EFFECT OF STRUCTURAL VARIATION ON THE PERFORMANCE OF MTMD AS A SEISMIC RESPONSE CONTROL DEVICE

Rildova[1] and D. Kusumastuti[1]

[1]*Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung, Indonesia*
Email: rildova@ocean.itb.ac.id

ABSTRACT :

This study was conducted to analyze the effect of Multiple Tuned Mass Damper (MTMD) on various structures, by varying MTMD parameters, i.e. mass ratio, placement and distribution. A set of structures with different number of stories and dynamic characteristics, including structures with stiffness and mass irregularities, were used in the analysis. The effects of each parameter on different structures were quantified and compared to the responses of structures without MTMD, using several ground motions. The performance was measured in terms of reductions of maximum displacement and drift of structures. The results show that seismic responses of structures can be improved using MTMD with optimum parameters, although the optimum values may vary according to structural and ground motion properties. The structural performance tends to improve as the mass ratio of MTMD increases. However, the effect of mass ratio also varies for different structures and ground motions. From location and distribution aspect, in general, adding MTMD to the structural system reduces structural responses regardless of the placement. However, it seems that MTMD located at the top story generates better performance for structures with dominant first mode, even if the structures have variations of story masses and stiffnesses along their heights. The result also shows that adding MTMD to the structural system somewhat reduces the drift demand and linearizes the drift pattern, thus easing the drift demand for the lower floors.

KEYWORDS: Multiple tuned mass dampers, seismic response control, passive control.

1. INTRODUCTION

Performance of structures under seismic loads can have significant impact on the number of fatalities and economic losses. Two distinct approaches have been developed to improve structural responses during earthquakes, one is to design building inelastically by allowing some damage, and another is to design building to behave in elastic manner, thus building has little or no damage under to seismic excitations. The first approach is commonly applied due to its cost benefit. However, the second approach is still in demand, especially for buildings such as hospitals that should remain functional during and after earthquakes.

Several additional devices were then developed to reduce the cost needed for the elastic design, and dampers have been used to improve the structural responses. One of the oldest types of dampers was Tuned Mass Damper (TMD), modeled as an additional mass with a certain stiffness and damping attached to the main structure. Key parameters for a TMD system are tuning frequency, mass, and damping ratio. Multiple Tuned Mass Damper (MTMD) was later introduced to improve the performance of TMD, which was found to be sensitive to mistuning and has limitation in the maximum mass ratio applied. MTMD can be modeled as several TMDs attached to the main structure. Key parameters of MTMD are similar to TMD, added with the frequency range, which is defined as half of the range between the lowest frequency and the highest frequency of TMDs. Studies have shown that with an optimum combination of key parameters, MTMD can be as effective as TMD in improving structural response due to earthquake loadings. Furthermore, MTMD remedies the problem of mistuning in the case of random loading. (Yamaguchi and Harnpornchai, 1992; Kareem and Kline, 1995; Abe and Fujino, 1994; Igusa and Xu, 1994; Kusumastuti and Rildova, 2006).

Many studies have been carried out for MTMD system applied to structure, and most of the structural models were regular structure with first mode dominant. Results of these studies show that MTMD is most beneficial if the dampers are located at or near the top of the structure to counter the first mode response. However, many buildings are irregular by nature due to asymmetrical building layout and load configuration, or imperfections. Experience reveals that buildings with irregularities show poor performance under earthquake loadings. A numerical study of MTMD system was conducted with some structural variations introduced to the models (Rildova, et.al, 2007). The variations were within the limitation of irregularities according to the building codes, and the results also reveal that MTMD at the top story is slightly more favorable than other configurations. The study offers some hindsight regarding damper placement and distribution along the height of the building as well. Therefore, this research aimed to further understand the application of MTMD in controlling the structural responses of buildings with irregularities. Structural models with different number of stories, stiffness, and mass irregularities, were used in this study. MTMD systems with certain key parameters were utilized, and a number of recorded ground motions were then applied to the structures. The effectiveness of MTMD was evaluated based on the reduction of the maximum displacement and drift.

