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EFFECTIVENESS OF TUNED MASS DAMPER IN DAMAGE REDUCTION OF BUILDING UNDER FAR-FIELD GROUND MOTIONS

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Abstract. *Damage reduction of existing tall buildings subjected to earthquake ground motions has been studied in recent decades. Seismic base isolations, strengthening of structural system and installation of damping devices such as viscous dampers, friction damper and buckling restrained brace, have also been introduced to either reduce the seismic demand, improve the strength or dissipation characteristics of the building. However, their applications are very limited since their investment costs seem to be prohibited. A tuned mass damper (TMD) installed at rooftop is proposed as an alternative method to reduce the seismic damage of the existing tall buildings under far-field earthquake excitations. Due to the long duration and narrow band nature of far-field excitation, its application becomes effective. In addition, the cost of the TMD is more attractive comparing to other seismic control systems. However, the performance of TMD might be seriously impaired due to the degradation of structural stiffness caused by severe earthquake. Therefore the real application of the TMD has to be extensively investigated. This paper studies the damage behavior of tall building under various magnitudes of harmonic and recorded ground motions. The dynamic inelastic analysis is employed. The effectiveness of TMD having mass ratio of 5% is evaluated considering the building's damage and performance. The obtained simulation results reveal the effectiveness of the TMD under various intensities of ground motions.*

1 INTRODUCTION

Tuned mass dampers, consist of stiffness, inertia and damping elements, has been used for vibration control of structures under lateral load such as wind [1,2] and earthquake. Tuned mass damper is an inexpensive and effective control device when compare to other applications. Tuned mass damper can greatly reduce the seismic response of the structure within elastic range but when experiences inelastic behavior, the effectiveness of tuned mass damper tend to decreases due to detuning effect under strong ground motion.

Pinkaew et. al. [3] proposed the damage index, based on Park et. al. [4], to describe the effectiveness of TMD instead of displacement reduction of inelastic structure. The efficiency of TMD for control 20 story reinforced concrete building subjected to 1985 SCT is considered. It is found that although TMD cannot reduce the peak displacement after yielding, it can significantly reduce the damages of the building and improve the ability to withstand the severe ground motions. Wong and Johnson [5] studied the seismic energy dissipation of inelastic structure of various placements of multiple TMDs. Their results indicate that placing one TMD at the top floor is the best location to dissipate a large amount of plastic energy. As a result, highest damage reduction in the structure can be expected. Rofooei and Abatahi [6] considered three structural models subjected to seven earthquakes varying the intensity. For the 12 and 15 story buildings, it is found that TMD can greatly reduce the damage of structure, however for the 8 story building, its performance significantly decreases at the same intensity because of the detuning effect. Assuming the building can be modeled by bilinear hysteretic SDOF, Zhang and Balendra [7] proposed a method to obtain the optimal parameters of TMD by minimizing the maximum inelastic response under narrow band excitations of long distance earthquakes. The effectiveness of TMD designed using their proposed method is investigated. It is found that the proposed optimal TMD can provide better damage reduction than traditional design formula.

Nevertheless, the above mentioned researches did not consider the realistic inelastic behavior of the buildings to evaluate the effectiveness of TMD. Therefore, in this study, the nonlinearity characteristics of a three dimensional 20-story reinforced concrete buildings are modeled by the lumped plasticity hinges according to ASCE 41 standard [8]. The Perform 3D program [9] is employed to conduct the inelastic dynamic analysis of the building under harmonic and actual earthquake ground motions with varying peak ground accelerations from zero to collapsed acceleration. The obtained results are used to evaluate the effectiveness of TMD and its control characteristics.

