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Seismic Response Control of Buildings by Perimeter Walls Functioning as Tuned Mass Dampers (TMDs)

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Abstract. In this study, a new and innovative system of perimeter walls is presented in which perimeter walls of buildings, in addition to separating inner and outer space, function as Tuned Mass Dampers (TMDs), and considerably reduce the structural responses to seismic excitations. Furthermore, compared to conventional TMDs, this system occupies much less space and also does not impose more gravitational forces on the structure. Performance of perimeter walls as TMDs was modelled by OpenSees and MATLAB Software by nonlinear dynamic time history analysis and the mass and stiffness of the damper springs were determined. Subsequently, the impact of damper location in the structure was further investigated.

Keywords: Tuned Mass Damper (TMD), perimeter walls, nonlinear dynamic time history analysis, OpenSees

1. INTRODUCTION

Application of a TMD in a building is a way to reduce the building's response to lateral forces such as wind and earthquake. TMD system is a passive damper which is applied in many tall structures and bridges. This system can reduce the building's response when it is subjected to seismic vibrations. Also, TMD system consists of several main components including mass, spring and damper. Performance of these components is mainly based on the reduction of the vibrational energy in the structure. This process will often have better efficiency when the frequency of TMD equals the frequency of the first mode of the structure. Finally, when the frequency of the damper is excited through the forces imposed on the structure, a movement will be formed in the opposite phase of the structure's movement and energy will be dissipated through the inertial force that the damper imposes on the structure. Thus, considering the points mentioned above, estimating the amounts of mass, stiffness, damping and location of the damper is of considerable importance. The main concept of TMDs can be found in the field of dynamic absorbers which was reviewed by Ferbam (1990). Ferbam, by studying a small mass that was connected to the main mass by a spring, proved that the main mass can be made quite persistent in case the frequency of the absorber is equal to the input frequency (4). Bishab & Velborne (1952) considered system damping in the analysis of dynamic vibration absorbers to be developed (5). Den Hortog (1956) first reviewed the theory of undamped & damped dynamic vibration absorbers in the absence of system damping, which led to the development of the basic principles of his work and a way for proper determination of the absorber parameters connected to the system (6). Leila Etemad Saeid, Seyed Ehsan Naraghi & Mehdi Zahraei (2008), using the neural networks, examined optimization parameters of Multiple Tuned Mass Dampers (MTMDs) and concluded that estimation of the MTMD parameters by this method will reduce the structural response (1). Hashem Shariatmadar & Mohammad Sadegh Akbarzadeh (2010) conducted some studies on the locating of one or several dampers in the

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upper stories of the building and concluded that locating TMD in the upper stories of the roof structure will not be effective in relative reduction of the drifts in the upper stories but will instead significantly reduce the relative drifts in the middle stories (2). Ahmad Shoshtari & Hamid Afzali (2008), considering the fact that the drift of TMD might affect the structural response, examined the effect of the drift of TMDs on the seismic response of RC buildings and concluded that in average earthquakes, if TMD is installed on the roof, the structural response will be reduced (3). Asgoba & Marano (2010) reviewed the performance of TMD in the structures with nonlinear behavior and concluded that application of TMD in nonlinear systems reduces the plastic energy dissipation (PED) and ultimately the structural response (9). Morizio et al. (2012) examined the dynamic behavior and the TMD seismic effects with large mass ratio (7). Raki et al. (2012) reviewed the effects of locating several TMDs in the structure and reached the conclusion that this method will improve the structural behavior.

2. THEORY REVIEW

The response of a single-degree-of-freedom (SDOF) structural system can be considered to be subjected to a vibratory force f(t) as shown in fig (1). If carefully considered, for TMD structural system the movement equations are based on relations (1) & (2):

$$M\ddot{y}_1(t) + \mathrm{C}\dot{y}_1(\mathrm{t}) + \mathrm{K}y_1(\mathrm{t}) = \mathrm{c}\dot{z}\,(t) + kz(t) + \mathrm{f(t)} \qquad (1)$$

$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) = -m\ddot{y}_1(t) + g(t) \qquad (2)$$