2. MODEL OF STRUCTURES

The numerical model of a structural system with MTMD consists of a main structure with some degrees of freedom. Then each TMD is modeled as a SDOF system attached to the main structure. Therefore, the entire structural system can be modeled as a multi-degrees-of-freedom (MDOF) system, and the general equation of motion for such system is as follows,

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f} \tag{2.1}$$

where **M**, **C**, and **K** are the mass, damping, and stiffness matrices, respectively, **x** is the displacement vector, and **f** is the seismic load applied to the structure. The structural responses in terms of displacement and drift can be obtained by solving this equation numerically.

Ten different structures were selected as the main structures in this study. They were 6-story and 12-story shear buildings with variations of structural irregularities. Structure 1A was a regular 6DOF structure, used as a benchmark for structures 1B, 1C, 1D, and 1E. Structures 1B and 1C had similar properties to model 1A, except for the stiffness of the first floor which was respectively 0.7 and 0.5 of the stiffness of other floors. Both represent structures with stiffness irregularity. Structures 1D and 1E represented structures with mass irregularity. The properties of Structure 1D was varied from Structure 1A by having half of the first floor mass, while the first floor mass of Structure 1E was doubled. Structure 2A was a regular 12DOF structure, also used for benchmark for structures 2B, 2C, 2D, and 2E. The variation of irregularities for structures 2B to 2E was similar to structures 1B to 1E. The dynamic properties of these structures are shown in Table 1.

Table 1. Dynamic Properties of Structures

Structure	Stiffness		Mass		Period
	1st story	Other stories	1st floor	Other floors	(sec.)
1A	k	k	m	m	0.7000
1B	0.7 k	k	m	m	0.7450
1C	0.5 k	k	m	m	0.8028
1D	k	k	0.5 m	m	0.6970
1E	k	k	2 m	m	0.7065
2A	k	k	m	m	1.3439
2B	0.7 k	k	m	m	1.3896
2C	0.5 k	k	m	m	1.4499
2D	k	k	0.5 m	m	1.3431
2E	k	k	2 m	m	1.3456

The MTMD parameters used were obtained from the previous study (Kusumastuti and Rildova, 2006b). The damping ratio for each TMD was set at 5 percent and the tuning for the dampers were carried out by selecting the middle frequency using the closed form solution for single TMD under harmonic ground motion (Den Hartog, 1984). The frequencies of the dampers were arranged to be evenly spaced near the middle frequency.

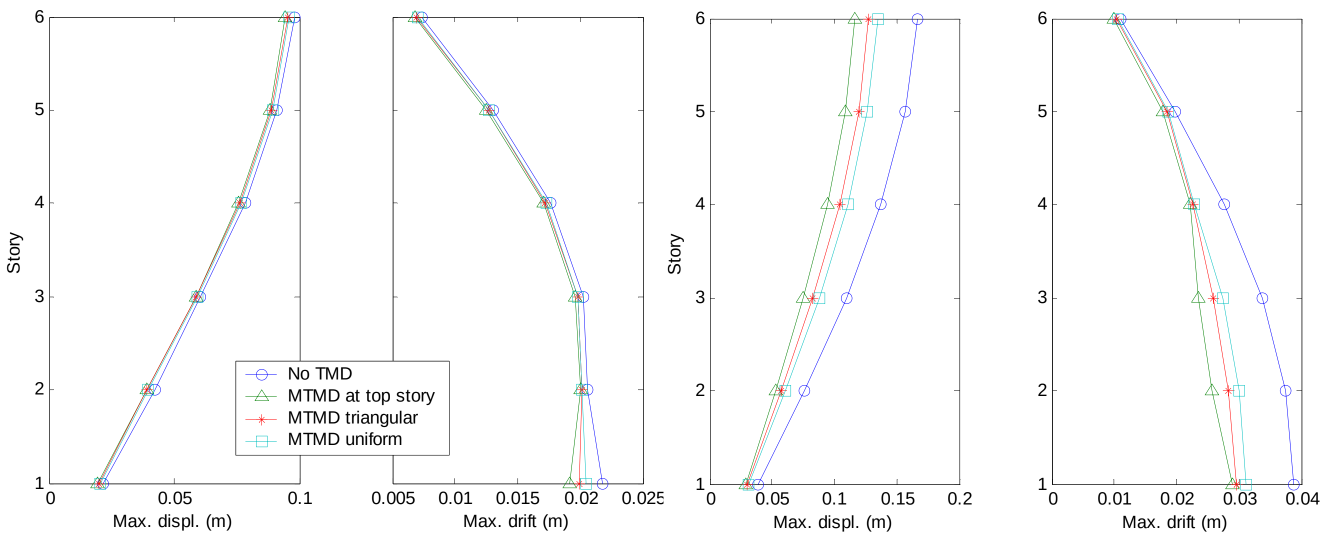
Three scenarios of MTMD location and distribution were analyzed, i.e., all dampers were located at the top story, uniform placement of which TMDs were evenly distributed on each floor of the structure, and a triangular placement of which the total mass of TMDs at each floor was varied linearly along the height of the structure. In the last scenario, the total mass of MTMD at the second floor was twice the total mass of MTMD at the first floor; the total mass of MTMD at the third floor was three times that of the first floor, and so on. The number of TMDs used at each floor with MTMD system was fixed at five. In all scenarios considered, the total mass of MTMD system attached to the structure was limited to 10 percent of the mass of a typical floor of the structure. A number of recorded ground motions were used as the input motions, namely, El Centro, Loma Prieta, and Northridge earthquakes.

