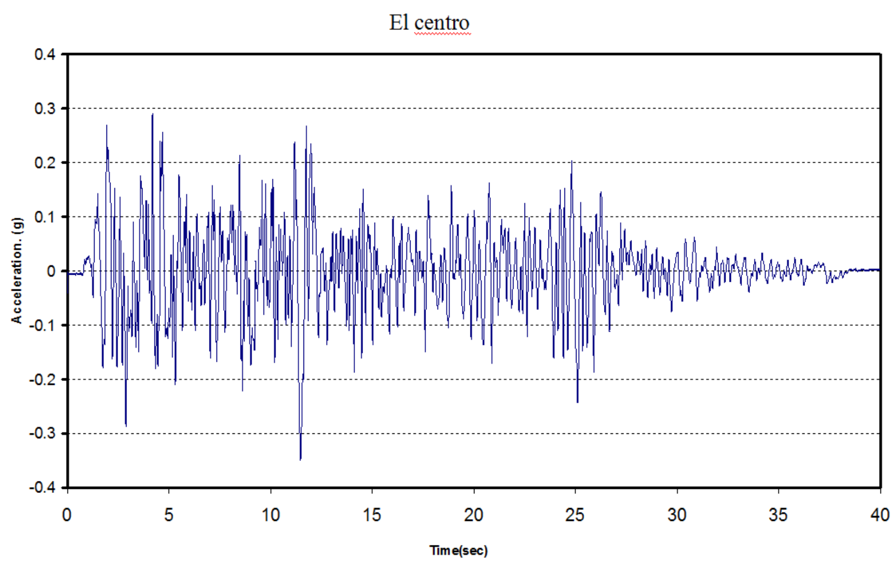


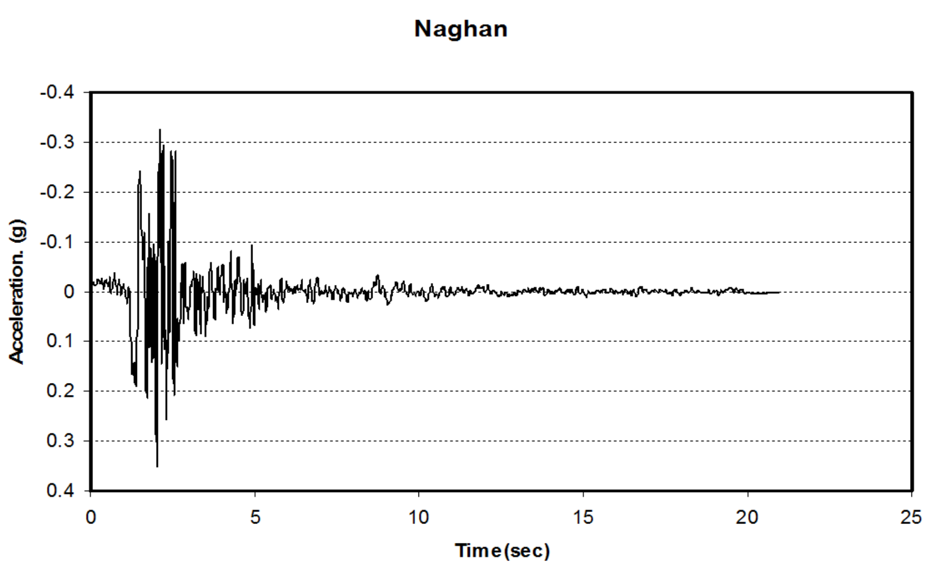
(c) 7-story

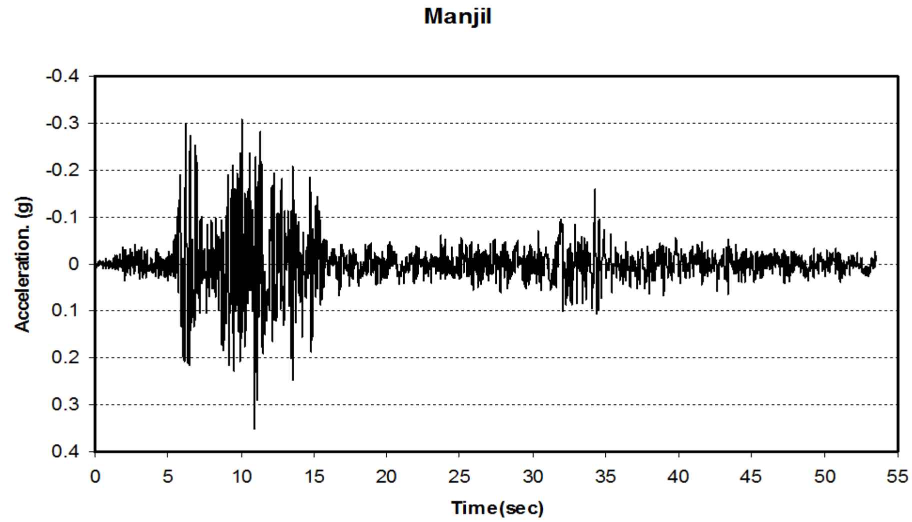
Fig. 3: Percent of absorbed energy by damper

also be mentioned that the maximum displacements of the structure were 1.29 and 12.82 cm for original and weakened conditions. The difference is about 3.5%. Moreover, the amount of base shear decrease by increasing elevations was pronounced in weakened structure. As another example, the base shear decreases to 5, 13.5 and 17% for 2, 4 and 7 stories for given displacement (10 cm).


loma prieta
