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PARAMETRIC STUDY ON THE EFFICIENCY OF THE SINGLE AND MULTIPLE TMD SYSTEM

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ABSTRACT

In this work, a parametric study is carried out for the study of a variety of R.C. building frames with different numbers and positions of TMDs to evaluate their efficiency in reducing their structural response when subjected to two well known earthquake excitation records. The frames investigated consist of two groups of R. C. buildings having different height to width ratios. The investigation included the effect of adding tuned mass damper on the dynamic characteristics such as the natural period and mode shapes and on the seismic response of the structures such as the lateral displacement and base moment. The study also included the effects of mass ratio, the structural modes to which the TMDs are tuned and the optimum location of single or multiple TMD system.

Introduction

Tuned Mass Dampers (TMD) as an added energy-absorbing system, which are also known as dynamic vibration absorbers, have been widely studied and applied to mitigate vibrations in buildings caused by wind (McNamara 1977; Luft 1979). In most applications, a single tuned mass damper is installed at the top floor of a structure and is tuned to the fundamental mode of the structure (Chen and Wu 2001). In designing a TMD, several types of optimization procedures have been considered to obtain the optimum parameters of TMDs attached to a SDOF structure. One of the earliest researches was conducted by Den Hartog (1985). An Improvement to that work was presented by Sadek et al. (1997). The successful application of TMDs in reducing wind–excited structural vibration has encouraged the researchers to perform numerical and experimental studies on the effectiveness of such a system in reducing the seismic response of structures. The results of these studies showed that the effectiveness of TMDs on reducing the response of structures during different earthquakes or the response of different structures during the same earthquake is significantly different (Housner et al. 1997), and often is not effective (Chen and Wu 2001). To overcome these shortcomings, more than one TMD can be used; each one is tuned to different modes and placed at various locations Clark (1988). Chen and Wu (2001) have concluded that MTMDs are more effective in reducing the accelerations at lower floors than at upper floors, but they do not appear advantageous over a single TMD for displacement control. Therefore, further investigations are recommended to examine thoroughly the performance of these devices to

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mitigate the total structural response subjected to earthquake excitations. This study investigates the effects of adding tuned mass dampers on the dynamic characteristics of structures such as natural period and mode shapes and on the seismic responses of the structures such as the lateral displacement, and base moment. The study also includes the effects of mass ratio, the structural modes to which the TMDs are tuned, and the optimum location of single or multiple TMD system.

Numerical Analysis

Two groups of R.C framed buildings having different (height/width) ratios are chosen to study the effect of the TMD on the dynamic response. The frames have been analyzed under the El Centro 1940 earthquake and Parkfield-California 1966 earthquake. The peak ground acceleration is scaled to 0.30g, and a damping ratio of 5% is assigned to all modes. The properties of added TMD systems (frequency ω_{tmd} and damping ratio ξ_{tmd} as function of its mass $\mathbf{m}_{tmd}$) and the mechanical characteristics of the main building are obtained utilizing equations suggested by (Abubakar 2006) for computing the optimum parameters of TMDs. The properties of added masses are modified according to the design procedures to minimize the peak response when compared with that of uncontrolled response. The buildings are provided either with a single TMD at the top floor or multiple TMDs at each story level, and they are studied extensively using a wide range of parameters. These parameters are:

- The tuned mass ratio (μ)
- The location of the TMDs
- The modes to which the TMD is tuned
- Use of multiple TMDs at various locations

Numerical Study for the First Group (Bulky Buildings)

The first group consists of two frames of different stories representing bulky buildings, where the height/ width ratio is less than 2. The first frame is a three-story, five bay frame shown in Fig. 1, with a bay width 5.0m; the height of typical floor is 3m, and the height of ground floor is 5.0m high. The mass of each floor is taken as 1250 KN.sec^2/m. The second frame is the five-story with, two bay frame shown in Fig. 2, with bay width 5.0m; the height of typical floor is 3m. The mass of each floor is taken as 500 KN.sec^2/m.