The option of using uniform or triangular distribution of MTMD offers possibilities of increasing mass ratio of MTMD since the dampers are spread at various stories. Therefore, the effect of total mass of MTMD was also investigated, using 5, 10, 20, and 50 percent of the typical floor mass for each structure.

3. NUMERICAL RESULTS

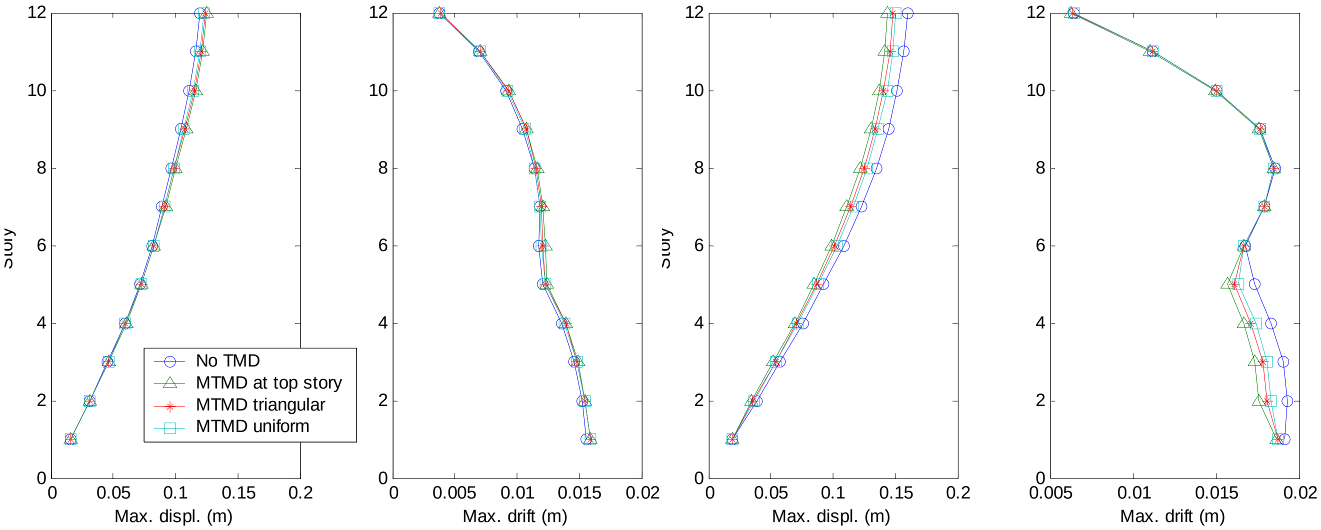
Figures 1 to 4 show the typical results of maximum displacement and drift at each story of the structures. While the patterns are somewhat similar, the reduction of displacement and drift appears to be dependent of the type of structure and the earthquake input motion. Table 2 presents the complete results of reduction of maximum displacement and maximum drift for every scenario considered in this study.