Acceleration. (g)
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0
5
10
15
20
25
30
35
40
Time(sec)


El centro
Acceleration. (g)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
5
10
15
20
25
30
35
40
Time(sec)


Naghan
Acceleration. (g)
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0
5
10
15
20
25
Time(sec)


Manjil
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
Acceleration. (g)
0
5
10
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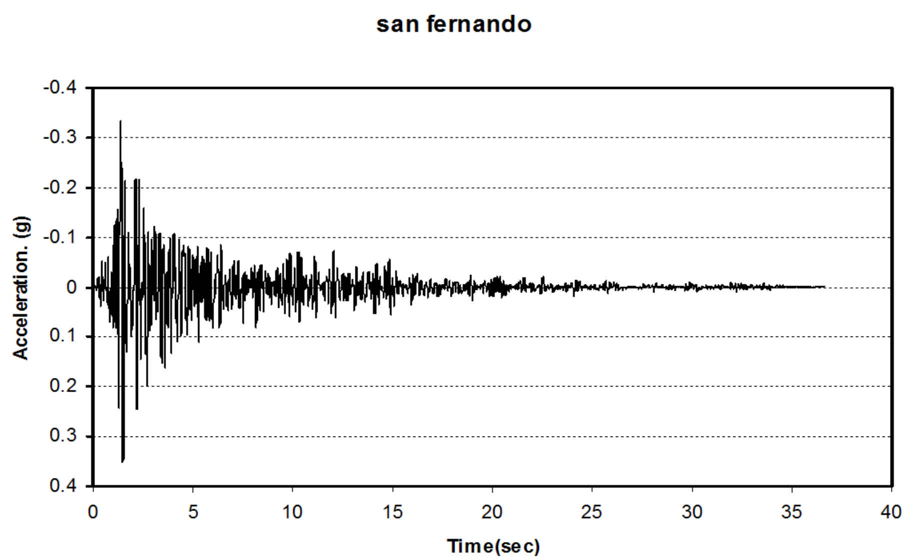
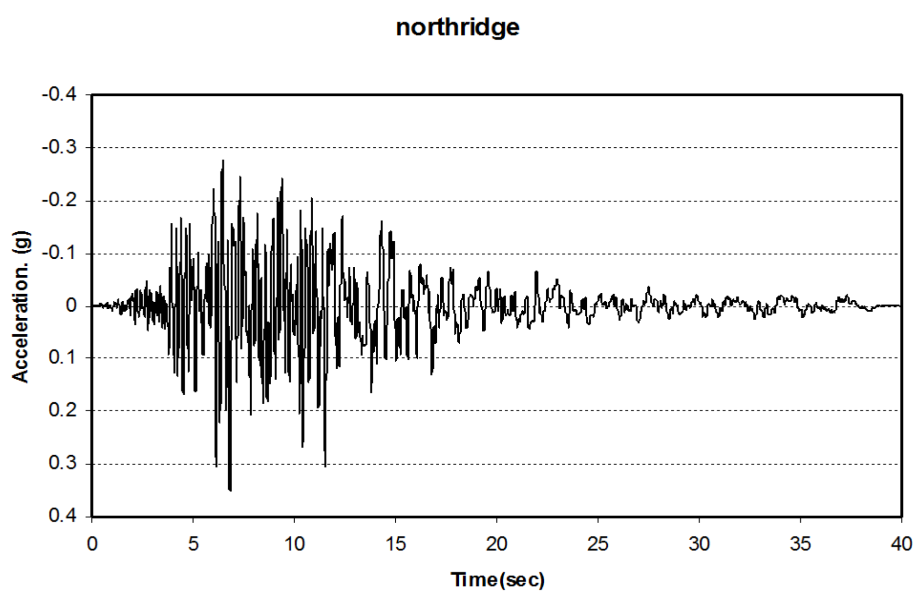
45
50
55
Time(sec)