Effect of Mass Ratio μ

In order to investigate the effect of mass ratioμ, a single tuned mass damper system is placed at the top floor of the frame with different mass ratioμ. Figs. 3 and 4 show the relation between the normalized top floor displacement (Δ/Δ_{max}) with the mass ratio μ for the two studied frames; where Δ is the top floor displacement with TMDs, and Δ_{max} is that without TMDs (i.e. without control). From these figures it can be noticed that the normalized top floor displacement decreases with the increase of μ, and there is no further decrease beyond mass ratio of 10%. For the practical mass ratio 5%, the decrease in the normalized top floor displacement is about 32%, 16% for the three story, and 40%, 16% for the five story frame, when they are subjected to the El Centro and Parkfield earthquakes, respectively.

Effect of Location of Single TMD

Considering the practical range of mass ratio (1 – 5 %) recommended by many researchers, the effect of the position of the TMD on the efficiency of reducing the structural response is investigated. A single tuned mass is located at each story in turn, and the normalized top displacement is plotted against the story number at which the TMD is placed as shown in Figs. 5 and 6 for the two frames respectively. In the case of the El Centro earthquake, the maximum reduction is 32% and 40% when the TMD is located at the top floor of the three and five story frames, respectively, compared with only 9% and 2% when the mass is attached at the bottom floor of the two frames, respectively. In case of the Parkfield earthquake, the maximum reduction is 16% for both frames when the TMD is located at the top floor, compared with only 7% and 2% when the mass is placed at the bottom floor of the two frames, respectively.

Effect of the Mode to Which the TMD is Tuned

Figs. 7 and 8 show the effect of the mode number to which the single TMDs is tuned on the normalized top displacement of the analyzed frames. The results show that when the TMD system is tuned to the first mode of uncontrolled three story frame and subjected to the El Centro and Parkfield earthquakes, the normalized top displacement of the frame is reduced by 32% and 16% respectively. The normalized top displacement of the five story frame is also reduced by 40% and 16%, when the TMDs are tuned to the first mode for the two earthquakes, respectively.

Effect of Multiple TMD with Different Locations

In order to investigate the effect of multiple TMDs, several TMDs (having total masses within the practical range of mass ratio 5%) are distributed at different floors levels of the studied frames and the properties of each TMD are widely varied. The following designations are used to describe some arrangements of the studied cases of TMDs:
Case1: without TMDs.
Case2: a single TMD with a mass ratio 5% placed at top floor.
Case3: two TMDs with mass ratios 1%, 4% placed at the top and the floor below it respectively.
Case4: two TMDs with mass ratios 4%, 1% placed at the top and the floor below it respectively.
Case5: two TMDs with mass ratios 2.5% placed at the top and the floor below it respectively.
Case6: several TMDs distributed at all floors with total mass ratio 5% divided equally at each floor and all are tuned to the first mode frequency.
Case7: several TMDs distributed at all floors with total mass ratio 5% divided equally at each floor but the TMD placed at the i^{th} floor is tuned to the (n-i+1) mode frequency (where n is the total number of story).

The effects of adding different number of TMDs described in the above cases on the normalized top floor displacement and on the normalized base moment for the two analyzed frames are shown in Figs. 9 to 12. The results show that the maximum reduction is obtained when several TMDs are distributed at all floors with total mass ratio 5% divided equally at each floor and they are tuned to the first mode (case 6). When these frames are subjected to *the* El Centro earthquake, the reduction is about 57% for the top floor displacement and 55% for the base moment, for the three story frame. This reduction is about 51% for both top floor displacement and base moment, for the five story frame. When the frames are subjected to the Parkfield earthquake, the reduction is about 47% for the top floor displacement and 52% for the base moment, for the three story frame; and the reduction is about 43% for the top floor displacement and 60% for the base moment, for the five story frame. From these figures it can also be seen that, when the frames are subjected to El Centro earthquake and adding a single TMD (case 2) or double TMDs (cases 3, 4 and 5) yield almost the same results in terms of the reduction of structural response of the two studied frames; for the three story frame, the reduction is about: 32% for the top floor displacement and 28% for the base moment. This reduction is about 40% for the top floor displacement and 36% for the base moment, for the five story frame. When the frames are subjected to the Parkfield earthquake, the reduction is about 16% for the top floor displacement and 13% for the base moment (case 3, 4, and 5), for the three story frame and the reduction is about 16% for the top floor displacement and 19% for the base moment, for the five story frame. For the five story frame, Figs. 13 and 14 show that dividing the mass of a single TMD into five equal masses tuned to different modes and distributed at the five floors (case 7) is insignificant compared to the single TMD (case 2). Fig. 9 shows that when a single TMD with mass ratio 5% (case 2) is placed at the top floor of the three story frame and subjected to the Parkfield earthquake, the base moment is increased by 9%. However, when the natural period of this frame is changed from 0.837 sec to 0.7253 sec, the base moment is reduced by 34% as shown in Fig. 15.