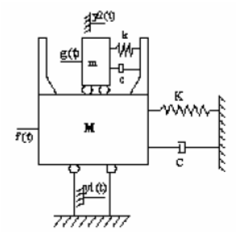


Figure 1. TMD system with the structure.

where $y_1(t)$ is the ratio of structural system displacement to the structural base and z(t) is the ratio of added mass relative displacement to it. The damping and stiffness coefficients are k & c for the added mass and by k & c for the structural system. The external force on the structure is shown by f(t) while g(t) for wind excitation equals zero:

$$(M + m)\ddot{y}_1(t) + \mathrm{C}\dot{y}_1(\mathrm{t}) + \mathrm{K}y_1(\mathrm{t}) = \mathrm{f(t)} + g(t) - m\ddot{z}(t) \qquad (3)$$

In this case, the net effect of added small mass (m) on the structure, aside from a slight decrease in natural frequency and a slight increase in external force from f(t) to f(t)+g(t), is addition of a force term $-m\ddot{z}(t)$ when f(t) is considered as a harmonic force or a sustained stochastic force.

3. UNDAMPED STRUCTURAL SYSTEM

One of the important advantages of the performance of TMD in reducing the structural seismic response can be obtained by **Den Hortog**'s review and basic development for the simple undamped structural system (c=0) when subjected to a sinusoidal excitation of frequency ω. In this method, the dynamic effect of a TMD is measured in comparison with the static deflection obtained from the maximum static load applied to the structure. For a sinusoidal excitation of frequency ω, static deflection is equal to $\mathrm{y_{st}} = \frac{\mathrm{p_0}}{\mathrm{k}}$ while dynamic amplification factor, namely R, for an undamped structural system, is obtained from the following equation:

$$R = \frac{y_{max}}{y_{st}}\sqrt{\frac{\left(\alpha^2-\beta^2\right)^2+\left(2\xi_a\alpha\beta\right)^2}{\left(\left(\alpha^2-\beta^2\right)\left(1-\beta^2\right)-\alpha^2\beta^2\mu\right)+\left(2\xi_a\alpha\beta\right)^2\left(1-\beta^2-\beta^2\mu\right)^2}} \quad (4)$$

where $\beta = \frac{\omega}{\omega_s}$ is the forcing frequency ratio, $\alpha = \frac{\omega_a}{\omega_s}$ the frequency ratio (natural frequencies), ${\omega_a}^2 = \frac{K}{M}$ the squared natural frequency of the damper, ${\omega_s}^2 = \frac{K}{M}$ the squared natural frequency of the structural system and $\xi_a = \frac{c}{c_c} = \frac{c}{2m\omega_a}$ the damping ratio of the damper. Amplification factor is a function of four main variables including: μ, ζa, α, β. Fig 2 shows diagram R which is a function of the frequency ratio for $\alpha = 1$ (tuned state), $\mu = 0.05$ and different values of the damping ratio of TMD, namely ζa.

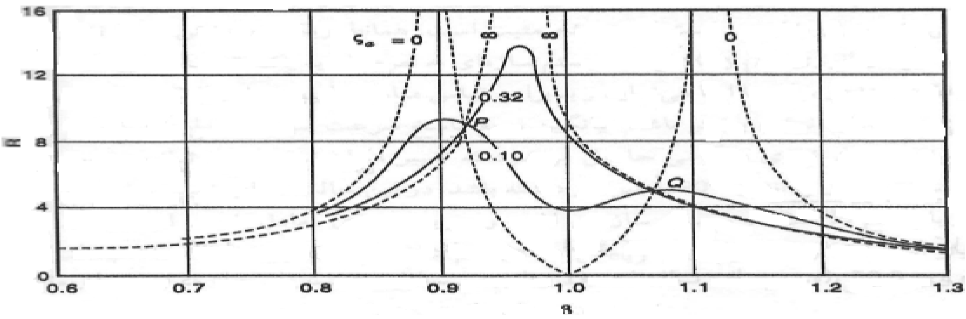


Figure 2. Amplification factor in terms of function β (μ= 0/05 α= 1).

