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Research Article

INVESTIGATION ON PERFORMANCE ENHANCEMENT OF STEEL STRUCTURES USING VISCOUS DEMPERS

***Mohammad Zeynali**
Department of Civil Engineering, Basmenj Branch, Islamic Azad University, Basmenj, Iran
**Author for Correspondence*

ABSTRACT

Earthquake is one of the natural disasters that take many lives annually. Most of the structures are analyzed and designed using linear procedures in the past. But, after some sever earthquakes such as Kobe and Northridge, the deficits of this procedure were revealed. Nonlinear analyses, give a better estimate of behavior of structures, facing severe earthquakes, by considering nonlinear behavior of structures. The two approaches to nonlinear analysis are pushover and time history analysis. Among them, pushover analysis is popular between structural engineers due to its simplicity and efficiency. In our country, most of the built structures are designed using old versions of 2800 standard. In this project, a number of 2D steel frames, designed by first revision of 2800 standard, is evaluated using nonlinear pushover analysis, and then are rehabilitated using linear viscous dampers.

Keywords: *Damper, Viscous, Steel Structures*

INTRODUCTION

In simple terms, the aim of rehabilitation is to reinforce the structural and non-structural members in a way that in case of an earthquake event, they suffer less damage. Authors of FEMA and ATC provisions, categorized the probable damages and rehabilitation levels, based on the structure importance and its post-earthquake performance. These provisions divide the whole structure into two categories of structural and non-structural members, and define a criteria set of performance levels from full functionality to severe damages for an earthquake with a definite return period. For example, the highest level of rehabilitation is defined for structures that must fully maintain their serviceability after an earthquake, and the lowest rehabilitation level is defined for structures that should only prevent collapsing during an earthquake. In highest rehabilitation level, structural and non-structural members shouldn't suffer from damages and failures, or if they suffer damages, they should be able to put back to full serviceability immediately. In the lowest rehabilitation level, structural members may reach their rupture level, residual deflections in the structure may occur, and non-structural members may be of no further use; but, the structural framing should be preserved, such that all the residents can move out the building and no casualties may happen. Other defined rehabilitation levels are considered between these two limit levels.

Based on client's opinion and post-earthquake expectations of a building, the rehabilitating engineer is advised of the damage and functionality preservation level of the structural and non-structural members. Design and rehabilitation in FEMA and other rehabilitation provisions is based on performance levels, but designing based on performance levels is a new approach that is still unknown to many. So, to choose the rehabilitation objective appropriately, the designer should be completely familiar with different performance levels of the building. He should familiarize the client with these basics, and choose the desired performance level in coordination with the owner (Taghinejad, 2010).

Principles and Concepts of Performance Based Design Approach

The aim of performance based design is to empower the engineers to design structures with predictable performance. The above objective has not defined recently, and the available codes and standards are already prepared by the same token. In fact, in the available standards, by presenting binding laws and provisions, it's been tried to assure the client and designer that in the structures designed based on these standards, a definite performance level is achieved under a definite loading. With the occurrence of severe earthquakes in recent years, and growth of engineering knowledge of structural behavior and the manner in which the earthquakes happen, it's been learnt that the available standards sometimes fail to reach their design objectives. In other words, the same performance level is not achieved in all the structures that were designed for the same objective. On the other hand, the huge financial loss in Life Safety performance level, made the designers to make possible the designing of structures for more strict performance objectives (i.e. to design the structures for higher hazard and performance levels, if needed or required by the client). The first step in developing concepts of performance based design was presented in the "Blue Book" of California Structural Engineers Society. In this document, three levels of seismic hazard and their corresponding performance levels were explained qualitatively (Niknam *et al.*, 2012).

Rehabilitation using Viscous Dampers

A lot of approaches are proposed to enhance the seismic performance of structures and to reduce the damaging effects of severe earthquakes, up to now. Adding energy dissipating systems to the structures is one of these approaches. Different types of energy dissipating devices such as friction dampers, viscoelastic dampers, yielding dampers, and viscous dampers are investigated and experimented by the researchers.

The following pictures demonstrate the results:

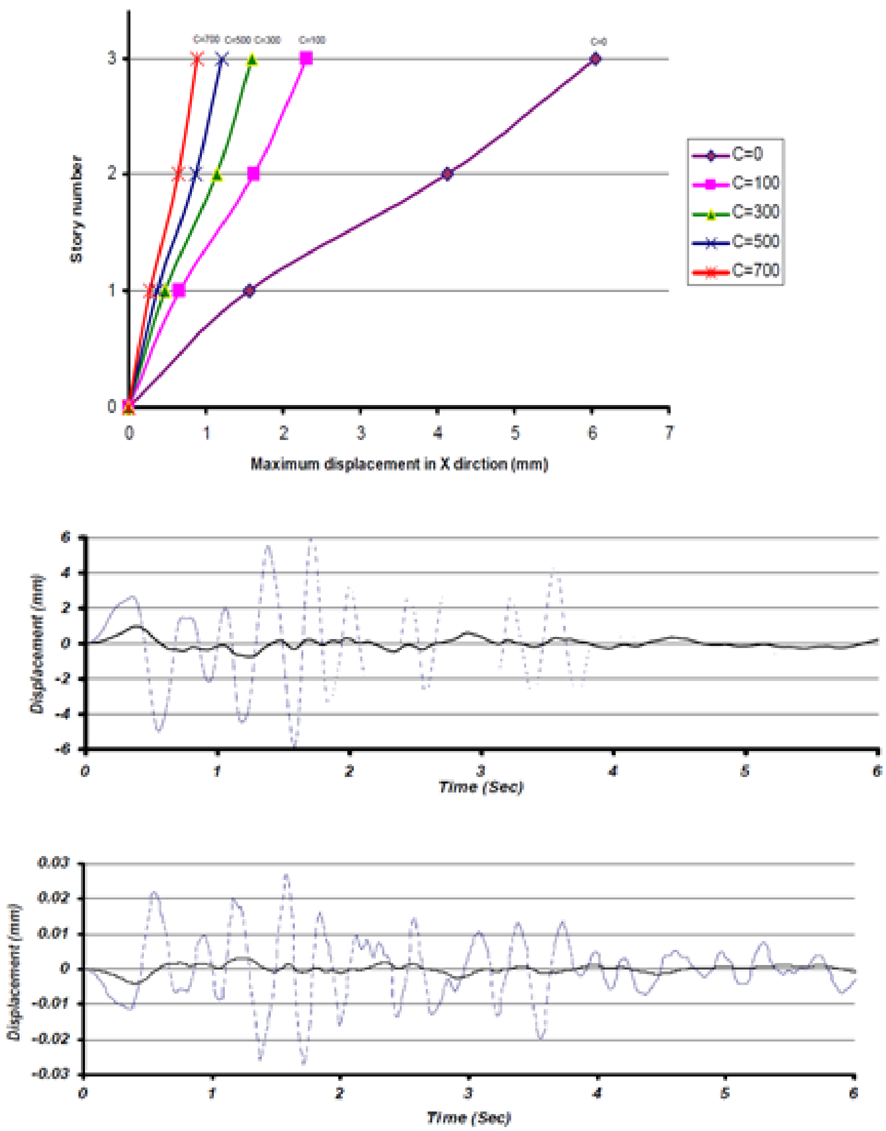

Figure 1: Reduction of deflection using viscous damper

Experimental investigations conducted by Constantinou & Symans in 1992 shows that using viscous dampers can significantly reduce seismic response of structures during earthquakes. As the rehabilitation objective defines the desirable damage limits, it can be generally expected that these devices are good candidates for projects having LS or IO performance levels. Viscous damper is one of these devices that is velocity dependent. Utilization of viscous dampers to reduce dynamic response of structures under seismic excitations by increasing the damping, has gained general popularity, because of the absence of activation threshold and also financial advantage. Another reason for usage growth of this type of damper in comparison to other technologies is due to their widespread usage during cold war and military programs to a large extent. Generally, energy dissipating devices, such as viscous dampers are placed diagonally in the structures. So, it's anticipated that adjoining columns in the frame, would experience larger axial forces. So, in this study, it's been tried to investigate the extent of this influence and the optimum placement of viscous dampers, through modeling and dynamic analyses.