Numerical Study for the Second Group (Slender Buildings)

The second group consists of two different frames representing slender buildings, where the height/ width ratio is larger than 2. The first frame of this group is a twenty four-story, five bay frame shown in Fig. 16. The bay width 5.0m; the height of typical floor is 3m, and the height of ground floor is 5.0m high. The mass of each floor is taken as 1250 KN.sec^2/m. The second frame is a ten- story, two bay frame shown in Fig. 17 with bay width 5.0m; the height of each floor is 3.5m. The mass of each floor is taken as 500 KN.sec^2/m.

Effect of Location of Single TMD

A single tuned mass is located at each story in turn, and the normalized top displacement is plotted against the story number at which the TMD is placed as shown in Figs. 18 and 19, for the two frames. Fig. 18 shows that when the TMD is located at the top floor of the twenty-four story frame, the maximum reduction of top floor displacement is 60% and 42% when the frame is subjected to El Centro and Parkfield earthquakes, respectively. The reduction is only 0.73%, 0.47% when the mass is located at the first floor. Fig. 19 shows that no reduction is obtained when the TMD is located at the top floor or at any other floor for the ten story frame. However, when the natural period of this frame is changed from 1.576 sec to 1.754 sec as shown in Fig. 20, the maximum reduction of top floor displacement became 33% and 37% when the TMD is located at the top floor and subjected to the two earthquakes, respectively.

Effect of the Mode to Which the TMD is Tuned

Figs. 21 and 22 show the effect of the mode number to which the single TMD is tuned on the normalized top displacement of the frames. Fig. 21 shows that when the TMD is tuned to the first mode of the uncontrolled twenty-four story frame and subjected to the El Centro and Parkfield earthquakes, the normalized top displacement of the frame is reduced by 60% and 42% respectively. Fig. 22 shows that the effect of TMD is negligible when the TMD is tuned to the different modes of the ten story frame. However, when the natural period of this frame is changed from 1.576 sec to 1.754 sec as shown in Fig. 23, the normalized top floor displacement is reduced by 33% and 37% when the TMD is tuned to the first mode of uncontrolled frame and subjected to the El Centro and Parkfield earthquakes respectively. The figures also show that the efficiency of TMD is decreased when the mass is tuned to the higher modes.

Effect of Multiple TMD with Different Locations

The effect of adding a different number of TMDs described before on the normalized top floor displacement and normalized base moment for the two analyzed frames are shown in Figs 24 to 26. The results show that the maximum reduction is obtained when several TMDs distributed at all floors with total mass ratio 5% divided equally at each floor and they are tuned to the first mode (case 6). When these frames are subjected to the El Centro earthquake, the reduction is about 69% for the top floor displacement and 75% for the base moment, for the twenty-four story frame. The reduction is about 22% for top the floor displacement and 27% for the base moment, for the ten story frame. When the frames are subjected to the Parkfield earthquake, the reduction is about 53% for the top floor displacement and the base moment, for the twenty-four story frame; and the reduction is about 33% for the top floor displacement and 40% for the base moment, for the ten story frame. From these figures it can be also seen that when the twenty-four story frame is subjected to the two earthquakes that adding a single TMD (case 2) or double TMDs (cases 3,4 and 5) yield almost the same results in terms of the reduction of structural response of the frame; the reduction is about 60% and 42% for the top floor displacement, and 52%, 30% for the base moment when the frame is subjected to the El Centro and the Parkfield earthquakes respectively. Fig. 26 shows that when the ten story frame is subjected to El Centro earthquake and adding a single TMD with mass ratio 5% (case 2), the displacement response is increased by 12%. When the frame is subjected to the Parkfield earthquake, the reduction is only 0.23% for the top floor displacement. However, when the natural period of this frame is changed from 1.576 sec to 1.754 sec, the reduction in case of adding single TMDs (case2) is about 33%, 37% for the top floor displacement, when the frame is subjected to the El Centro and Parkfield earthquakes, respectively.