2 AN EXAMPLE REINFORCED CONCRETE BUILDING

In this study, a 20 story reinforced concrete residential building as outlined in Moehle et.al. [10] is considered. The moment resisting frame and shear wall are re-designed to resist the gravity load based on ASCE7-10 and ACI318-08. The plan and elevations are shown in Fig. 1. This building is not designed for earthquake but only gravity loads and uniform wind pressure of 2.0 kN/m^2 are taken into account. Compressive strength of concrete of 30 MPa and yield strength of reinforcement of 400 MPa are used. The thickness of shear wall is 0.15 m with 0.33% and 0.25% of reinforcement in vertical and transverse directions, respectively. The cross-section of columns vary from 0.30 m x 0.30 m to 0.75 m x 0.75 m while the thickness of slabs are 0.2 m in every floors.

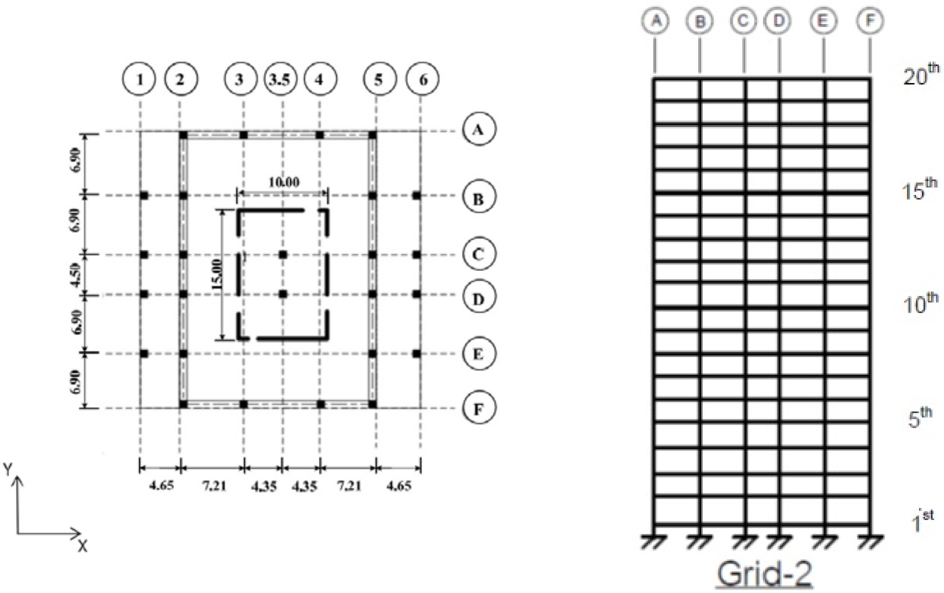


Fig. 1. Plan and elevation

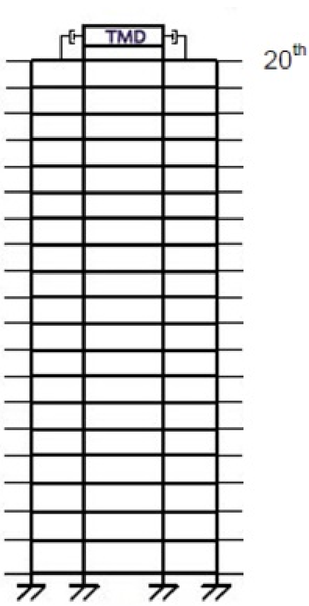


Fig. 2. Example building installed by TMD

3 THE PROPERTIES OF TUNED MASS DAMPER

The example building as previously mentioned is installed by the tuned mass damper (TMD) on the top roof, Fig. 2. To design the optimal parameters of TMD, the equivalent SDOF system of the building is considered based on the fundamental mode of vibration.