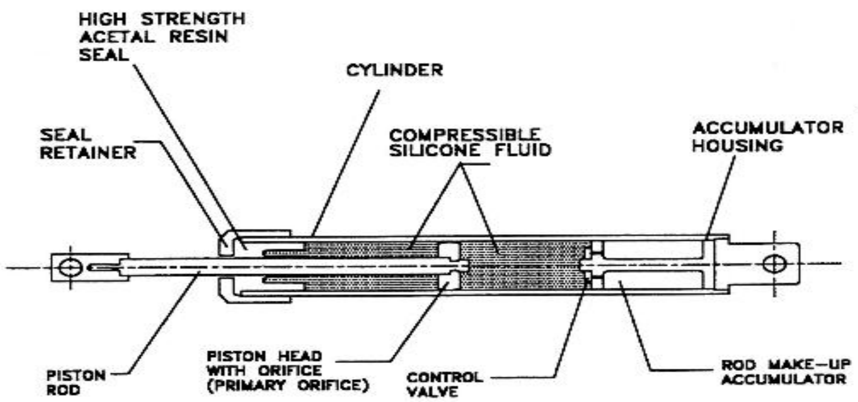

Figure 2: Details of a viscous damper

In the below picture, operating differences of linear viscous damper and two types of nonlinear viscous dampers are shown.

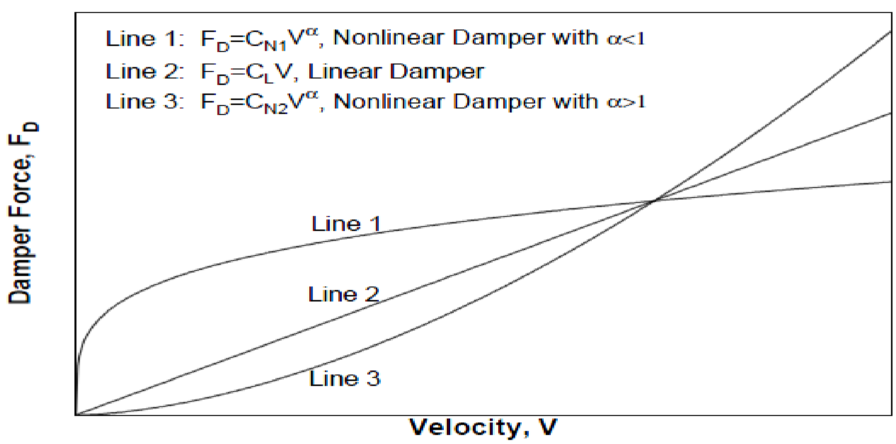

Figure 3: Velocity- developed force relationship in viscous damper (JehnShing)

The stiffness reduction along with using viscous dampers is of new approaches in rehabilitation of structures. In this approach, the base shear is reduced through reduction of stiffness and then the seismic demands are reduced mainly by viscous dampers. Researchers have used this approach limitedly. This approach hasn't been used for seismic rehabilitation of irregular structures. The seismic rehabilitation approaches have changed significantly during recent years (Mirzagoltabaar, 2012).

Functionality base of these dampers is to dissipate energy through high pressure passage of a fluid through orifices of the piston head during dynamic vibrations. High pressure passage of the fluid through piston orifices yields a pressure gradient on the two sides of the piston and therefore the damping force is produced. Hejazi *et al.*, (2009) studied a reinforced concrete structure equipped with viscous dampers. The studied frame was a single, 5 meters bay, 3 story frame. Each story as 3 meters high. As you can see in the above picture, deflections are reduced by 80%. A view of viscous damper is presented in the following picture (JehnShing).

Figure 4: Application of dampers in the structure

Then, the effective damping percentage is calculated. These dampers are successfully used in the structures. The following pictures demonstrate the application of these dampers (Douglas).
Lots of researches are also conducted on distribution of these dampers. MonirehBagheri and NosratollahFallah (2009) used genetic algorithm to determine the optimum formation of the dampers. They chose a frame equipped with dampers and studied it. Three time history cases were used in the research. The following pictures illustrate the results for uncontrolled and controlled cases.

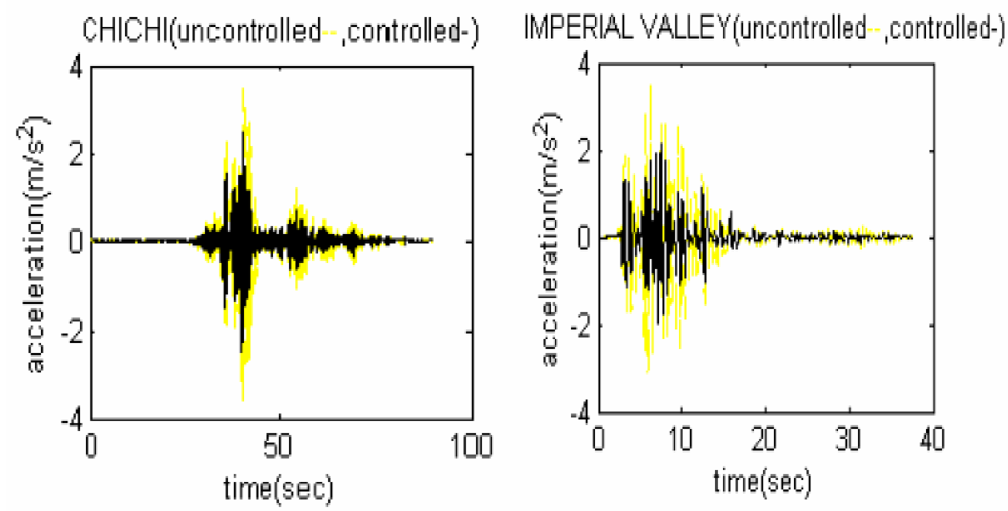

Figure 5: Reduction of structural acceleration using viscous dampers

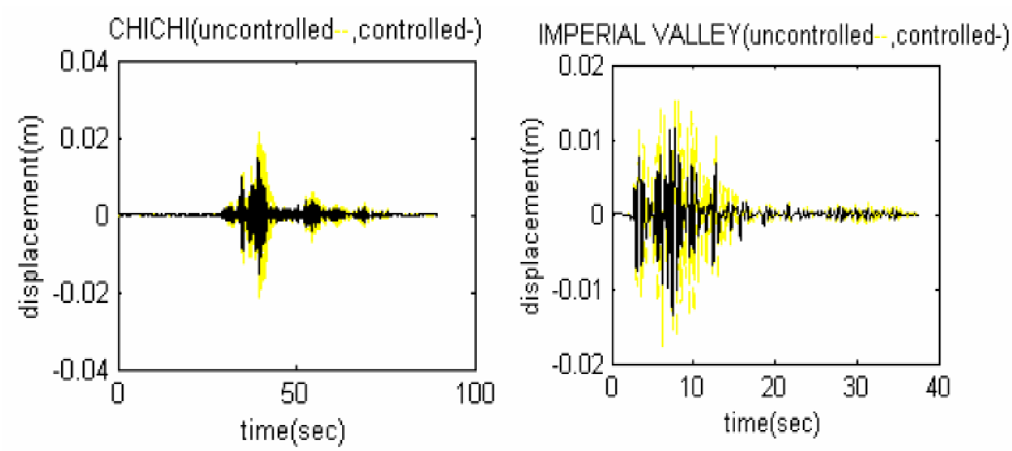

Figure 6: Reduction of structural displacement using viscous dampers

Dethariya *et al.*, (2011) conducted researches on seismic response of structures with and without dampers. Story drifts are presented in the following picture.
The research resulted that maximum story drifts were reduced from 3.187% to 1.19%. This showed a great advantage compared to rehabilitation using steel braces.
In the most rehabilitation cases with dampers, nonlinear time history analysis was used. Another nonlinear method that's been noticed in recent years is called "pushover analysis". This method is one of the best in seismic rehabilitation, due to its capability in illustration of realistic nonlinear behavior of the structure. Structural performance level is the base of this method. After establishment of the bilinear model of structural behavior, one can calculate the response modification factor, and this can be considered as another advantage of this method. Unfortunately, very few researches are conducted on nonlinear static analysis of the buildings equipped with dampers.