Discussion of the Results

The results of this study show that the normalized top displacement decreases with the increase of mass ratio (μ), and there is no further decrease beyond mass ratio 10% (see Figs. 3 and 4). This may be due to the fact that the heavier TMD reaches its full potential slowly. A single TMD is more efficient when located on the upper floors and tuned with the first mode, and its effect decreases considerably when it is located on the lower floors as shown in Figs. 5 and 6. This is true for both bulky and slender frames and for different earthquakes loadings. This is expected since the maximum displacement in first mode (which is the dominant mode) occurs at the top floor. The study has shown that a single TMD in some cases is not only effective in reducing seismic responses, but also amplifies the responses of few studied frames as shown in

Figure 19. This may be attributed to the following: (i) the earthquake loads are typically impulsive and reach the maximum values rapidly, and a TMD usually is not fully developed yet in such a short period, (ii) earthquake ground motions include a wide spectrum of frequency components and may induce significant vibration in the fundamental and higher modes of a tall building structure. Therefore, a single TMD may fail to reduce the total responses of the structures. It was found that a TMD is not efficient for reducing the structural response of some frames due to some earthquakes, but these disadvantages can be overcome by changing the dynamic properties of these frames. This means that, the effect of TMDs does not depend only on the characteristics of the earthquake, but also on the properties of the building. The study shows that a TMD is only effective when tuned to the first mode for the bulky frames and to the first few modes for the slender frames. This agrees with the fact that structural response to earthquakes is primarily due to the first few modes of vibration. These results are also in good agreement with that of previous studies, where in the most applications, the TMDs are tuned to the fundamental mode of the structure. As discussed above, the main disadvantages of a single TMD is the sensitivity problem due to the fluctuation in tuning the TMD's frequency to the controlled frequency of a structure and/ or that in the damping ratio of the TMD. The mistuning or off-optimum damping will significantly reduce the effectiveness of a TMD. Instead, more than one tuned mass damper, with different dynamic characteristics and different arrangements may be utilized in order to improve the effectiveness and robustness of TMD. The study has demonstrated that the multiple TMDs with identical stiffness, damping, and equal masses placed at each floor of the studied frames provides better effectiveness than a single TMD and other arrangements of multiple TMDs. It is found that the multiple TMD can effectively reduce the displacement and moment of uncontrolled structure by 10-40% more than a single TMD. It should be noted that the improvement is obtained when the tuning is based on the first mode.

Conclusions

Based on the present work, the following conclusions can be drawn:

- The tuned mass damper is a powerful technique in reducing the response of multistory building. This reduction depends on the properties of the building and characteristics of the earthquake. A TMD has more efficiency in reducing structural response with the increase of mass ratio. However, no much reduction is gained with mass ratio larger than 10%.
- The TMD is efficient when located on the higher floors and its effect decreases considerably when located on the lower floors.
- A Multiple TMD system (with total masses equal to the mass of the single TMD) is always more efficient than the single TMD in reducing structural response. Moreover, the multiple TMD can make full use of the spare space at different floors of the building, where it consists of distributed damper of small masses and often does not require any devoted space to house them.

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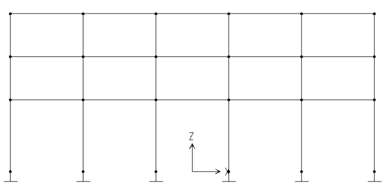

Figure 1. Three-story frame

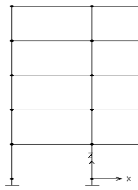

Figure 2. Five-story frame

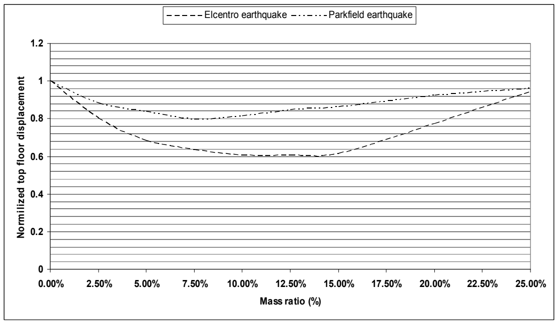

Figure 3. The effect of mass ratio on the top floor displacement for the 3-story frame.