4. DAMPED STRUCTURAL SYSTEM

It can be shown that equation 5, when the structure has damping, is also the case for R, while the unchangeable points of P and Q that were available for the undamped structure are no longer available here. Thus, in order to determine the optimal values of α and ζ_a numerical methods must be used. The methods proposed by Randall are in such a way that by minimizing the higher peak, from among the two peaks available in the amplification curve in Fig 2, α and ζ_a are optimized by numerical calculation methods. Optimal values of α & ζ_a for small values of ζ_s can also be empirically formulated. The results are as below:

$$\tilde{\zeta}_{opt} = \zeta_{opt} + \left[0.13+0.12\mu+0.4\mu^2\right]\zeta_s - \left[0.01+0.9\mu+3\mu^2\right]\zeta_s^2 \quad (5)$$

$$\tilde{\alpha}_{opt} = \alpha_{opt} - \left[0.241+1.7\mu-2.6\mu^2\right]\zeta_s - \left[1.0-1.9\mu+\mu^2\right]\zeta_s^2 \quad (6)$$

Where ζ_s is the damping ratio of the main mass. The allowable error limit related to the above equations has been obtained to be less than 1% for $0.03< \mu <0.4$ and $0.0 < \zeta <0.15$, which are proper practical limits. Another method of geometric location has also been proposed by Thompson for optimization of α & ζ_a for a damped structure; in this method, α is optimized by numerical methods and ζ_a can be determined analytically by having α. Also, a detailed analysis was carried out by Warburton in order to determine the optimal parameters of the damper for both harmonic and stochastic excitations, in which the stochastic excitation was applied to the structure as a force (like the wind) or as base acceleration (like the earthquake). Again, in this analysis the main structure was assumed to have low damping.

5. STRUCTURAL MODEL REVIEW

The reviewed structure was primarily modeled as 3D with 15×15 dimensions, 3 bays and 5 stories in ETABS Software. Then, the stiffness and mass of the structure were located in a 2D frame. As can be seen in the schematic view of Fig (5), the perimeter walls are considered as TMDs. Subsequently, the 2D model was developed in SAP2000 Software and then the main model was modelled in OpenSees and MATLAB Software. Finally, before starting the main analyses of the structure, the time period values of both 2D models in SAP2000 & OpenSees Software were compared and they were almost the same with a slight difference, which can be seen in table (1).

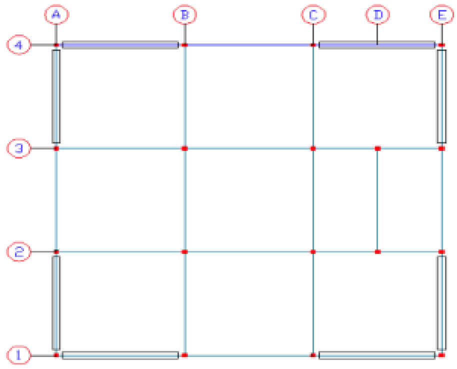


Figure 3. Location plan of the perimeter walls.

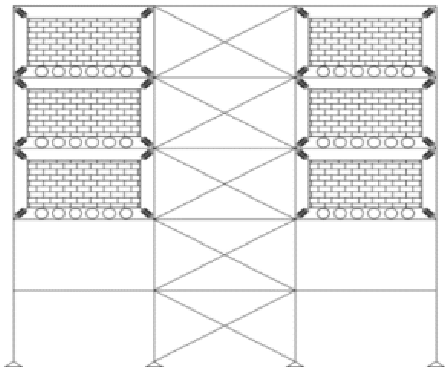


Figure 4. Schematic view of the perimeter walls.