In general, attaching MTMD to the structure can help reducing the maximum displacement and drift of the structure, as well as linearizing drift patterns. The latter is more obvious for 6-story structures. In all cases considered, placing all MTMD at the top floor gives the best reduction of maximum displacement and drift.



(a) (b)

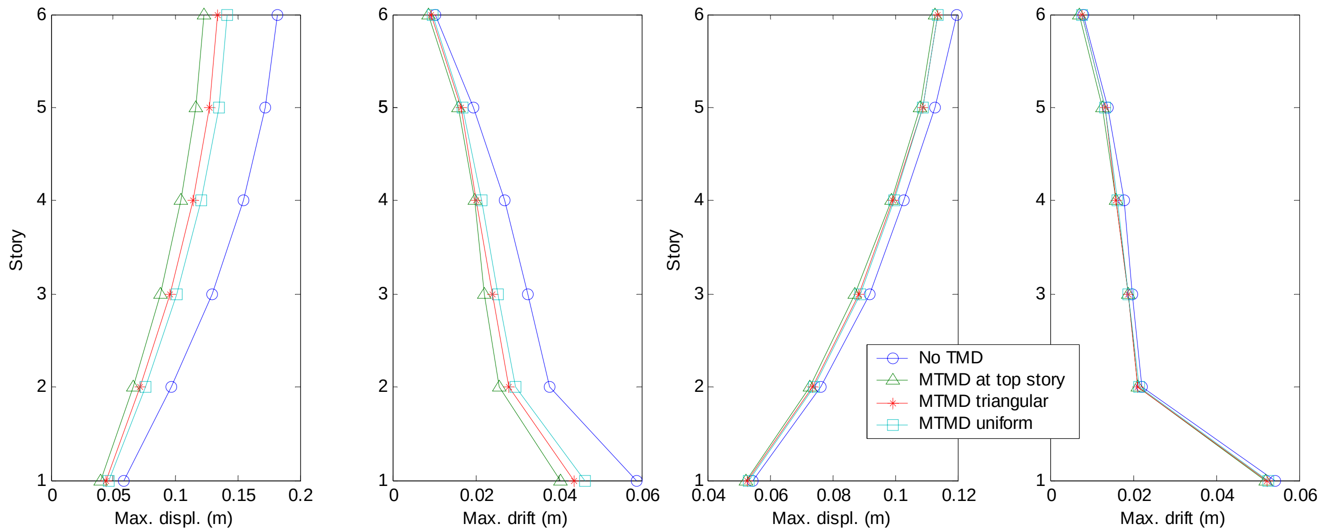
Figure 1 Maximum displacement and drift of Structure 1A under (a) El Centro and (b) Loma Prieta earthquakes.



(a) (b)

Figure 2 Maximum displacement and drift of Structure 2A under (a) El Centro and (b) Loma Prieta earthquakes.

Figure 3 shows the results for structures with soft first story. It is clear that this type of structure tends to have significant drift at the first story. The first story drift increases with larger reduction of first story stiffness, as shown in Figure 3(b). The effectiveness of MTMD seems to be affected by stiffness irregularity. Comparing the performance of MTMD on structures 1B and 1C, also 2B and 2C, it can be seen that the device performs better when the stiffness reduction at the first story is less (structure 1B and 2B).