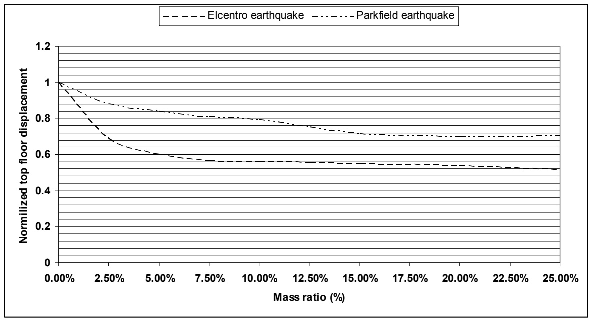

Figure 4. The effect of mass ratio on the top floor displacement for the 5-story frame.

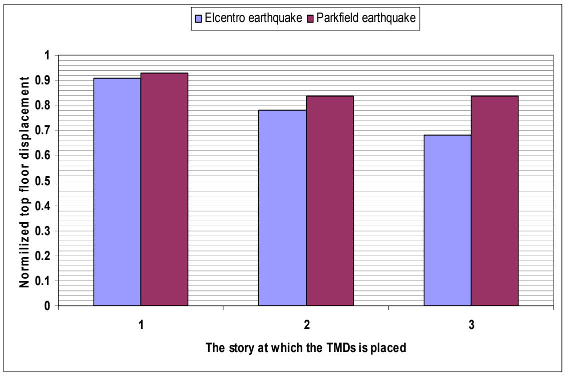

Figure 5. The effect of location of a single TMD placed at different stories of 3-story frame.

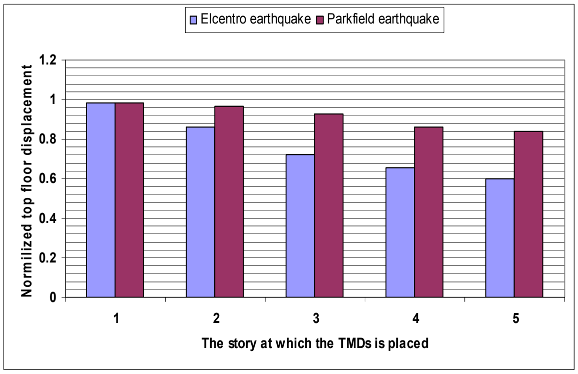

Figure 6. The effect of location of a single TMD placed at different stories of 5-story frame.

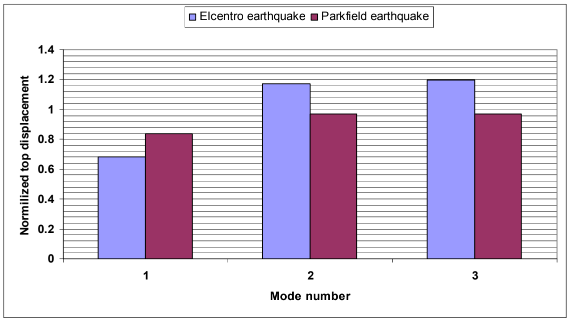

Figure 7. The effect of structural mode number to which the TMD is tuned on the top floor displacement of 3-story frame.

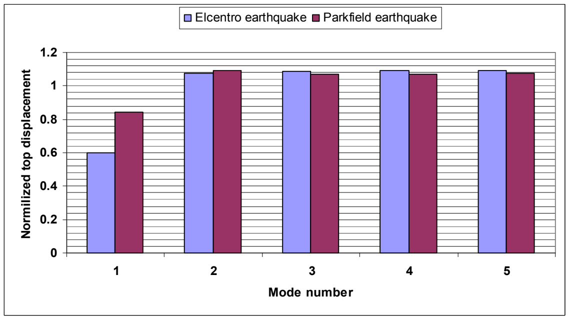

Figure 8. The effect of structural mode number to which the TMD is tuned on the top floor displacement of 5-story frame.