san fernando
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
Acceleration. (g)
0
5
10
15
20
25
30
35
40
Time(sec)


northridge
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
Acceleration. (g)
0
5
10
15
20
25
30
35
40
Time(sec)

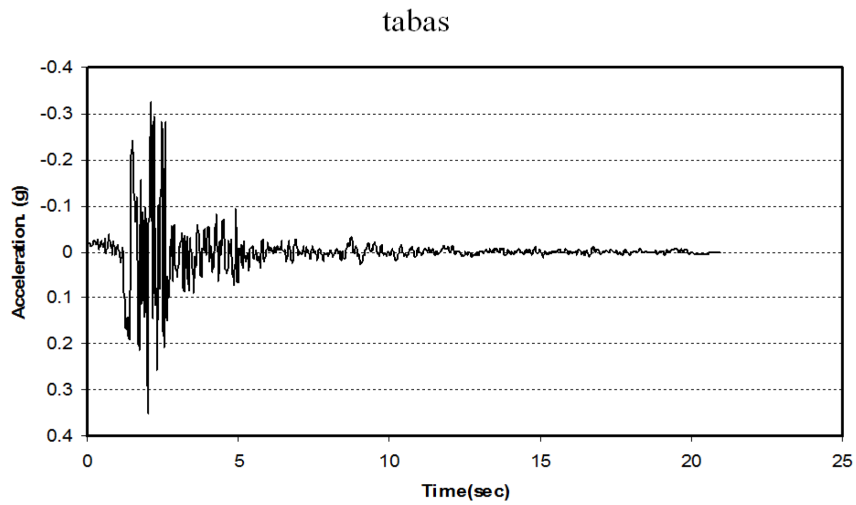


Fig. 4: Scaled spectra of earthquakes

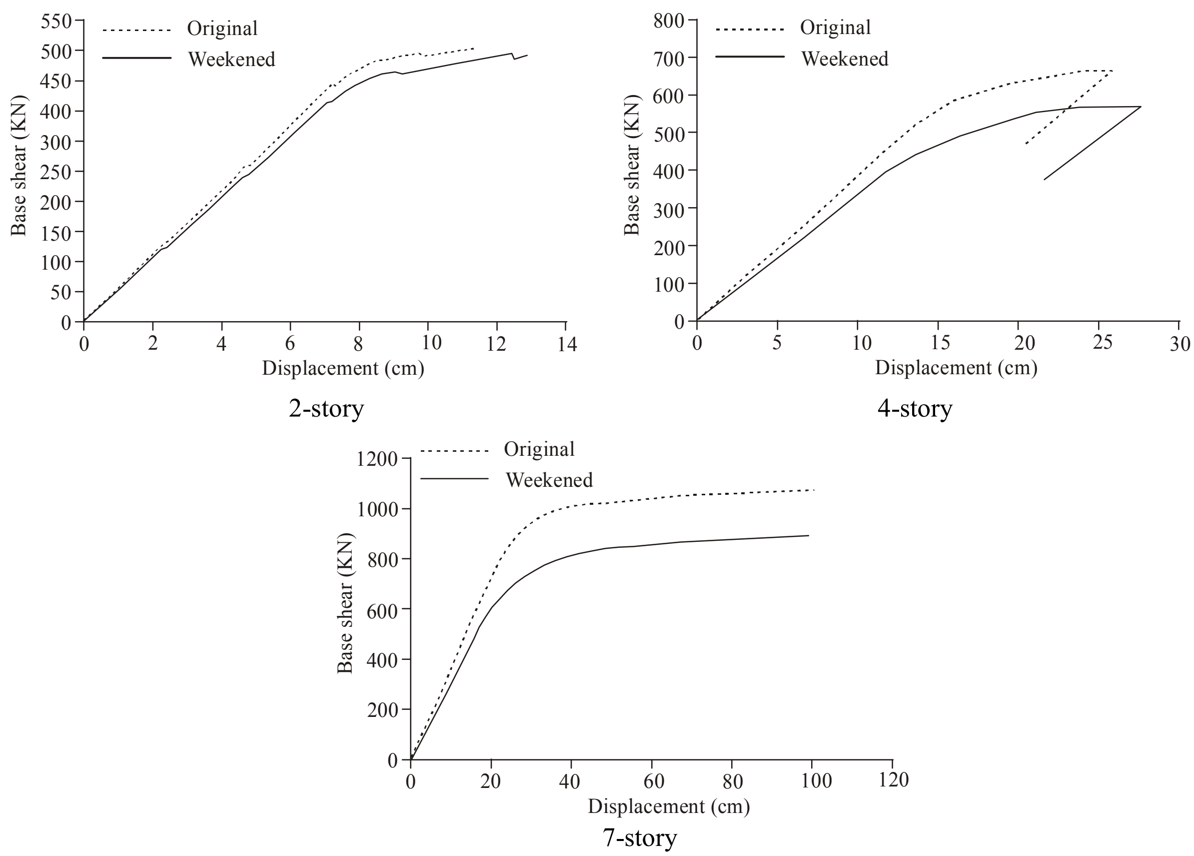


Fig. 5: Base shear-displacement curves of 7-story structure

Results of the dynamic analysis: In this section, three conditions including original structure, weakened structure and weakened structure with damper were analyzed under El Centro spectra. Figure 6 and 7 provide some information on the pattern of the hinge formation and the historical displacement of the roof of the 2-stroty structure respectively. As seen in Fig. 6, the structure resisted up to 14.82 sec and then collapsed and the related displacements were very large in the time. But, the performance of the structure with reduced strength is different. Although the structure is out of balance, it can respond to the end of the historical spectra.

Besides, the internal forces were reduced in weakened structure. The structure can respond longer to earthquake according to Fig. 6. In addition, the