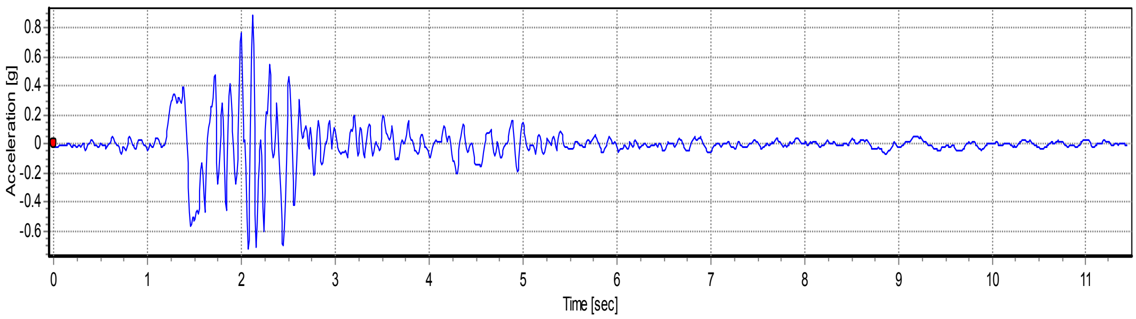


Figure 5. Naghan earthquake accelerograph.

Table 1. The frequency and time period values in the two SAP2000 & OpenSees software.

	Time period	Frequency
SAP2000	0.6123	1.63318
OpenSees	0.5975	1.67360

Then the nonlinear time history analysis was carried out on the main model without damper and the models with damper in the three Naghan, El Centro and Tabas earthquake records. Accelerographs of the aforementioned earthquakes have been depicted in figures 5 to 7:

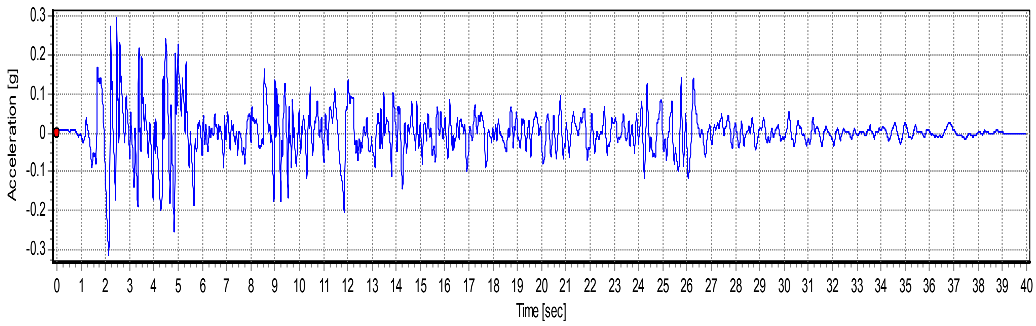


Figure 6. El Centro earthquake accelerograph.

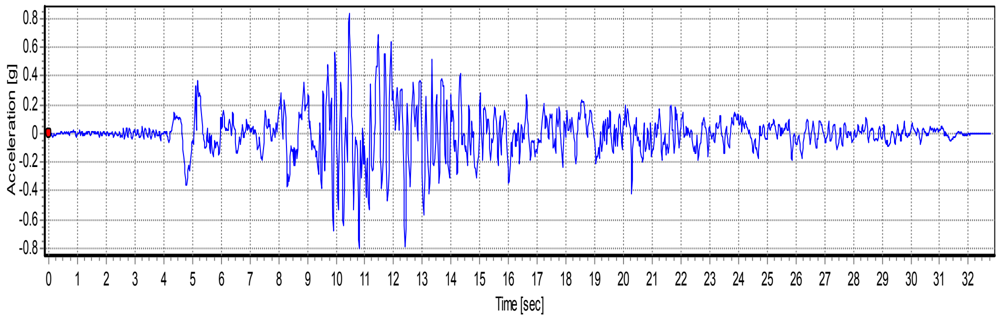


Figure 7. Tabas earthquake accelerograph.

For calculation of damper spring stiffness, first by considering damper mass values between 0.1 and 0.6% of the structure mass and solving $\mu = 0.1 \text{ to } 6 = \frac{m}{M}$ equation, the amount of damper mass was calculated; then by equalizing the damper frequency with the frequency of the first to sixth modes of the structure, the amount of damper spring stiffness was obtained with respect to the $w_d = \sqrt{\frac{k_d}{m_d}}$ equation. Next, due to the four springs available in four corners of perimeter walls, the amount of stiffness was divided by four and the stiffness of each spring was calculated. Then, with respect to the 3 available accelerographs which were equalized and 8 damper locations and 36 analyses for the masses between 0.1 and 0.6 and the frequencies of the first to sixth modes, the related structure was analyzed for about 864 times with damper and for 3 times without damper, which contained proper outputs. The results shown in what follows is for when damper mass equals 0.6 of the total structure mass and damper frequency is tuned on the frequency of the first mode. Figures 9 & 10 show a step of OpenSees Software which is a view of the damper location.