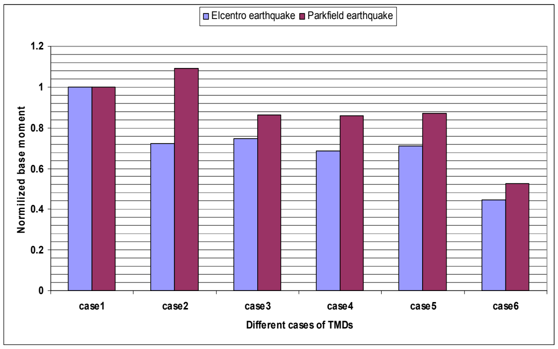

Figure 9. The effect of adding different number of TMDs with different mass ratios at different position on the top floor displacement for the 3-story frame.

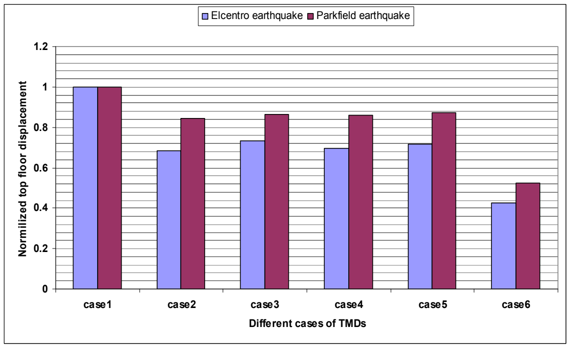

Figure 10. The effect of adding different number of TMDs with different mass ratios at different position on the base moment for the 3-story frame.

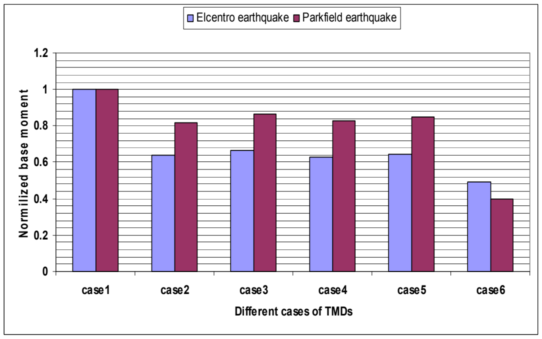

Figure 11. The effect of adding different number of TMDs with different mass ratios at different position on the top floor displacement for the 5-story frame.

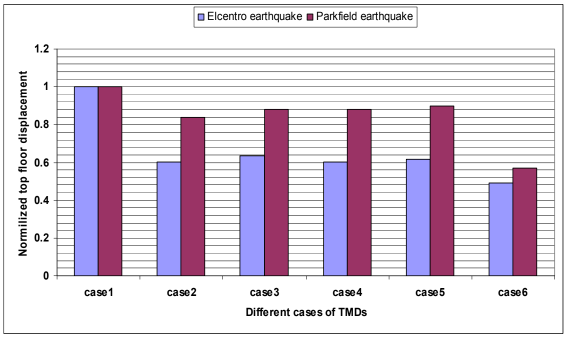

Figure 12. The effect of adding different number of TMDs with different mass ratios at different position on the base moment for the 5-story frame.

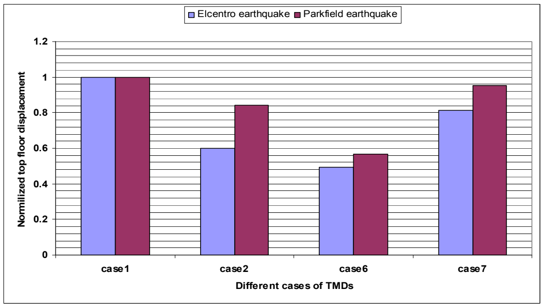

Figure 13. The effect of adding different numbers of TMDs with different mass ratios at different positions on the top floor displacement for the 5-story frame.