In this study, the tuned mass damper with 5% mass ratio is provided to resist both harmonic ground motion and far-field earthquake with varying amplitudes until the collapse of the building. The parameters of TMD are set to the optimal values of the TMD installed on linear structure under harmonic loading given by Den Hartog [11] as shown in Eq.(1)

$$\gamma_{opt} = \frac{1}{1+\mu}$$
$$\zeta_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{1}$$

Where μ, γ and ζ are, respectively, mass ratio, frequency ratio, and damping ratio

Building	Total	Mass = 19,941 tons
	SDOF (Mode 1)	Mass = 5,334 tons, Stiffness = 43,859 kN/m, Period = 2.19 s, Damping ratio = 0.015
TMD		Mass = 997 tons, Stiffness = 5,839 kN/m, Damping ratio = 0.24

Table 1 : Properties of the equivalent SDOF system and tuned mass damper

4 DAMAGE AND PERFORMANCE OF BUILDING

4.1 Damage Index

4.1.1 Component Damage

To quantify the effectiveness of the tuned mass damper in damage reduction of the building induced by strong ground motion, the modified Park and Ang damage index as proposed by Kunnath et al. [12] is employed. This index consist of term of rotation and dissipated energy as in Eq.(2)

$$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_h \tag{2}$$

Where θ_m, θ_u and θ_r are, respectively, maximum rotation, ultimate rotation, and recoverable rotation (unloading)

M_y is the yielding moment

E_h is the dissipated energy of the element

β is the strength deterioration parameter (assumed to be 0.27 by Ciampoli et. al. [13])

4.1.1 Story Damage

Damage index of story is evaluated by weighted average of dissipated hysteretic energy in the component, Eq.(3) . In this study, the maximum grid damage in each story is represented as a story damage of the building.

$$DI_{story} = DI_{grid}\Big|_{MAX} = \sum_{i=1}^{n} (DI_i)_{component} \left[\frac{E_i}{\sum_{i=1}^{n} E_i} \right]_{component} \tag{3}$$

Where E_i are the total absorbed energy by the component "i".

4.1.2 Building Damage

Building damage is assumed to be the maximum story damage of the building.

4.2 Building Performance Levels

Besides the quantitative evaluation of building damage as previously mentioned, this study also calculate the building performance based on the maximum plastic rotation of every structural components according to ASCE41 as following

4.2.1 Operational

Very light damage, no permanent displacement, substantially original strength and stiffness, and backup utility services maintain functions.

4.2.2 Immediate Occupancy (IO)

Very light damage, no permanent displacement and substantially original strength and stiffness, Minor cracking, and The building remains safe to occupy; any repairs are minor.

4.2.3 Life Safty (LS)

Moderate damage, Some permanent displacement, Residual strength and stiffness in all stories. Structure remains stable and has significant reserve capacity; hazardous nonstructural damage is controlled.

4.2.4 Collapse Prevention (CP)

Severe damage, Large permanent displacement, Little residual strength or stiffness, Gravity elements function. Some exits blocked. The building remains standing but near collapse and other damage or loss is acceptable.

5 EFFECTIVENESS OF TMD UNDER ASSUMED HARMONIC GROUND MOTION

The effectiveness of TMD are evaluated under an assumed harmonic ground motion with time-varying amplitudes, as shown in Fig. 3. The amplitude of ground motion is assumed to be linearly increased from t = 0 s to reach its PGA at t = 15 s and is kept constant from t = 15-45 s, then, is assumed to be linearly reduced to zero at t = 60 s. The ground motion frequency is set to the first natural frequency of the building and its PGA is varied from zero until the collapse of the building is obtained.