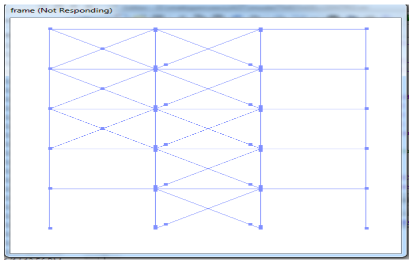


Figure 8. The damper view in the 3rd to 5th stories.

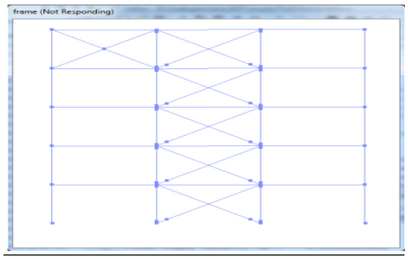


Figure 9. The damper view in the 5th story.

6. REDUCTION RATE OF STORY DRIFT CHANGES BY USING PERIMETER WALLS AS TMDS

After 867 analyses on the reviewed structure, the given results of the studies on the story drift in diagrams 1 to 3 showed that story drift reduces largely depending on the type of earthquake and its location. In case one TMD is used, the best reduction rate of the structure drift is when the damper is installed on the 5th story of the structure. For **El Centro** earthquake, the drift reduction rate is **35%** and for **Naghan** earthquake, it is **25%**. Also, for **Tabas** earthquake, a great dispersion can be seen in story drift, which shows the effect of the type of earthquake on the performance of damper.

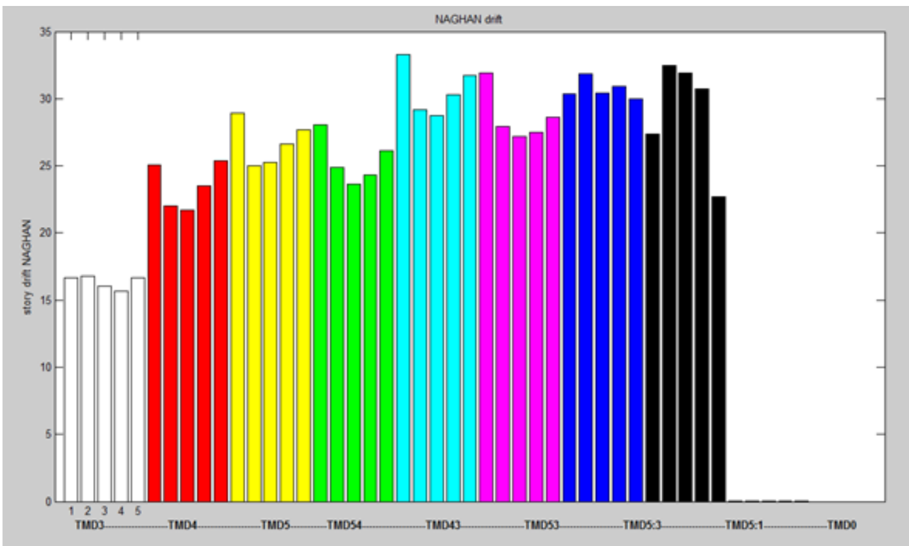


Diagram 1. Reduction rate of structure drift in the stories in Naghan earthquake.