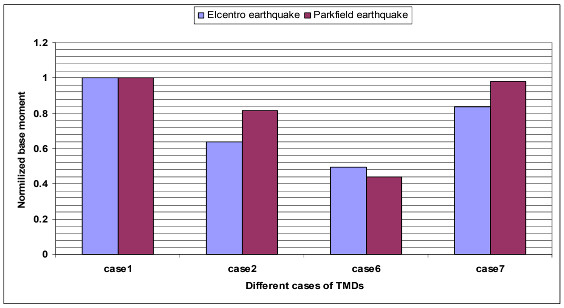

Figure 14. The effect of adding different numbers of TMDs with different mass ratios at different positions on the base moment for the 5- story frame.

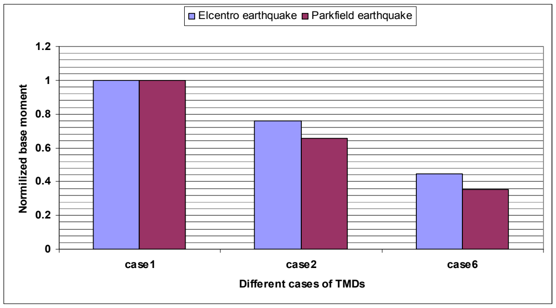

Figure 15. The effect of adding different numbers of TMDs with different mass ratios at different positions on the base moment for the 3-story frame with different dynamic properties.

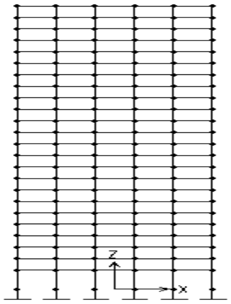

Figure 16. Twenty four story frame.

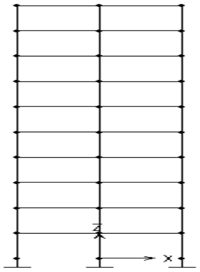

Figure 17. Ten-story.

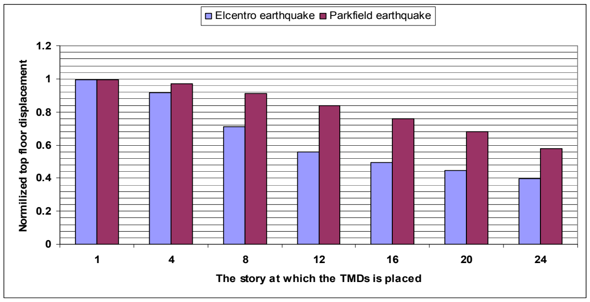

Figure 18. The effect of location of a single TMD placed at different stories of 24-story frame.

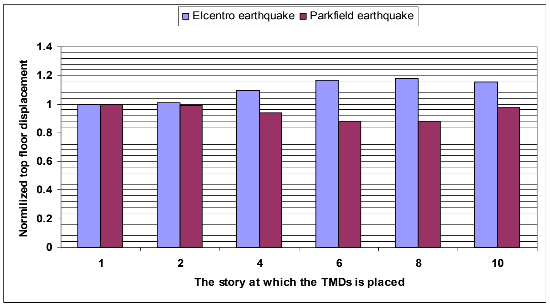

Figure 19. The effect of location of a single TMD placed at different stories of 10-story frame.

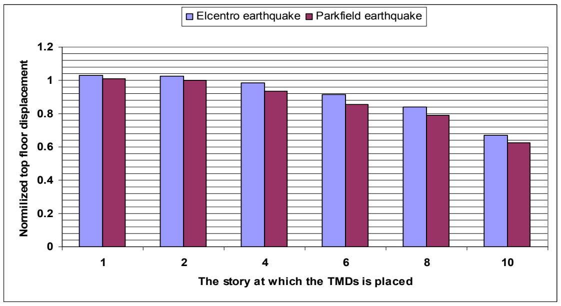

Figure 20. The effect of location of a single TMD placed at different stories of 10-story frame with different dynamic properties.