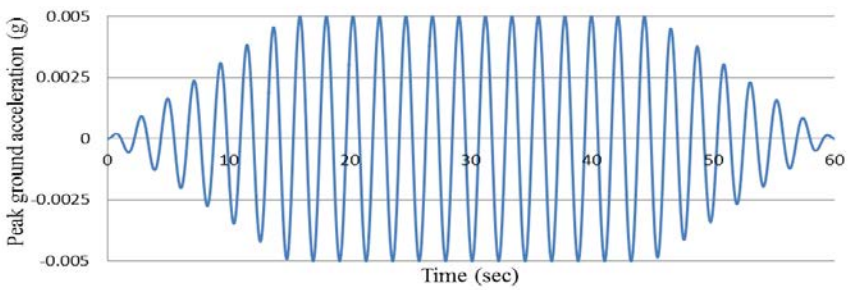


Fig. 3. An assumed harmonic ground motion

Fig. 4. shows the typical roof displacement of the building with and without TMD when PGA of ground motion is 0.02g. Since the excitation frequency is intentionally set to the natural frequency of the building, the resonance vibration of the building is expected. With this magnitude of excitation, it is found that the building without TMD exhibits excessive vibration with building damage = 1.0 and the building performance goes beyond the collapse prevention limit (CP) while that with TMD gets no damage and its performance are well within operational limit. It is noted that about 83% of roof displacement reduction by TMD can be observed.

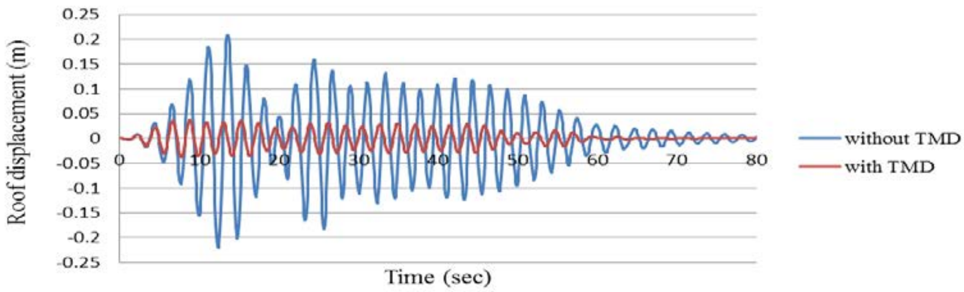


Fig. 4. Roof displacement of the building along X direction with and without TMD under an assumed harmonic ground motion with PGA = 0.02g

Fig. 5 shows the comparison of damage index between building without and with TMD under harmonic ground motion with varying PGA. Damage Index of the building with TMD is equal to 1 when a PGA is 0.115g, while damage index of the building without TMD exceeds the collapse line when PGA is only 0.02g. Fig. 6 show the damage reduction from TMD, for PGA less than 0.002g, there is no damage to both buildings, so the damage reduction is not defined. For PGA between 0.002g and 0.05g, TMD can prevent the building damage. In particular, the building without TMD collapses when PGA reaches 0.02g while that with TMD can resist the ground motion without any damage until PGA = 0.05g. Although, the building with TMD shows some damages when PGA is greater than 0.05g. The building is protected from collapse until PGA reaches 0.115g. In addition, it can be seen that when the structure is vibrated within a range of slight inelasticity, damage reduction slowly decreases. However, due to the de-tuning effect, the damage reduction rapidly decreases when the building is vibrated within a range of significant inelasticity.