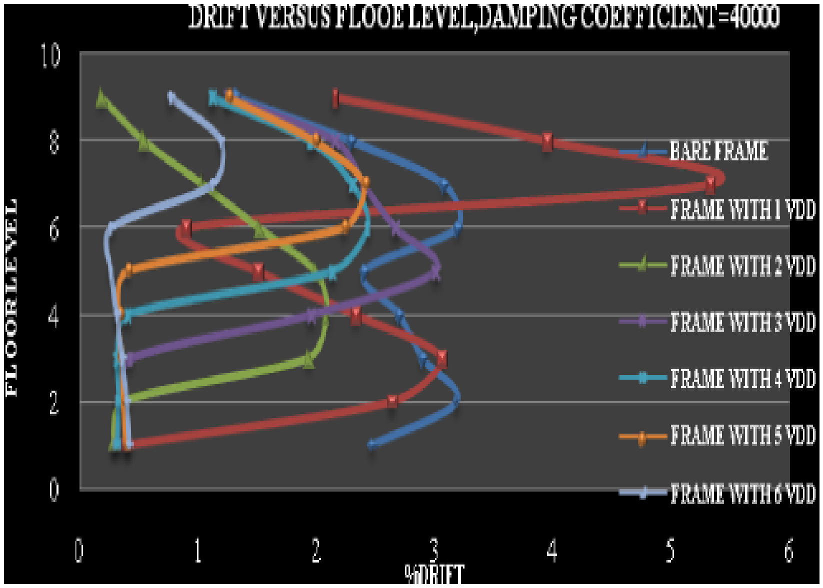

Figure 7: Story drift reduction due to viscous damper

RESULTS AND DISCUSSION

Research Finding

The proposed equation for viscous damper is presented below: (ASCE 41-06) (4)

$F = C_0 \left|\dot{D}\right|^{\alpha} \operatorname{sgn}(\dot{D})$ (Eq. 11-4)

In the above equation:

C_0 : damping coefficient of the damper

α : velocity exponent of the damper

$\dot{D}$: relative velocity of the two damper ends

sgn : sign function

The following picture demonstrates the relationship between velocity and force of the damper for exponents, $\alpha = 1$, $\alpha < 1$ and $\alpha > 1$. (9)

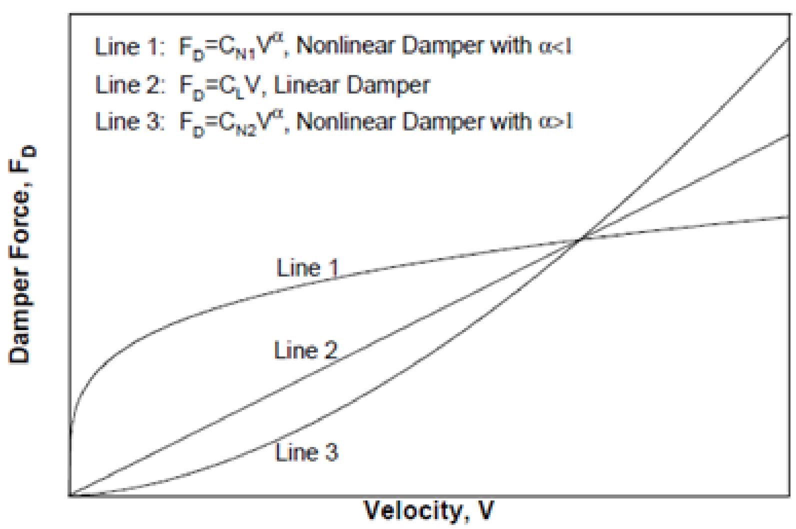

Figure 8: Viscous damper's force-velocity relationship for different velocity exponents

A damper with $\alpha = 1$ is called a linear viscous damper, which is also used in this research.

Modeling of Linear Viscous Damperinsap2000 using nonlinear pushover Analysis

As we know, the basic function of structural dynamics is as follows:

$$m\ddot{u} + C\dot{u} + Ku = F(t) \qquad \text{(Eq. 12-4)}$$

In the above equation:

m :structural mass matrix

C :structural damping matrix

K :structural stiffness matrix

$F(t)$: external applied force (may be seismic force)

As we discussed in the previous section, viscous damper is a velocity dependent damper. In static analysis –whether linear or nonlinear-, only structural stiffness effects the solution, so direct modeling of velocity dependent dampers is impossible in static analysis. However, based on ASCE 41-06 this type of damper may be used in nonlinear static analysis, if the target displacement of the structure is reduced. This reduction is applied through available equations presented in this provision. According to this provision, damping lowers the spectral acceleration and consequently the target displacement of the structure.

The equation used for calculation of target displacement is as follows:

$$\delta_t = C_0 \; C_1 \; C_2 \; Sa \; \frac{Te^2}{4\pi^2} g \qquad \text{(Eq. 13-4)}$$

Sa in above equation is spectral acceleration, that is generally in the form of the following picture:

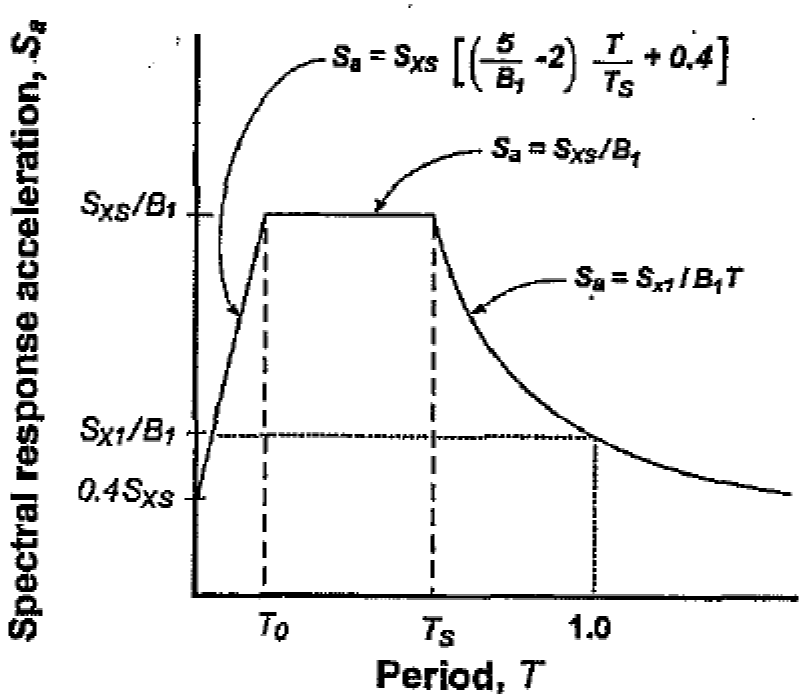

Figure 9: Period-spectral acceleration relationship in ASCE 41-06 provision

As previously mentioned, the parameters in the above curve are extracted from tables and maps provided for different states of the US. However, using these maps for the construction site (Tabriz) would be inappropriate. So, curves and equations presented in 3rd revision of Iraninan 2800 Standard were used to calculate the site spectral acceleration and parameters T_0, Ts, Sx_1, and Sx_5 were extracted from those curves.