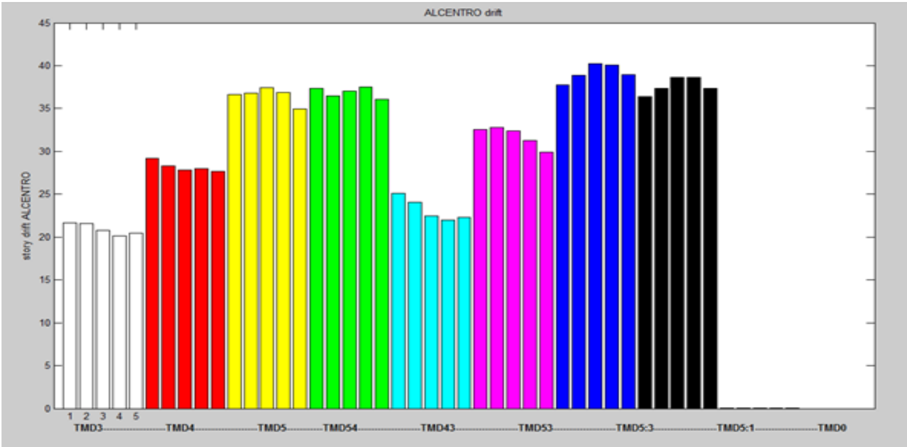
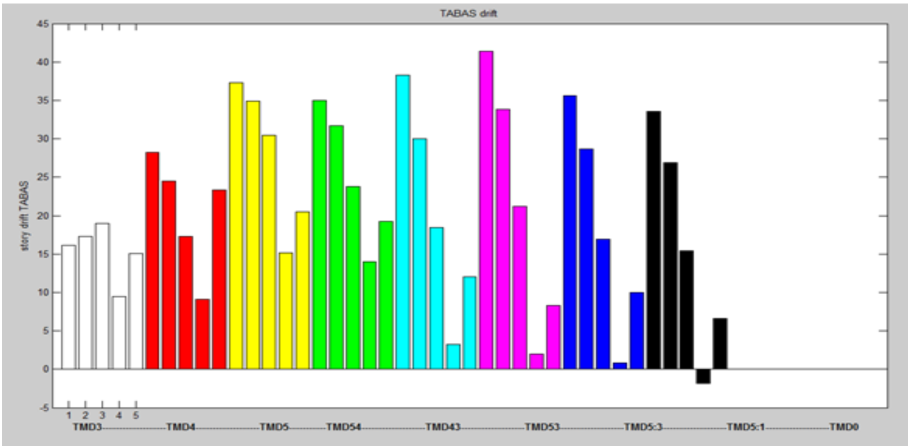


Diagram 2. Reduction rate of structure drift in the stories in El Centro earthquake.



Diagrams 3. Reduction rate of structure drift in the stories in Tabas earthquake.

As you can see, in Tabas earthquake not only structure drift reduction is not regular but also in some spots increase in drifts was observed as well. However, the above results are the case when damper mass is 0.6 of the structure mass and damper frequency is equal to the frequency of the first mode.

7. BASE SHEAR REDUCTION VALUES AND BASE SHEAR REDUCTION RATE IN THE REVIEWED STRUCTURE

It can be seen in tables 2 to 4 that in Naghan & El Centro earthquakes, base shear values have decreased in all damper location states, but in Tabas earthquake not only there has been no reduction but also an increase in base shear is observed as well which again indicates the improper performance of TMD in Tabas earthquake.

Table 2. Base shear values with reduction rate due to damper location in the system for Naqhan earthquake.

	Base shear values with reduction rate due to damper location in the system for Naqhan earthquake								
TMD	0	3	4	5	54	43	53	543	54321
Base shear	392906	318933	274433	232516	306164	282437	296292	332503	355858
Reduction rate	0	18.82	30.15	40.82	22.07	28.11	24.58	15.37	9.42

Table 3. Base shear values with reduction rate due to damper location in the system for El Cantro earthquake.

	Base shear values with reduction rate due to damper location in the system for El Cantro earthquake							
TMD	0	3	4	5	54	43	53	543	54321
Base shear	815688	587245	466884	359779	472811	451215	416521	562375	618131
Reduction rate	0.0000	28.00	42.76	44.68	55.89	44.68	48.93	31.05	24.21

Table 4. Base shear values with reduction rate due to damper location in the system for Tabas earthquake.

	Base shear values with reduction rate due to damper location in the system for Tabas earthquake							
TMD	0	3	4	5	54	43	53	543	54321
Base shear	478939	419783	411130	495226	489875	542754	528333	513613	560533
Reduction rate	0	12.35	14.15	-3.40	-2.28	-13.32	-10.31	-7.23	-17.03

In diagrams 4 to 6, base shear reduction rate can also be clearly observed in all three Naghan, El Centro and Tabas earthquakes.