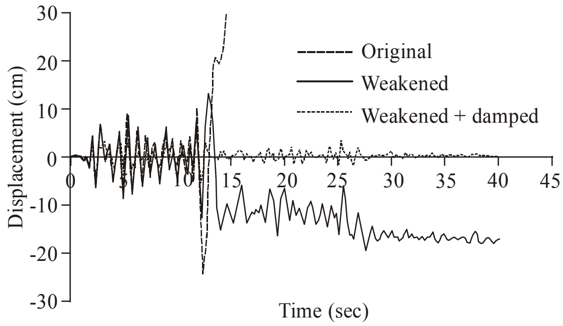
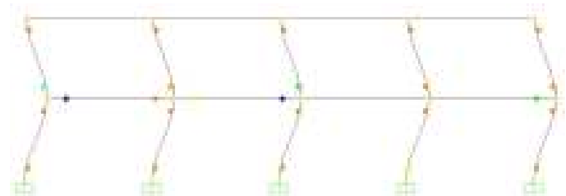
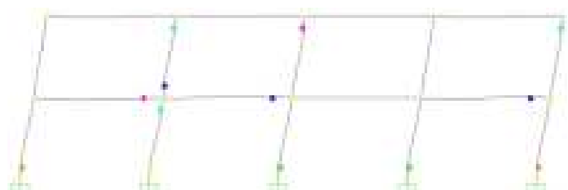


Fig. 6: Historical displacement of a 2-story structure under El centro spectra



(a) Original structure



(b) Weakened structure

(c) Weakened structure with damper

Fig. 7: Pattern of the formation of the plastic hinges under El centro earthquake

maximum displacement is significantly decreased by increasing damping in the second step.

As seen in Fig. 7a, many hinges were formed in the 2-story structure. But they reduced in number by the first step of the retrofitting process. Figure 7b shows the second step of the retrofitting (adding damper) which performs linearly and consequently, no hinges were formed. The positive effect of the retrofitting can be also seen in Fig. 7c.

The historical displacement of the roof of the 4-story structure is presented in Fig. 8 underel Centro earthquake. The structure undergoes too many failures. The third floor faces soft failures after 12 sec. Two

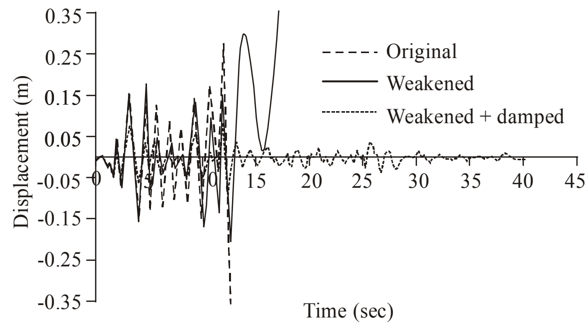
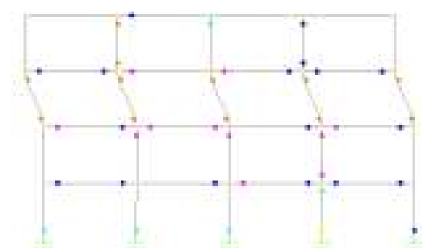
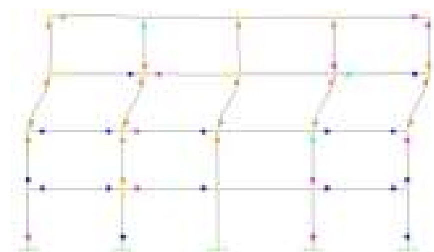


Fig. 8: Historical displacement of a 4-story structure under El centro spectra



(a) Original structure



(b) Weakened structure

(c) Weakened structure with damper

Fig. 9: Pattern of the formation of the plastic hinges under El centro earthquake

floors below, the structure resists by formation of many plastic hinges (Fig. 9a). In the first step of the retrofitting by reducing lateral strength, the structure resists up to 20.24 sec by formation of many hinges (Fig. 9b). Beyond this time, it collapses but with the increase of 40% in durability of the structure. In the