This process is used in calculation of target displacement of the desired structures. To model the viscous damper, spectral acceleration of the structure in case of viscous damper utilization should be determined. All the structures have a period more than 0.5 seconds (Ts), so, the spectral acceleration of the structures is in the third part of these curves. As it can be seen from the above curve, the equation for this part is as the following:

$$Sa = \frac{Sx_1}{B_1 T} \qquad \text{(Eq. 14-4)}$$

Viscous dampers do not change the period and frequency of the structures (4).
To calculate the Sa based on 2800 Standard, we should perform as follows:

$$B = (S+1)\left(\frac{Ts}{T}\right)^{\frac{2}{3}} \qquad T \geq T_S = 0.5$$

Type II soil : $S = 1.5 \quad Ts = 0.5$ (Eq. 15-4)

$$B = 2.5\left(\frac{0.5}{T}\right)^{\frac{2}{3}}$$

$$Sa = A \cdot B = 0.35 \times 2.5\left(\frac{0.5}{T}\right)^{\frac{2}{3}}$$

By comparison of the I and II formulas, it can be realized that to consider the B_1 factor, presented in ASCE 41-06 provision, in the spectrum presented in 2800 Standard, spectral acceleration calculated based on 2800 Standard (Sa) should be divided by B_1.

Calculation of B_1: The provided formula in ASCE 41-06 provision for calculation of β_1 is as follows:

$$B_1 = 4/[5.6 - Ln(100\beta)] \qquad \text{(Eq. 16-4)}$$

where β is the effective viscous damping ratio.

To calculate β, section 9 of the ASCE 41-06 provision is used. Simplified equation for calculation of C (damping coefficient of dampers) for linear viscous damper is presented below:

$$\beta_{eff} = \beta + \frac{T\sum C_j \cos^2\theta_j \varphi_{rj}^2}{4\pi\sum\left(\frac{w_i}{g}\right)\varphi_i^2} \qquad \text{(Eq. 17-4)}$$

In the above equation:

β : intrinsic damping of the structure assumed as 5%

T : period of the first mode of the structure

C_j : damping coefficient of the j-th viscous damper

w_i : weight of the i-th story

φ_{rj} : horizontal relative displacement of the j-th damper in the first mode

φ_i : displacement at the i-th story level in the first mode

θ_j : angle of damper placement as illustrated in the following picture (9)

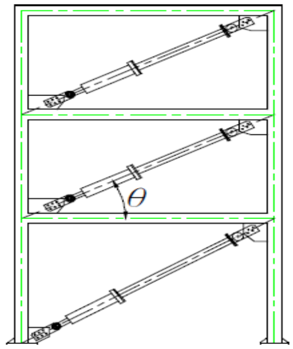

Figure 10: Angle of damper placement

First, the required β for rehabilitation is calculated. Our rehabilitation goal is to prevent all the beam and column members from overpassing the Life Safety (LS) level.
For example, calculated target displacement for the 12 story structure is equal to 71cm. Now, to prevent the plastic hinges from overpassing the Life Safety level, the target displacement should be reduced to a definite value using viscous dampers. As it can be seen, none of the frame members overpassed the Life Safety level in the 7th step of the pushover analysis.

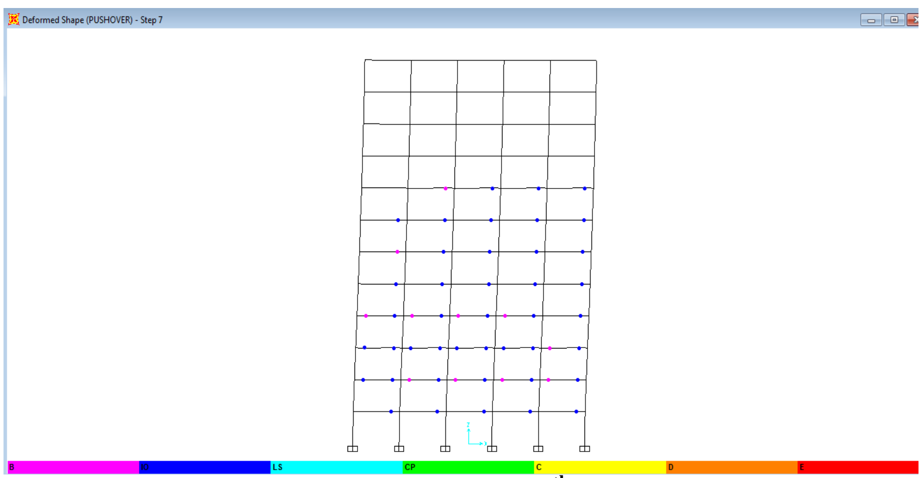

Figure 11: Condition of the plastic hinges in 7th step of the pushover analysis

Now, the current step's corresponding displacement is extracted from pushover tables, which is equal to 43.72cm in this example. Therefore, the target displacement should be reduced to this value using viscous dampers. So, B_1 is equal to:

$$B_1 = \frac{71}{43.72} = 1.63$$

By simplifying the equations used for calculation of the target displacement and spectral acceleration, for nonlinear pushover analysis using viscous dampers, we have:

$$\delta_t = C_0 \ C_1 \ C_2 \ \frac{Sa}{B_1} \frac{Te^2}{4\pi} \ g \qquad \text{(Eq. 18-4)}$$

By substituting the 1.63 value, target displacement of 43.72cm is achieved.
Now β_{eff} is calculated. To calculate the β_{eff}, ASCE 41-06 provision has proposed the following equation:

$$\beta = \beta_{eff} = 4/[5.6 - Ln(100B_1)]$$
(Eq. 19-4)
$$\Rightarrow \beta_{eff} = 4/[5.6 - Ln(100\times 1.63)] \Rightarrow \beta_{eff} = 24\%$$

5% of the calculated 24% damping is due to intrinsic structural damping, and the other 19% should be provided using viscous dampers. In designing and practical view, damping percentage is not of importance and the damping coefficient of the viscous damper (C) is of significance. As previously mentioned, the following relationship stands between β_{eff} and C_j:

$$\beta_{eff} = \beta + \frac{T\sum C_j \cos^2\theta_j \varphi_{rj}^2}{4\pi\sum m_i\ \varphi_i^2} \qquad \text{(Eq. 20-4)}$$

Now we must define the number of viscous dampers. The following arrangement of viscous dampers is as follows:

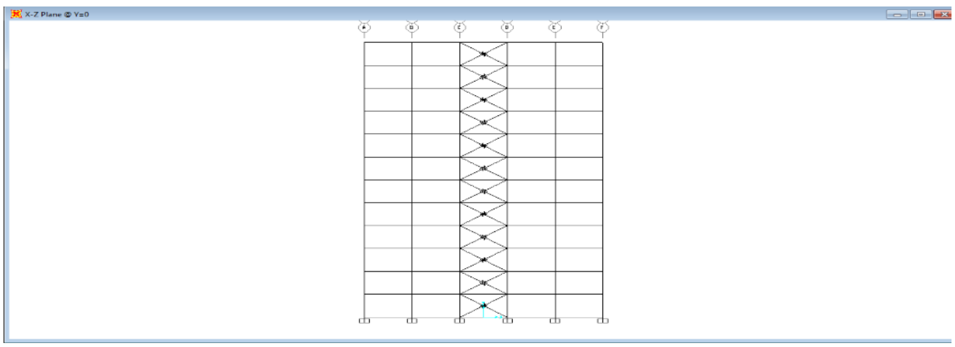

Figure 12: Arrangement of viscous dampers in the frames

Mass matrix is extracted from Sap2000:
$$m = <6120\ \ 6091\ \ 6082\ \ 6076\ \ 6066\ \ 6062\ \ 6048\ \ 6038\ \ 6017\ \ 5989\ \ 5955\ \ 5857>T$$
Then, the normalized eigenvector by the roof value is calculated:
$$\varphi = <0.048\ \ 0.13\ \ 0.23\ \ 0.32\ \ 0.42\ \ 0.52\ \ 0.61\ \ 0.7\ \ 0.78\ \ 0.87\ \ 0.94\ \ 1>T$$
Story drifts matrix of the first mode (i.e. φ_{rj}) is then calculated:
$$\varphi_{rj} = <0.048\ \ 0.084\ \ 0.097\ \ 0.095\ \ 0.098\ \ 0.095\ \ 0.093\ \ 0.088\ \ 0.085\ \ 0.084\ \ 0.07\ \ 0.06>T$$
The placement angle of the dampers is determined next:
$$\theta = tg^{-1}\frac{3.2}{5} = 32.62^\circ \qquad \text{(Eq. 21-4)}$$
The calculated values are substituted in the corresponding formula:
$$24 = 5 + \frac{2.53C_j(0.048^2 + 0.084^2 + 0.097^2 + ... + 0.06^2)}{4\pi(6120\times 0.048^2 + ... + 5857\times 1^2)}$$

$$19 = \frac{1.8C_j(0.0861)}{4\pi(28331.46)} \Rightarrow C_j = 436472\, ton\cdot s/m$$