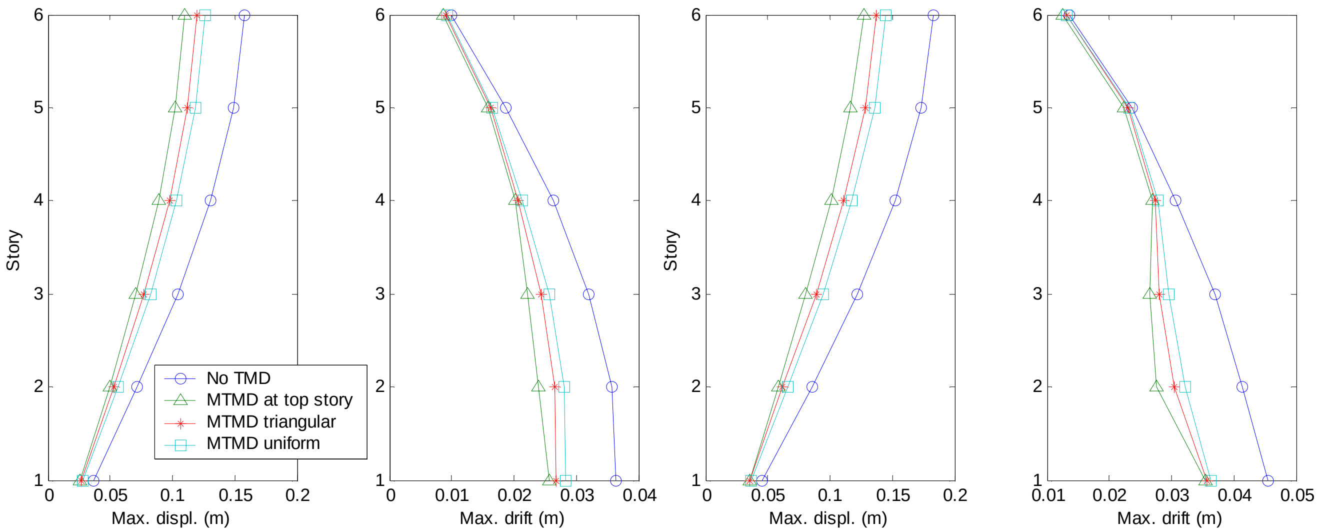
(a) (b)

Figure 3 Maximum displacement and drift of Structures (a) 1B and (b) 1C under Loma Prieta earthquake.

Table 2. Reduction of Maximum Displacement and Maximum Drift

Struct.	MTMD Location	Displacement Reduction			Drift Reduction		
		El Centro	Nortridge	Loma Prieta	El Centro	Northridge	Loma Prieta
1A	Top story	3.47%	3.20%	30.42%	7.82%	3.75%	25.57%
	Triangular	2.52%	2.28%	23.50%	7.44%	2.67%	23.87%
	Uniform	1.99%	1.74%	18.90%	5.91%	2.04%	19.64%
1B	Top story	8.62%	4.62%	32.38%	9.13%	5.28%	31.30%
	Triangular	6.45%	3.48%	26.27%	6.48%	3.87%	25.35%
	Uniform	5.13%	2.78%	21.93%	4.81%	2.90%	21.17%
1C	Top story	6.91%	4.92%	5.70%	6.99%	5.38%	4.73%
	Triangular	5.35%	3.83%	4.99%	5.24%	4.11%	3.64%
	Uniform	4.37%	3.15%	4.97%	4.08%	3.23%	2.94%
1D	Top story	4.44%	3.81%	30.79%	9.11%	4.72%	29.25%
	Triangular	3.43%	2.92%	24.57%	8.29%	3.61%	26.49%
	Uniform	2.87%	2.41%	20.33%	7.37%	2.98%	21.99%
1E	Top story	4.04%	3.73%	30.54%	7.59%	3.72%	22.22%
	Triangular	3.09%	2.78%	25.35%	6.12%	2.67%	21.34%
	Uniform	2.55%	2.22%	20.95%	5.14%	2.08%	20.15%
2A	Top story	-5.17%	1.33%	9.99%	-2.11%	1.51%	3.60%
	Triangular	-3.87%	0.97%	7.36%	-1.77%	1.09%	3.27%
	Uniform	-2.89%	0.70%	5.64%	-1.57%	0.76%	3.12%
2B	Top story	-5.57%	1.35%	10.28%	-5.08%	1.41%	3.07%
	Triangular	-4.23%	1.00%	7.75%	-4.08%	1.05%	2.31%
	Uniform	-3.24%	0.74%	6.02%	-3.41%	0.78%	1.84%
2C	Top story	-1.95%	3.45%	11.30%	-4.71%	1.36%	2.34%
	Triangular	-1.48%	3.13%	9.35%	-3.80%	1.03%	1.89%
	Uniform	-1.15%	2.51%	7.29%	-3.18%	0.78%	1.57%
2D	Top story	-4.85%	1.59%	10.40%	-1.13%	1.94%	8.59%
	Triangular	-3.58%	1.23%	7.79%	-0.85%	1.49%	7.38%
	Uniform	-2.62%	0.96%	6.09%	-0.66%	1.16%	5.76%
2E	Top story	-4.77%	1.41%	10.05%	-0.34%	1.68%	0.91%
	Triangular	-3.63%	1.05%	7.48%	-0.18%	1.26%	0.65%
	Uniform	-2.75%	0.79%	5.81%	-0.09%	0.95%	0.54%