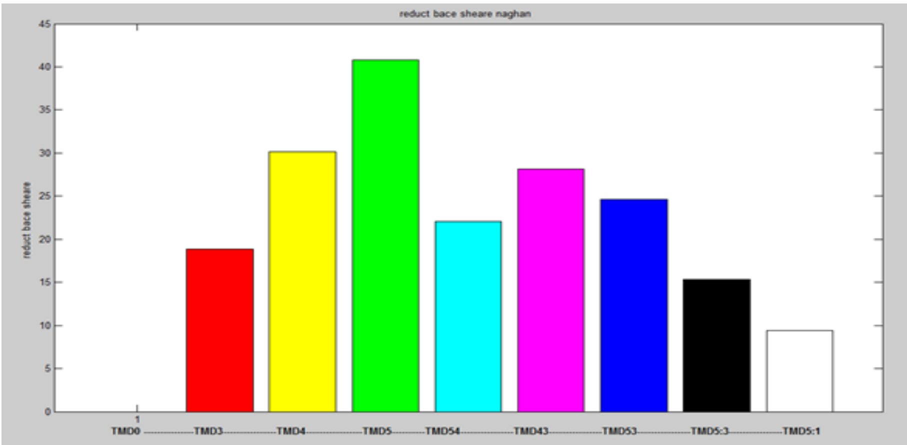


Diagram 4. Base shear reduction rate in Naghan earthquake.

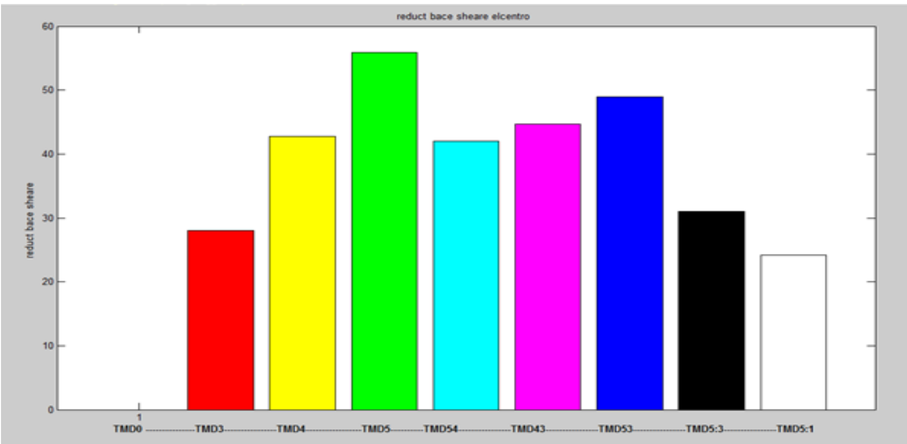


Diagram 5. Base shear reduction rate in El Centro earthquake.

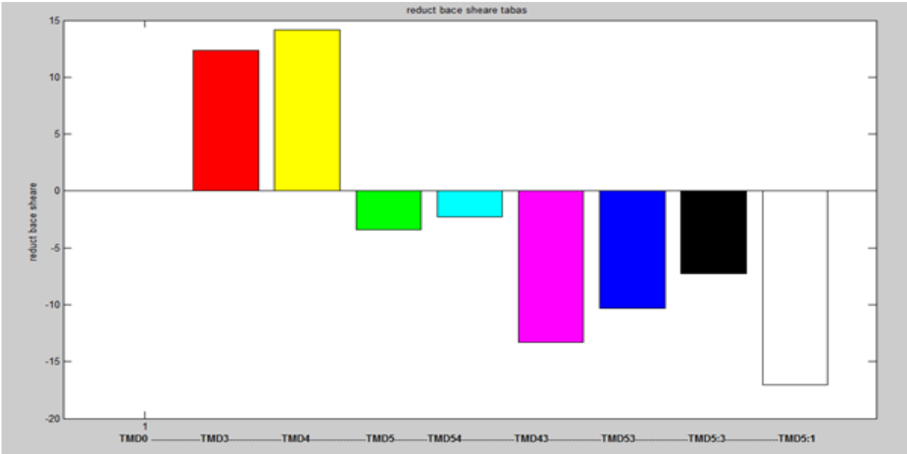


Diagram 6. Base shear reduction rate in Tabas earthquake.