The calculated C_j above, is the damping coefficient of all the needed dampers. The damping coefficient should be distributed among all the dampers in the structure, and the simplest method is to distribute it uniformly. We have 24 viscous dampers, so damping coefficient of each one is equal to:

$$C = \frac{C_j}{24} = 18186\, ton\cdot s/m$$

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The calculated damping coefficient (C), is the damping coefficient of each damper, which is required for the structure to gain its desired performance level in nonlinear pushover analysis. This process should be repeated for a nonlinear pushover analysis with the load pattern of $Q_G = 0.9DL$, for each structure, and the most critical result is chosen as the final result.
After doing all the aforementioned steps, the following results are obtained:

Table 1: Target displacement of the structure with and without damper

Number of Stories	$\delta_t (cm)$	$\delta'_t (cm)$	β_{eff} %	$C_j (ton \cdot s/m)$
3	30	12	55	2510
6	45	24.4	31	18080
9	54	35.5	20	1360
12	71	48.43	18	1247
15	83	60.5	15	1020

Post-rehabilitation pushover of the structures is as follows:

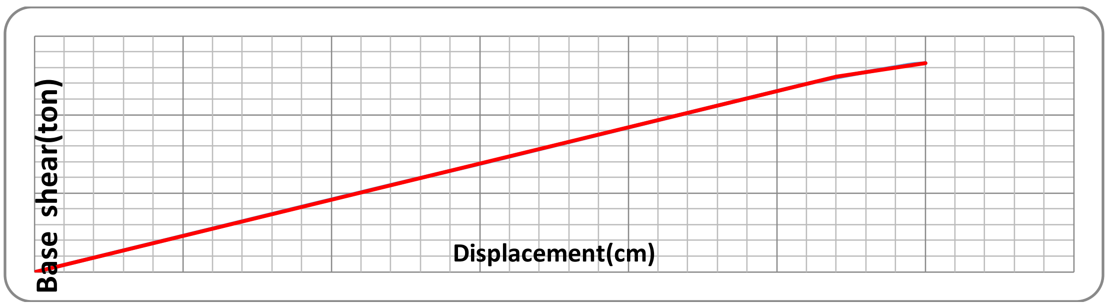

Figure 13: Pushover of the 3 story frame after rehabilitation under gravity load of QG = 1.1(DL+LL)

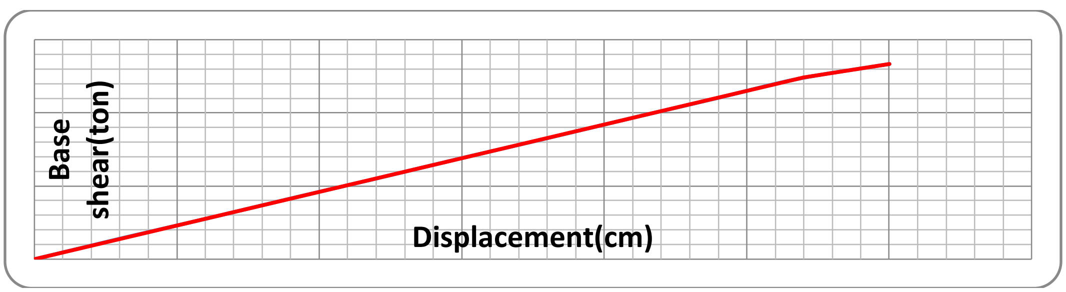

Figure 14: Pushover of the 3 story frame after rehabilitation under gravity load of QG = 0.9DL

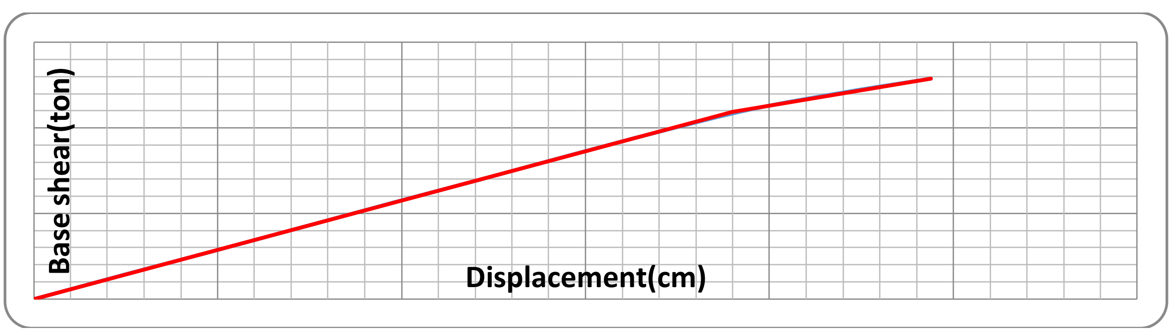

Figure 15: Pushover of the 6 story frame after rehabilitation under gravity load of QG = 1.1(DL+LL)

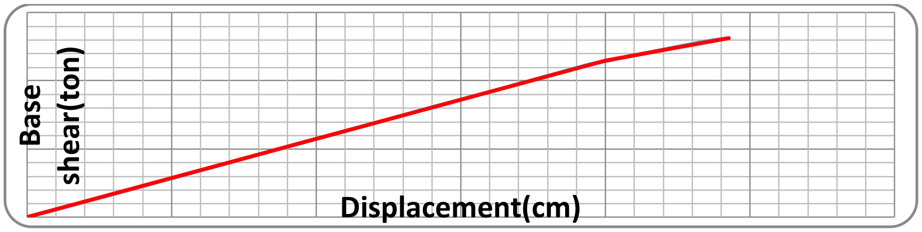

Figure 16: Pushover of the 6 story frame after rehabilitation under gravity load of QG = 0.9DL

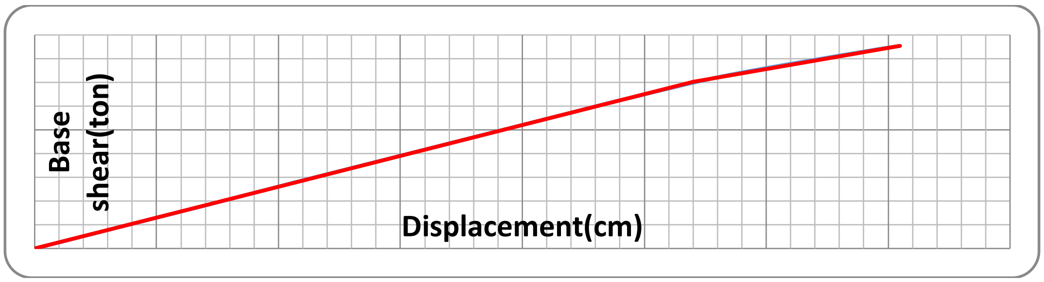

Figure 17: Pushover of the 9 story frame after rehabilitation under gravity load of QG = 1.1(DL+LL)