Figure 4 presents the maximum displacement and drift for structures with mass irregularity at the first floor. The effectiveness of MTMD seems to be less affected by the changes of the first floor mass.



(a) (b)

Figure 4 Maximum displacement and drift of Structures (a) 1D and (b) 1E under Loma Prieta earthquake.

One of the advantages of using MTMD system with uniform or triangular distribution is that the total mass of MTMD is distributed along the height of structure and not accumulated on a certain floor. Therefore, the mass ratio can be increased without having significant additional mass at each floor which may induce more irregularity on the structure. The top floor configuration probably limits the maximum mass ratio to 10 percent due to available space and other practical considerations. However, with the 10 percent limit of mass ratio of MTMD at each floor, the total mass ratio in a 6-story building can reach 60 percent using uniform distribution and 35 percent with triangular distribution. Therefore, the study also considered different mass ratios for MTMD systems.

The results for different mass ratio of MTMD for all structures under Loma Prieta earthquake are presented in Table 3. In general, higher mass ratio produces better results. However, there seems to be an optimum mass ratio of MTMD for Structure 1B and most of the 12-story structures. The optimum mass ratio for these structures is 20 percent.

Table 3. Reduction of Maximum Displacement and Drift for Different Mass Ratio of MTMD (Loma Prieta Earthquake)