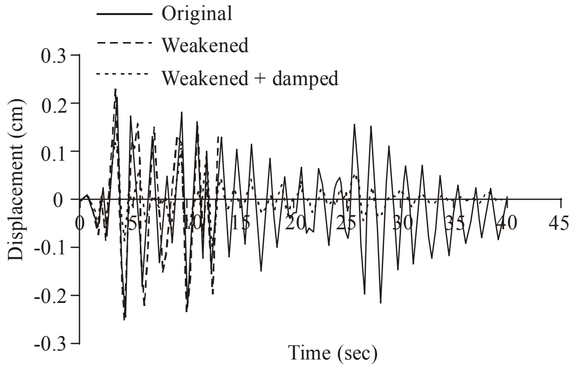
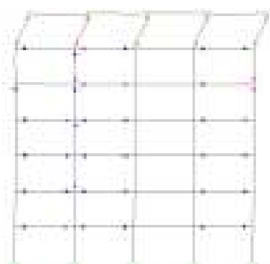
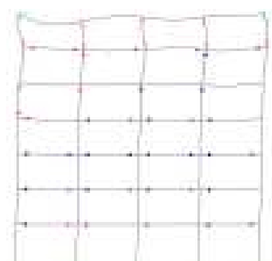


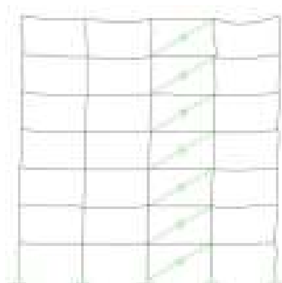
Fig. 10: Historical displacement of a 7-story structure under El centro spectra



(a) Original structure



(b) Weakened structure



(c) Weakened structure with damper

Fig. 11: Pattern of the formation of the plastic hinges under El centro earthquake

second step, the structure responds linearly by the end of the earthquake without any failures in members (Fig. 9c).

Historical displacement of the roof of the 7-story structure is provided in Fig. 10. The structure undergoes many failures under El centro earthquake as well, but it resists until the end. It remains up to 13.02 sec in the weakening process (Fig. 11a) and then collapses because of the formation of too many joints (Fig. 11b). By adding dampers, the structure maintains its linear functionality without formation of the joints by the end of 40 sec (Fig. 11c). Failures are reduced considerably to zero. It can be concluded that displacements are increased and hence, it leads to collapse of the structure by reducing strength. The performance of the structure is also improved in which it remains in linear step.

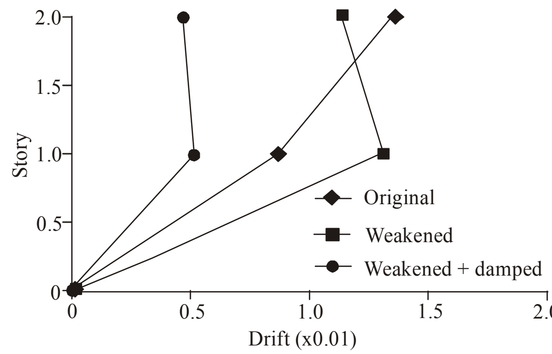


Fig. 12: Average of maximum relative displacement of a 2-story frame resulting from dynamic analysis

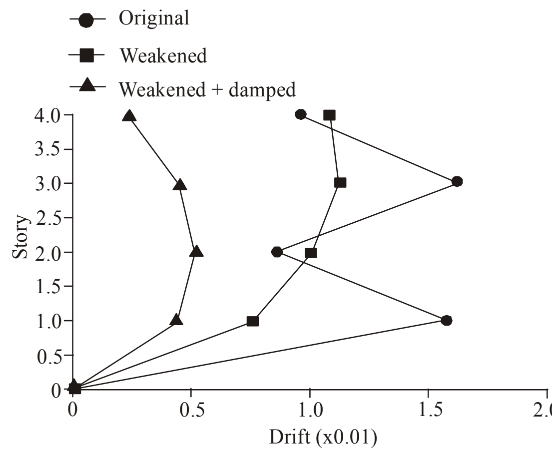


Fig. 13: Average of maximum relative displacement of a 4-story frame resulting from dynamic analysis