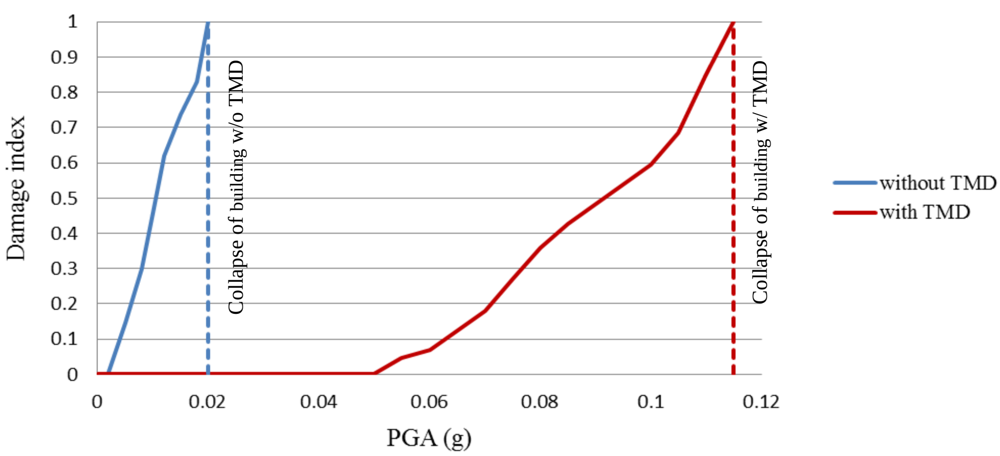


Fig. 5. Damage index of the building against PGA under harmonic ground motion

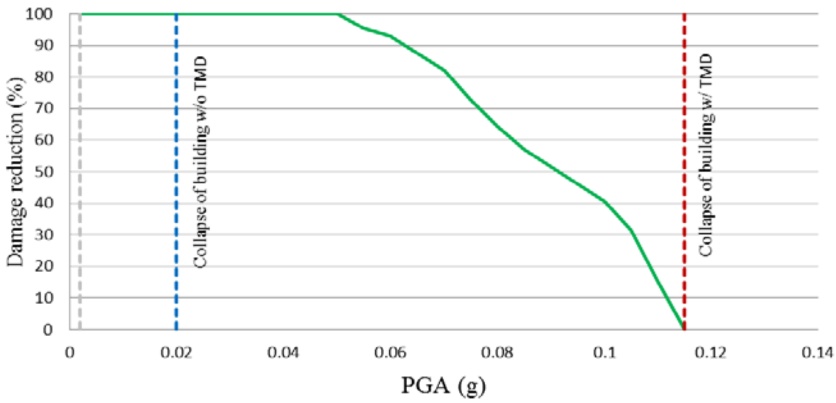


Fig. 6. Damage reduction of the building with TMD under harmonic ground motion

Fig. 7 shows the seismic performances of the critical frames and walls of the building with and without TMD under collapse ground motions. Frames along Grid A and F in the top floor are the most damaged zones of both structures. While the shear wall damages are found only at the ground floor. Fig.7a shows the damage scenario of the building without TMD under PGA = 0.02g, it can be seen that the columns in the upper story get more damage than lower story. In particular, the corner columns in the 18th -19th floor reach CP performance limit, while the performances of internal columns are well within LS limit. The damage in shear walls is found at the ground floor with CP performance limit. Fig. 7b, on another hand, shows the damage scenario of the building with TMD under PGA = 0.115g. It is found that it looks quite similar with that without TMD except the ground motion is about 5.7 times larger.