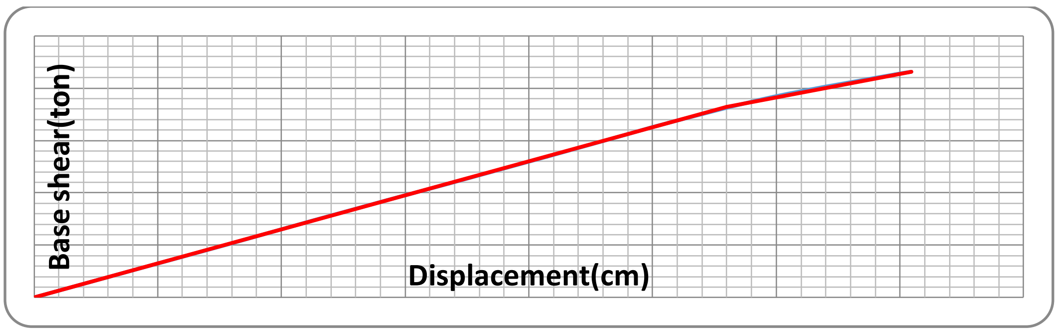

Figure 18: Pushover of the 9 story frame after rehabilitation under gravity load of QG = 0.9DL

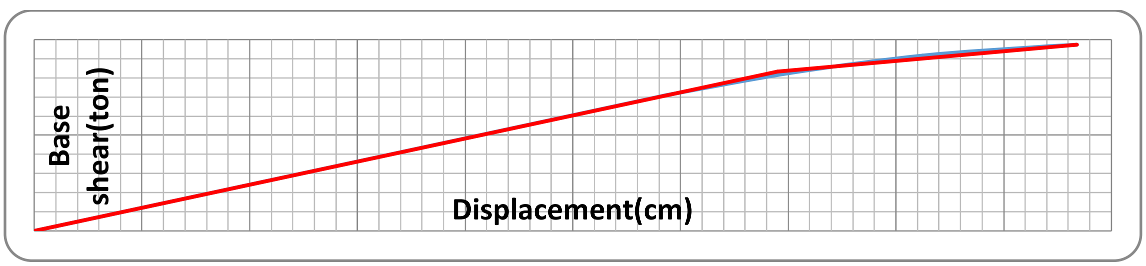

Figure 19: Pushover of the 12 story frame after rehabilitation under gravity load of QG = 1.1(DL+LL)

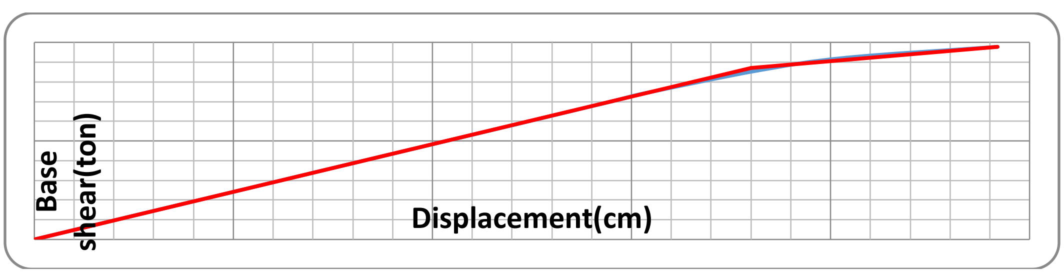

Figure 20: Pushover of the 12 story frame after rehabilitation under gravity load of QG = 0.9DL

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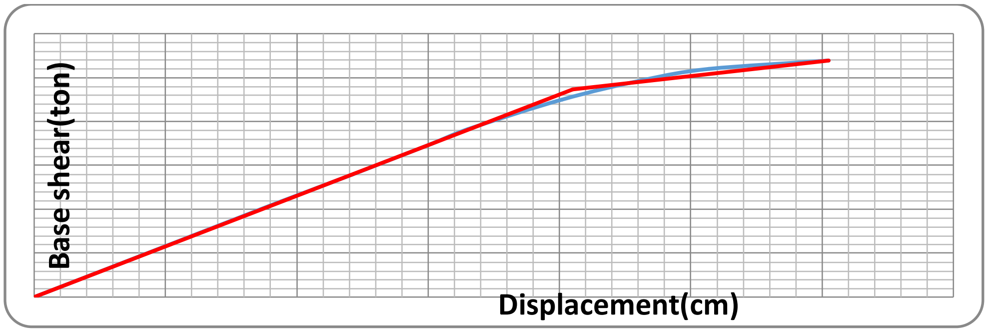

Figure 21: Pushover of the 15 story frame after rehabilitation under gravity load of QG = 1.1(DL+LL)

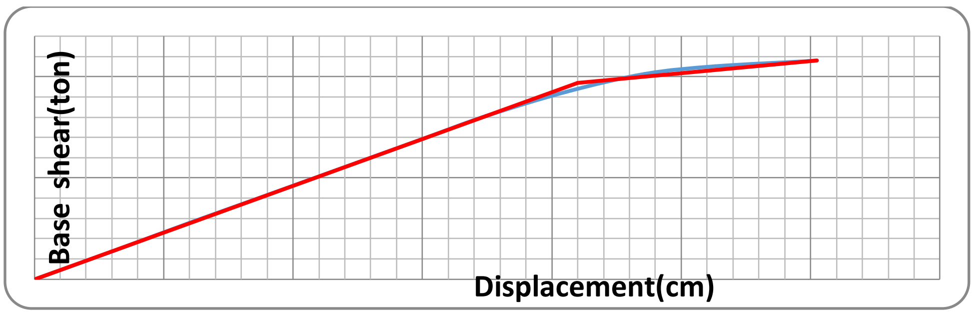

Figure 22: Pushover of the 15 story frame after rehabilitation under gravity load of QG = 0.9DL

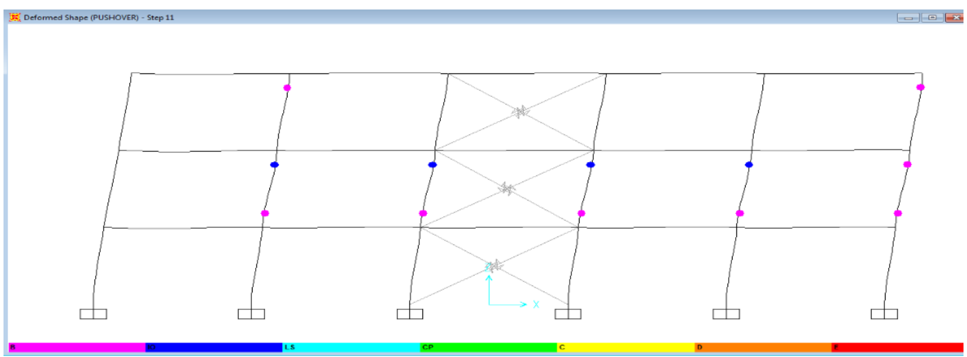

Figure 23: Plastic hinges condition of the 3 story structure after rehabilitation under gravity load of $Q_G = 1.1(DL + LL)$

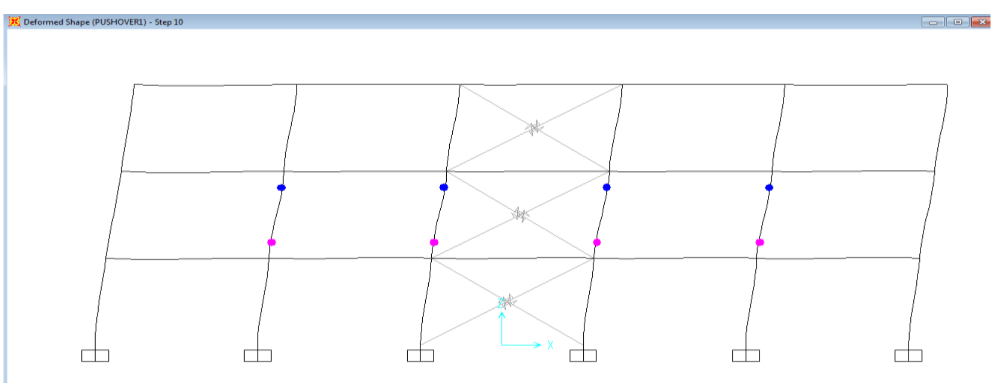

Figure 24: Plastic hinges condition of the 3 story structure after rehabilitation under gravity load of $Q_G = 0.9DL$