Struct.	MTMD Location	Displacement Reduction				Drift Reduction			
		Mass Ratio of MTMD				Mass Ratio of MTMD			
		5%	10%	20%	50%	5%	10%	20%	50%
1A	Top story	16.28%	30.42%	35.00%	37.05%	18.49%	25.57%	27.44%	31.01%
	Triangular	11.95%	23.50%	31.83%	33.95%	14.14%	23.87%	26.08%	29.46%
	Uniform	9.32%	18.90%	30.07%	31.59%	11.18%	19.64%	25.29%	28.36%
1B	Top story	20.24%	32.38%	40.77%	20.07%	19.93%	31.30%	34.98%	19.73%
	Triangular	15.91%	26.27%	34.13%	13.86%	15.53%	25.35%	32.99%	14.87%
	Uniform	13.03%	21.93%	28.47%	10.27%	12.54%	21.17%	27.81%	11.68%
1C	Top story	7.87%	5.70%	-7.90%	-12.46%	2.51%	4.73%	0.11%	-4.93%
	Triangular	7.71%	4.99%	-7.93%	-8.78%	1.88%	3.64%	2.59%	-0.90%
	Uniform	7.36%	4.97%	-7.03%	-5.30%	1.49%	2.94%	4.13%	2.31%
1D	Top story	17.61%	30.79%	35.43%	37.56%	19.64%	29.25%	31.04%	34.50%
	Triangular	13.78%	24.57%	32.24%	34.22%	15.42%	26.49%	29.91%	33.19%
	Uniform	11.50%	20.33%	30.37%	32.36%	12.89%	21.99%	29.20%	31.97%
1E	Top story	18.48%	30.54%	34.66%	36.98%	17.98%	22.22%	24.05%	27.32%
	Triangular	14.28%	25.35%	31.83%	33.80%	15.11%	21.34%	22.62%	25.79%
	Uniform	11.67%	20.95%	30.29%	30.31%	13.37%	20.15%	21.85%	23.96%
2A	Top story	5.34%	9.99%	16.20%	8.82%	3.09%	3.60%	4.17%	4.62%
	Triangular	3.84%	7.36%	12.29%	6.25%	2.89%	3.27%	3.75%	4.23%
	Uniform	2.90%	5.64%	9.60%	4.80%	2.44%	3.12%	3.55%	4.10%
2B	Top story	6.09%	10.28%	12.85%	2.24%	1.78%	3.07%	4.51%	4.71%
	Triangular	4.47%	7.75%	9.84%	1.16%	1.31%	2.31%	3.54%	4.00%
	Uniform	3.43%	6.02%	7.82%	0.79%	1.03%	1.84%	2.93%	3.56%
2C	Top story	6.76%	11.30%	8.07%	-3.51%	1.39%	2.34%	3.35%	3.39%
	Triangular	5.05%	9.35%	7.38%	-2.13%	1.09%	1.89%	2.82%	3.10%
	Uniform	3.90%	7.29%	7.08%	-0.69%	0.88%	1.57%	2.44%	2.90%
2D	Top story	5.77%	10.40%	16.68%	9.48%	5.30%	8.59%	8.74%	8.65%
	Triangular	4.28%	7.79%	12.76%	6.90%	4.04%	7.38%	8.64%	8.60%
	Uniform	3.36%	6.09%	10.07%	5.43%	3.20%	5.76%	8.63%	7.22%
2E	Top story	5.52%	10.05%	15.98%	8.87%	0.51%	0.91%	1.37%	1.77%
	Triangular	4.05%	7.48%	12.18%	6.47%	0.35%	0.65%	1.03%	1.42%
	Uniform	3.14%	5.81%	9.57%	5.08%	0.27%	0.54%	0.89%	1.33%

Figure 5 shows the results for cases where the maximum MTMD ratio at any floor is limited to 10 percent. This means that the mass ratio for MTMD at the top story is 10 percent; the MTMD ratio at each story of uniform distribution is 10 percent; while the MTMD ratio at the top story of triangular distribution is 10 percent and reduced linearly for the stories below. Therefore, the total mass ratio of MTMD system for the three scenarios varied, 10 percent for top floor, 35 percent for triangular distribution, and 60 percent for uniform distribution.

For Structure 1A under El Centro earthquake, both uniform and triangular distribution produce better results than placing all MTMD at the top floor. When the same structure is subjected to Loma Prieta ground motion, the best results are given by the triangular distribution.