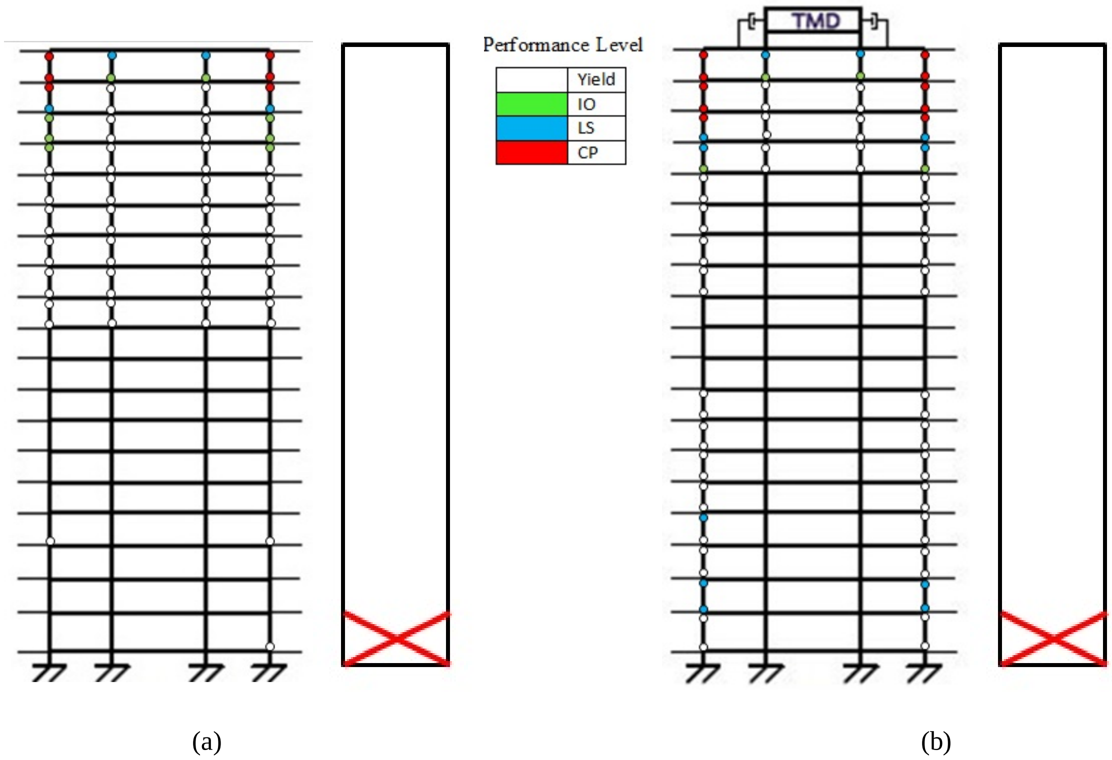
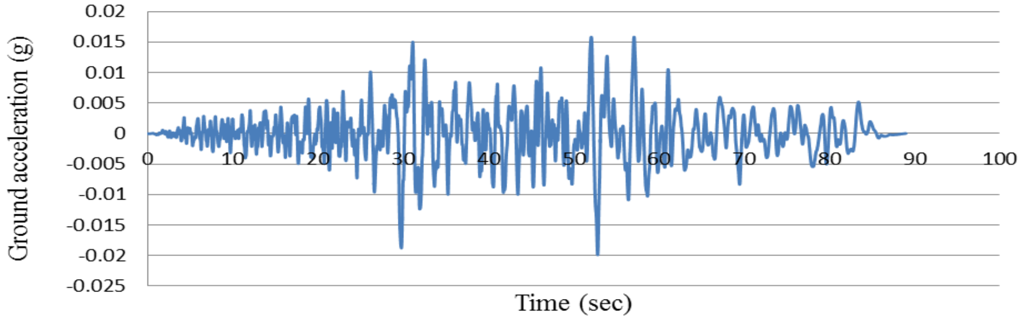


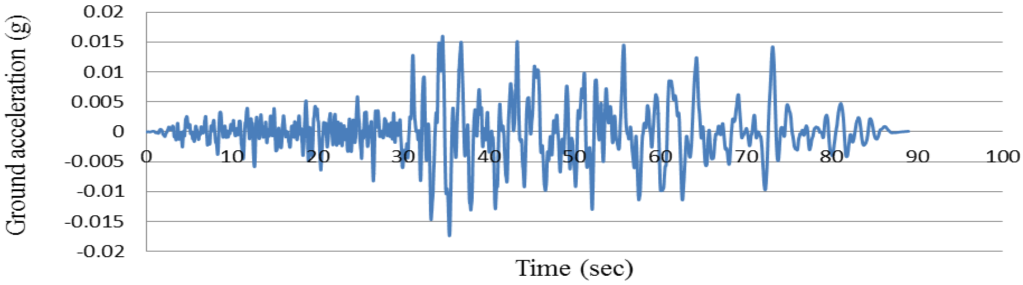
Fig.7. (a) Performance of building without TMD under a harmonic ground motion with PGA = 0.02g
(b) Performance of building with TMD under a harmonic ground motion with PGA = 0.115g

6 EFFECTIVENESS OF TMD UNDER A FAR-FIELD GROUND MOTION

In this study, the Chi-Chi earthquake record (1999) at KAU082 station is adopted as a far-field ground motion as shown in Fig. 8. It is noted that this record has a dominant frequency close to the natural frequency of the building and therefore the resonance vibration of the building can be expected