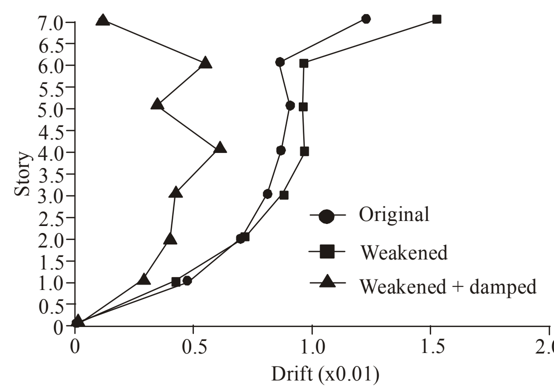


Fig. 14: Average of maximum relative displacement of a 7-story frame resulting from dynamic analysis

Another parameter which can be assessed in nonlinear analysis is the relative lateral floor Displacement (Drift) which can be obtained by using historical lateral floor displacement time series. The maximum values of Drift are determined under mentioned earthquake spectra. The average of such values for three conditions is provided in Fig. 12 to 14. As seen in Fig. 12, the relative lateral displacement of

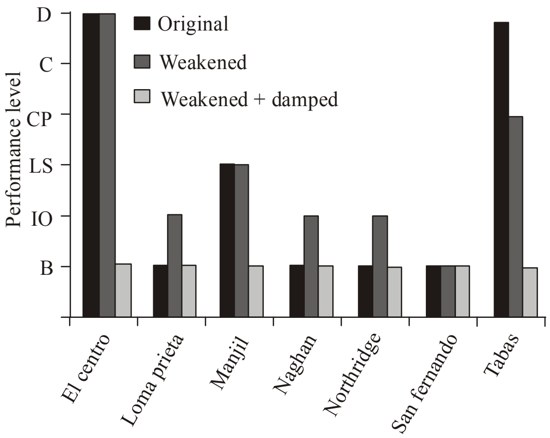


Fig. 15: Performance level of a 2-story frame resulting from dynamic analysis

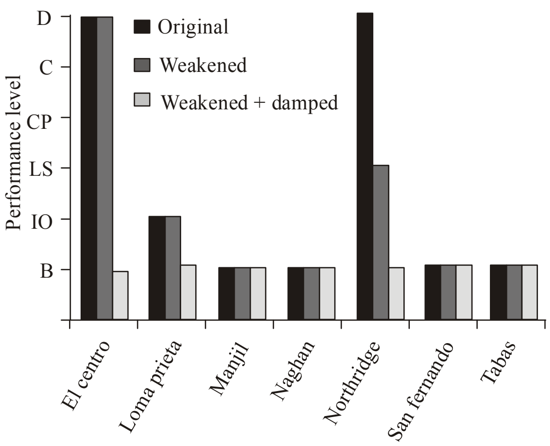


Fig. 16: Performance level of a 4-story frame resulting from dynamic analysis

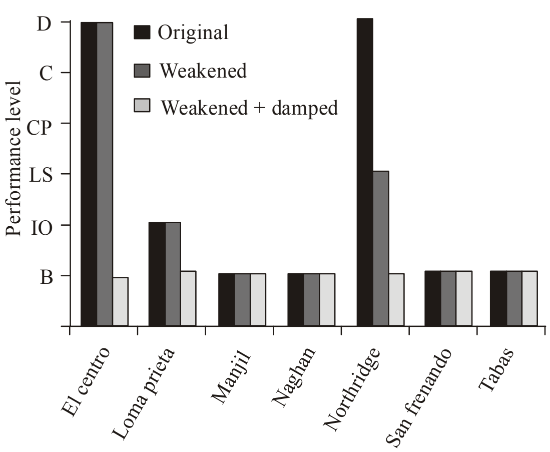


Fig. 17: Performance level of a 7-story frame resulting from dynamic analysis

the first and the second story were 52.5% increased and 16.3% decreased, respectively in the first step of retrofitting of a 2-story structure. In the next step, adding damper decreased the retrofitted DRIFT values to 45.6 and 66% for the first and the second story respectively in comparison with original structure. It is concluded that, reducing strength may cause to decrease or increase displacement in some stories while adding damper always has positive effects in decreasing displacement. According to Fig. 13, displacement of the first and third floor in a 4-story frame was increased to 52 and 30.5% compare to those of the original condition by weakening the structure. As seen, adding dampers can cause the displacement to decrease more than 70% in most cases.