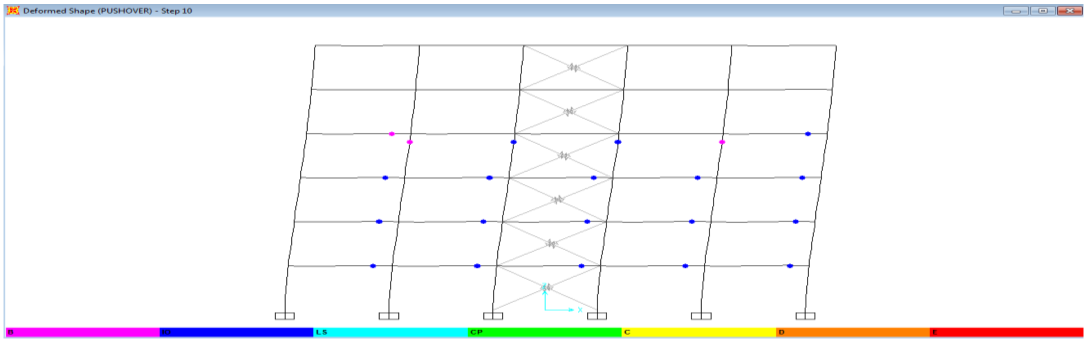

Figure 25: Plastic hinges condition of the 6 story structure after rehabilitation under gravity load of $Q_G = 1.1(DL + LL)$

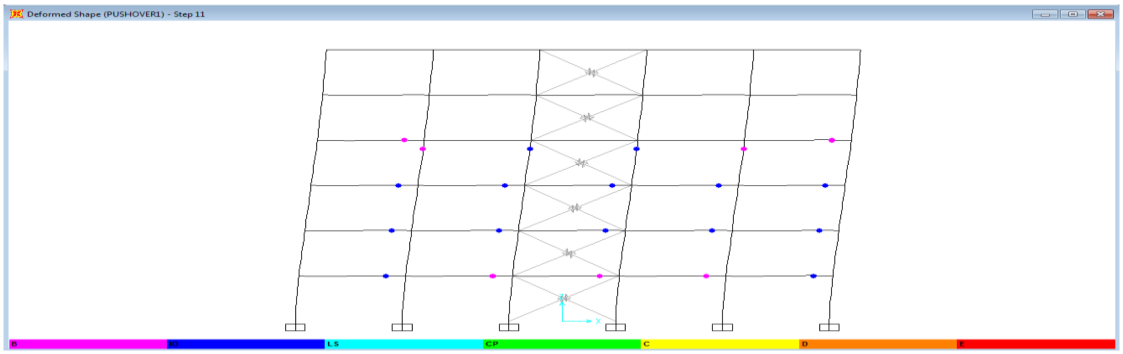

Figure 26: Plastic hinges condition of the 6 story structure after rehabilitation under gravity load of $Q_G = 0.9DL$

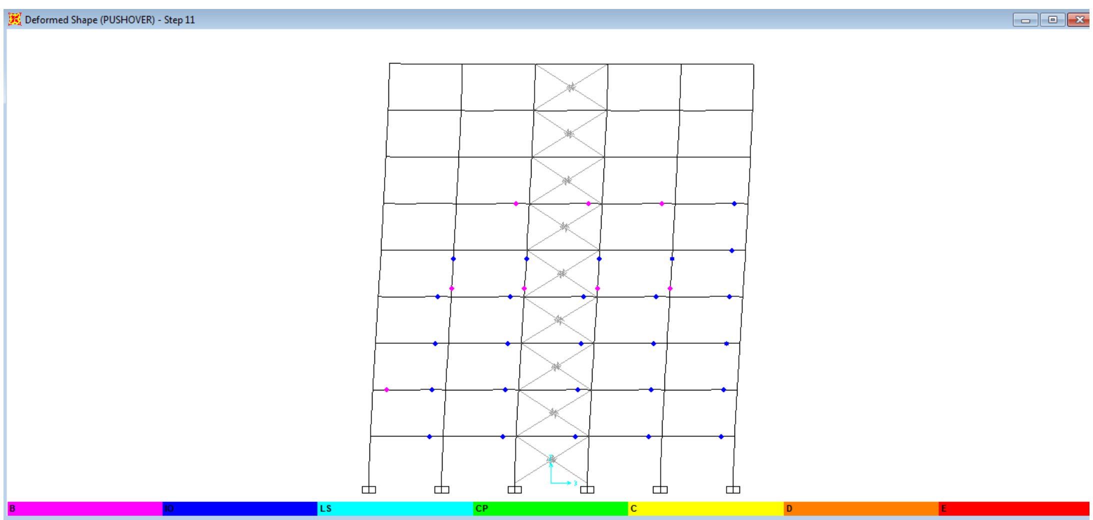

Figure 27: Plastic hinges condition of the 9 story structure after rehabilitation under gravity load of $Q_G = 1.1(DL + LL)$

Structural performance level after installation of the dampers for each structure is as follows:
In the above table (1), δ_t is the target displacement of the structure without damper, and δ_t' is the target displacement of the structure equipped with viscous damper. β_{eff} is the effective damping percentage of the structure resulted from the sum of structure's intrinsic damping and the damping provided by the

dampers. C_j is the damping coefficient of each damper, assuming that the dampers are installed in the middle bay in the form of X.

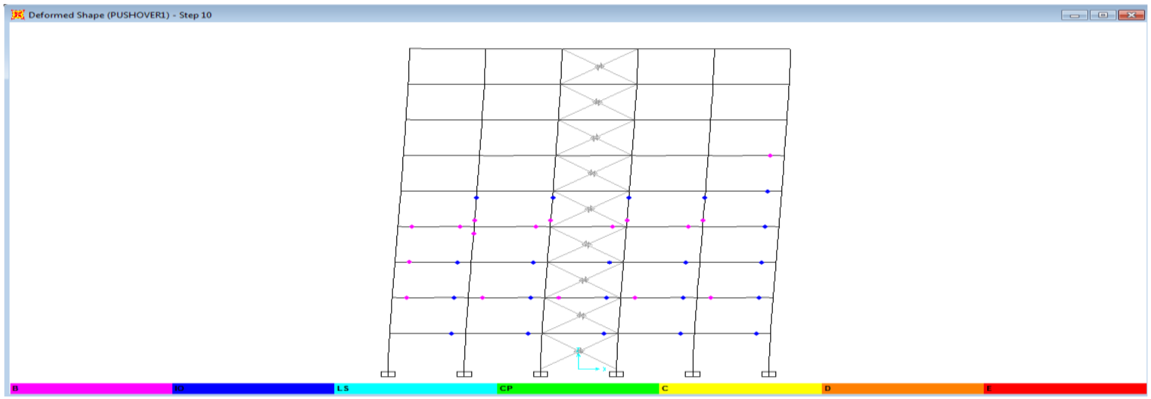

Figure 28: Plastic hinges condition of the 9 story structure after rehabilitation under gravity load of $Q_G = 0.9DL$

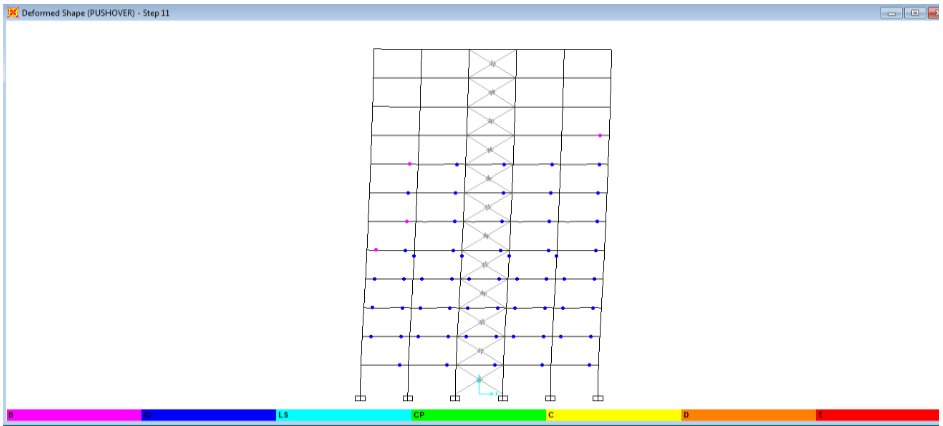

Figure 29: Plastic hinges condition of the 12 story structure after rehabilitation under gravity load of $Q_G = 1.1(DL + LL)$