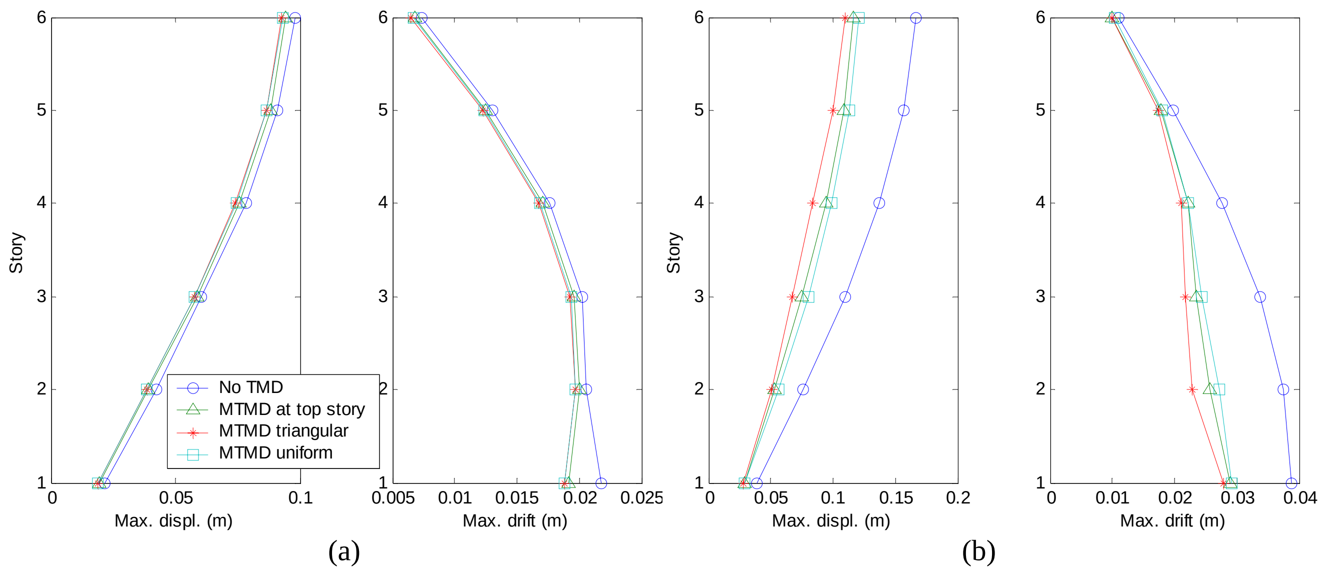


Figure 5 Maximum displacement and drift of Structure 1A under (a) El Centro and (b) Loma Prieta earthquake using maximum mass ratio of 10% at any story.

4. CONCLUDING REMARKS

Numerical analysis has been carried out to better understand the effect of structural variation on the performance of MTMD system using 6-story and 12-story structures with different stiffness and mass irregularity subjected to El Centro, Northridge, and Loma Prieta ground motions. The results show that attaching MTMD to the structure can help reducing the maximum displacement and drift of the structure, as well as linearizing drift patterns. In all scenarios, placing all MTMD at the top floor gives the best reduction of maximum displacement and drift.

Structures with soft first story tend to have significant drift at the first story. The effectiveness of MTMD tends to be affected by this irregularity. The study found that MTMD performed better when the stiffness reduction at the first story is smaller. However, MTMD system appears to be less affected by irregularity of the first floor mass.

The results for different mass ratio show that generally higher mass ratio of MTMD produces better responses. However, in some cases, MTMD with 20 percent mass ratio gives the highest reduction of maximum displacement and drift. When the limit of MTMD mass ratio was changed to 10 percent at any floor, the uniform and triangular distribution can utilize larger total mass ratio and thus improve their performances compared to placing all MTMD at the top floor.

REFERENCES

Abe, M. and Fujino, Y. (1994). Dynamic characterization of Multiple Tuned Mass Dampers and some design formulas. *Earthquake Engineering and Structural Dynamics* **23**, 813-835.

Den Hartog, J. P. (1984) Mechanical Vibrations, Dover Publications, Inc.

Igusa, T. and Xu, K. (1994). Vibration control using Multiple Tuned Mass Dampers. *Journal of Sound and Vibration* **175**, 491-503.

Kareem, A. and Kline, S. (1995). Performance of Multiple Mass Dampers under random loading. *Journal of Structural Engineering* **121**, 348-36.

Kusumastuti, D. and Rildova (2006a). Seismic performance of structures with Multiple Tuned Mass Dampers. *Proceedings of 10th East Asia Pacific Conference on Structural Engineering and Construction*, *Bangkok*, *August 2006*, **7**, 89-94, AIT Thailand.

Kusumastuti, D. and Rildova (2006b). Parametric Study of Multiple Tuned Mass Dampers in Reducing Seismic Response of Building Structures. Technical Report of ITB Research Grant 2006 No. 0018/K01.03.2/PL2.1.5/I/2006, LPPM-ITB, Bandung, Indonesia.

Rildova, Kusumastuti, D., and Handayani, N. (2007). Optimal placement of multiple tuned mass dampers to improve structural performance of buildings under earthquake excitation. *Proceedings of the 1st European Asian Conference on Civil Engineering* (*EACEF*), *Lippo Karawaci, September 2007,* C123-C130.

Yamaguchi, H. and Harnpornchai, N. (1992). Fundamental characteristics of Multiple Tuned Mass Dampers for suppressing harmonically forced oscillations. *Earthquake Engineering and Structural Dynamics* **22**, 51-62.