8. 8GENERAL DISCUSSION ABOUT STORY DRIFT

The results show that dampers play an important role in drift reduction with regard to location in the structure. However, the type of earthquake applied to the structure is also extremely effective in the increase or decrease of the relative displacement of the structure. In Naqhan earthquake, the results indicate that when one TMD is used in the structure, again the best state would be the location of the damper in the 5th story; but when two dampers are used, the best state would be reduction of relative displacement in the 3rd and 4th stories. Nevertheless, 10% difference can be seen from the state of the 4th and 5th stories. In case 3 & 5 dampers are used in the structure, drift reduction will not be improved and the best possible state would be the application of two dampers in the structure. In El Centro earthquake, the results observed were slightly different from Naghan earthquake. In this earthquake (El Centro), when one damper is used in the structure, the best state would be the location of the damper in the 5th story and when two dampers are used, the best state would be reduction of relative displacement in the 5th & 4th stories. Application of 3 & 5 dampers will face improvement in the drift reduction by 2%, which again will not be economical or affordable in economic terms. In Tabas earthquake also dispersion of results can be seen as before but if we examine it further based on the same results, it will be shown that the best state would be the location of one damper in the 5th story and two dampers in the 5th & 4th stories; finally, in the case of 3 dampers no effect was observed and in the case of 5 dampers there was an increase in displacement compared to the case of no dampers.

9. GENERAL DISCUSSION ABOUT BASE SHEAR

It was necessary to review the given results of the effects of TMDs on base shear. As reduction of base shear is of special importance, it was therefore decided to continue the studies in this field and also conduct a control over the increase or decrease of the base shear in the earthquakes under study. In Naghan earthquake, the results showed that using one damper in the structure, when the damper location is in the 5th story, will have a considerable reduction compared to the other stories. In this state, 41% reduction of the base shear has occurred. Also when two dampers are used in the structure, the best state would be location of the dampers in the 3rd & 4th stories, which will have a 39% reduction in the base shear. When 3 or 5 dampers are used in the structure, the results would be a reduction by 18% for three dampers and by 10% for five dampers; thus, in Naghan earthquake, one TMD installed in the 5th story would be the best possible location. In El Centro earthquake also, when one damper is used, the results show that by locating the damper in the 5th story we will face a 56% reduction of the base shear which is highly appropriate. When two dampers are used, the results show that the best location of the damper would be in the 5th & 3rd stories, which shows a 49% reduction for base shear. Also, when 3 & 5 dampers are used in the structure, 31% & 24% reductions are observed in the structure respectively. Therefore, the above results show that application of one damper in the 5th story is also the best location in El Centro earthquake. In Tabas earthquake also as before, the results obtained weren't tuned with any specific amounts of stiffness and frequency and when the damper mass was considered as 0.6 of the structure mass and its frequency was considered equal to the frequency of the first mode of the structure, not only no reduction was observed in the base shear, but in most cases even a considerable increase in base shear was observed.

10.CONCLUSION

Using perimeter walls functioning as TMDs in nonlinear analyses brings about a considerable reduction in lateral displacement or drift of the stories. Also, using perimeter walls with larger mass often increases their performance; but this is not always the case and changes depending on the type of earthquake. In case application of the perimeter walls in only one story is considered, the best location for it in the related building would be the 5th story; but when there is no limitation for using perimeter walls in different stories, using the perimeter walls of the upper stories in the aforementioned building is more appropriate. Natural frequency of TMD depends on damper mass and stiffness. In this study, the results were obtained by tuning the damper frequency on the frequencies of the first to sixth modes and also by tuning the structure mass so that it is 0.1 to 0.6 of the total structure mass. Thus, the studies showed that tuning of the damper on the first mode and the total structure mass of 0.6 will have the best performance in El Centro and Naghan earthquakes but in Tabas earthquake the results are different.

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