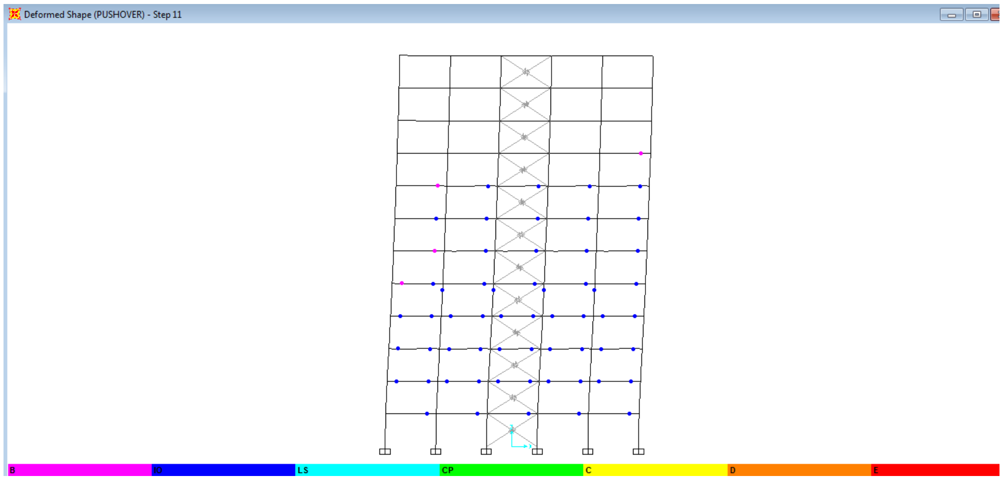

Figure 30: Plastic hinges condition of the 12 story structure after rehabilitation under gravity load of $Q_G = 0.9DL$

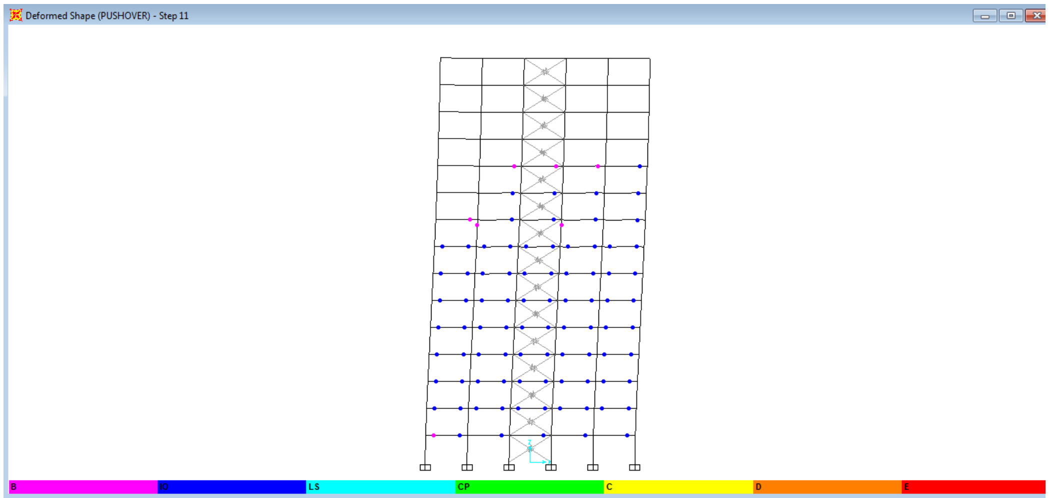

Figure 31: Plastic hinges condition of the 15 story structure after rehabilitation under gravity load of $Q_G = 1.1(DL + LL)$

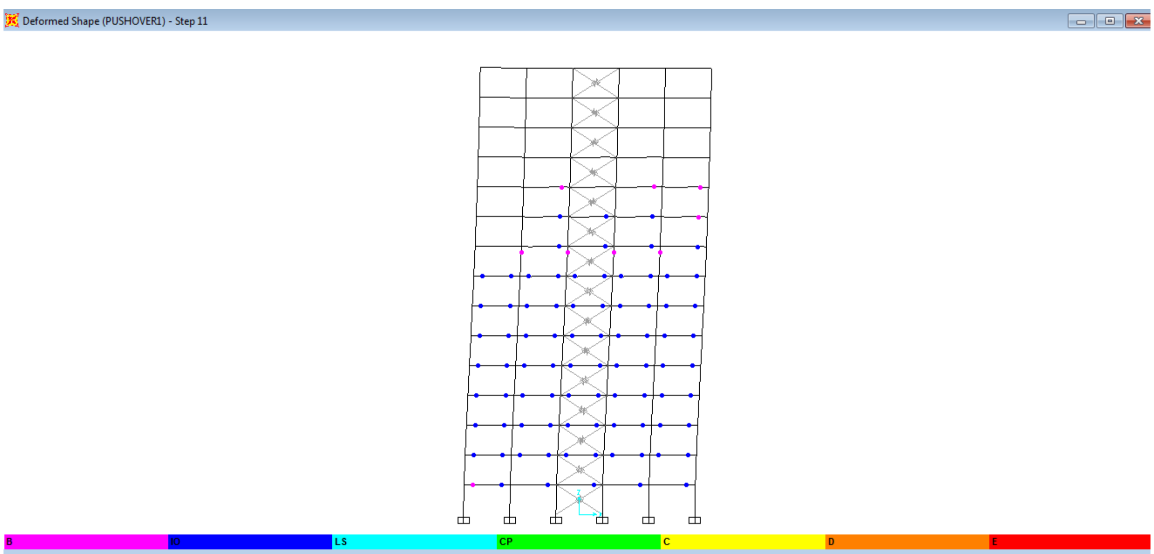

Figure 32: Plastic hinges condition of the 15 story structure after rehabilitation under gravity load of $Q_G = 0.9DL$

It should be noted that, as previously mentioned, presence of viscous dampers doesn't have any direct influence on nonlinear static analysis, and the dampers illustrated in the above pictures are just defined to give a sense of dampers arrangement in the structure.

Conclusion

As shown, the higher the height of the structure, the less critical the plastic hinges formed in the structural members. This could be due to the fact that with increase in the height, the degree of indeterminacy increases, and the plastic hinges will distribute in a larger number of members, rather than being concentrated in a specific number of members, leading to less critical plastic hinges. Less effective damping percentage is required for rehabilitation of taller buildings. This research was conducted on intermediate moment frame. This research may be repeated on structures with different systems (pinned braced frame and …), and also on frames with different bay widths, to lead to more general and reliable results. Also, the research may be redone using non-automatic hinges defined by the user, to lead to more precise results.

Maximum axial column force in a system with inclined damper may be several times larger than the axial column force in a system with horizontal damper with the same damping ratio, in a harmonic loading. Amplification factor increases with the increase of frequency ratio and damping ratio. Although the phase degree between the total axial force and the elastic component is important, but these two are not completely out of phase. In fact, maximum column force happens somewhere between the maximum elastic force and the maximum damping force. Consideration of phase delay can be useful for the proper design of the column. The calculated results for the chosen earthquake record, confirms the findings from the simple harmonic loading. Specially, it should that the amplification factor for the systems having larger period, is higher and increases by the increase in damping ratio. It seems that due to deteriorating effect of inclined damper on exacerbation of the column forces, placing the dampers horizontally would be more desirable.

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