As seen in Fig. 14, the relative displacements are increased in most of the floors by reducing lateral strength in 7-story frames. It is only in the first floor with 10% reduction in displacement. Besides, adding dampers leads to reduction in relative lateral floor displacement significantly. Considering the above curves, it is concluded that reducing lateral strength causes more lateral displacement with increasing elevation and adding dampers make the advantage of this technique more pronounced. As discussed earlier, the pattern of the formations of the plastic hinges can provide some information about the structural behavior. So, the frames performance levels with different elevations in three conditions (Original structure, weakened structures, weakened structure with damping) are presented in the following.

Determining the frames performance level, it is assumed for the first hinge in a member to be considered as the performance level of the frame. In other word, if a hinge is formed in a member of a frame in life safety level, the level of the performance of the frame will be life safety though hinges are not formed in other members nor they are formed in lower levels. Figure 15 to 17 show performance level of 2, 4 and 7-story structure. Considering Fig. 15, the performance level of the 2-story structure is D for El Centro and Tabas earthquake in the first step. It reaches to B by adding dampers which show linear performance of the structure. Also, the structures perform linearly under Loma Prieta, Naghan, Northridge and San Fernando earthquakes. It reaches immediate occupancy by reducing lateral strength, but again, it reaches to linear function by adding dampers. It should be mentioned that displacements became less by adding dampers under Manjil earthquake. There is no negative effect on level of performance by weakening and in fact, it reaches linear performance level by adding dampers.

As observed, weakening sometimes may improve the performance level and sometimes reduce it or may have no effect. Adding viscous damper, it always results in improvement of the structure substantially. The structure reaches the linear level of the performance by retrofitting in all cases which show the considered damping value is appropriate one for linear performance. However, proper dampers can be selected based on designer's opinion and also performance level.

According to Fig. 16, weakening has no effects on 4-story structure in most of the cases in linear structures. Also, the performance level of the original structure was improved under Northridge earthquake. By adding dampers to structure, it reaches linear level of performance under all earthquake conditions.

As seen in Fig. 17, the performance of 7-story frames under most of the spectra was linear like 2 and 4-story structures. Similarly, no significant variation in level of performance was observed by weakening. For Northridge earthquake, weakening leads to better performance. Structure reaches linear level by adding damper as well.

Considering Fig. 15 to 17, it can be concluded that weakening can improve the level of performance under most of the earthquakes in which structure pass the failure limits. El Centro earthquake is an exception for this statement in which weakening can cause failure of the structure. In some cases (2-stroty frame), weakening may cause the level of performance to be more critical.

Enhancing damping characteristic of the structure by linear viscous damper leads to improve the level of performance of the structure significantly which implies the advantage of using this method.

CONCLUSION

- Retrofitting by weakening and adding viscous damper in most cases reduce seismic demands such as acceleration, displacement and base shear. So, it is an effective method for retrofitting of most structures.
- Retrofitting by mentioned method (weakening + damping) improve performance point.
- By reducing the strength of the structure (weakening), acceleration and base shear are reduced while displacements are increased.
- Adding dampers in second step (damping), displacement are always reduced significantly.
- Reduction of the lateral strength in the first step of retrofitting sometimes reduces displacements which can be positive performance in structure.
- By increasing elevations and stories of the structure, the effect of the first step of the method on performance, base shear reduction and acceleration is magnified (as seen in 4 and 7-story structure). This may the results of reducing strength in the first step in structure with more stories.
- The method of retrofitting used in this study, due to the considerable reduction in acceleration and displacement at the same time, can be effective technique for the structures such as hospitals and laboratories and advance research centers in which non-structural elements are of a great importance.

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