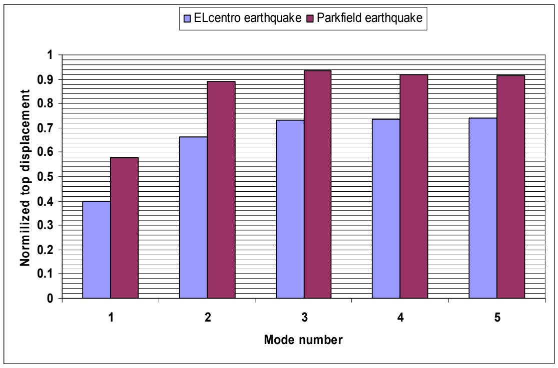

Figure 21. The effect of structural mode number to which the TMD is tuned on the top floor displacement response of 24-story frame.

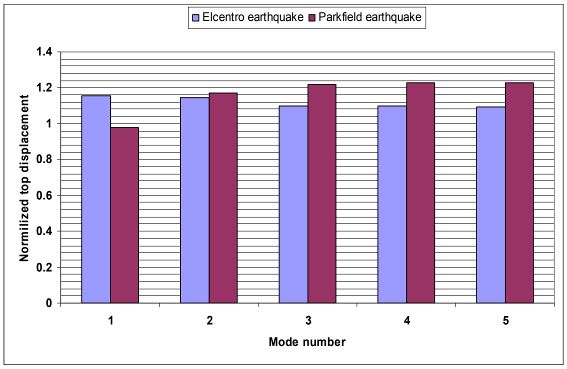

Figure 22. The effect of structural mode number to which the TMD is tuned on the top floor displacement response of 10-story frame.

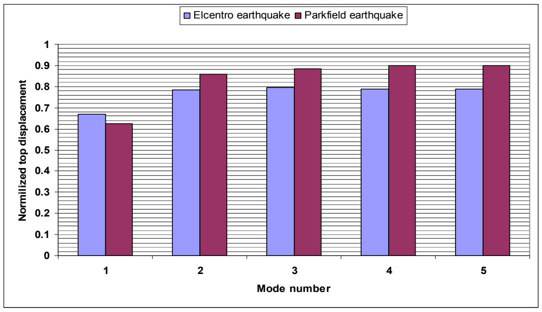

Figure 23. The effect of structural mode number to which the TMD is tuned on the top floor displacement response of at 10-story frame with different dynamic properties.

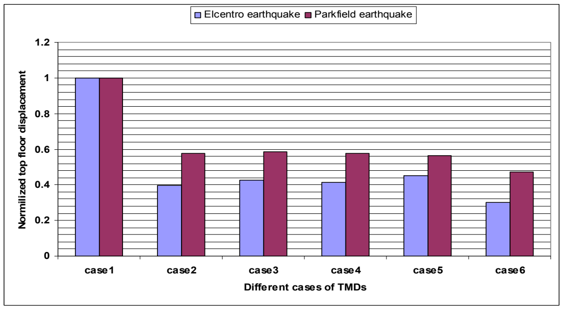

Figure 24. The effect of adding different numbers of TMDs with different mass ratios at different position on the top floor displacement for the 24- story frame.

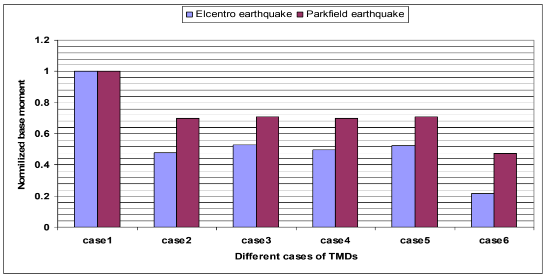

Figure 25. The effect of adding different numbers of TMDs with different mass ratios at different positions on the base moment for the 24- story frame.

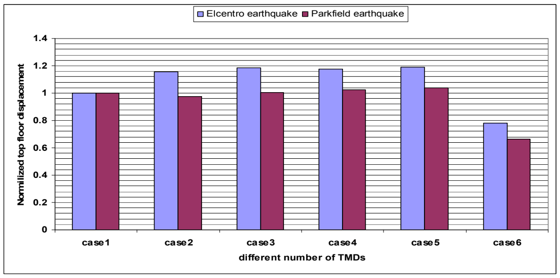

Figure 26. The effect of adding different numbers of TMDs with different mass ratios at different positions on the top floor displacement for the 10-story frame.