(a)



(b)

Fig. 8. Chi-Chi (1991) earthquake in, (a) X direction and (b) Y direction

Fig. 9 shows the roof displacement of the building along XX direction with and without TMD under the input ground motion with PGA of 0.0116g. With this magnitude of PGA, both buildings are vibrated within elastic range. It is observed that about 41.7% of displacement reduction can be gained from TMD. Fig. 10 shows the roof displacement of the building with and without TMD when the PGA of the input earthquake is increased to the collapse PGA of the building without TMD at 0.042g. It is clearly seen that TMD is not effective in displacement reduction of the structure. In particular, only 0.04% displacement reduction is obtained. By comparing with elastic range of Building, TMD's effectiveness in roof displacement decreases when PGA increases.

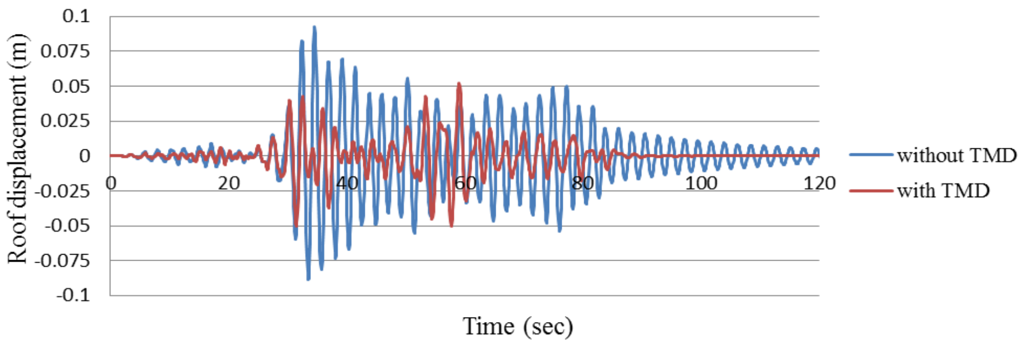


Fig. 9. Roof displacement of the building along X direction with and without TMD under Chi-Chi earthquake with PGA of 0.0116g

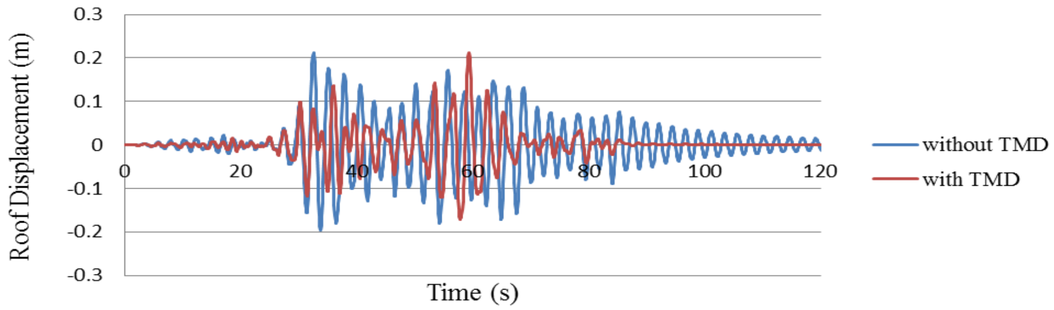


Fig. 10. Roof displacement of the building along X direction with and without TMD under Chi-Chi earthquake with PGA of 0.042g

Fig. 11. shows the comparison of damage index between buildings without and with TMD under input earthquake with varying PGA. It is noticed that the damage index of the building with TMD equals to 1 when PGA is 0.054g, while damage index of the building without TMD equals to 1 when PGA is 0.042g. This indicates about 30% enhancement of collapse prevention by TMD. Fig. 12 shows the damage reduction and roof displacement reduction by TMD. In term of damage reduction, for PGA less than 0.0116g, there is no damage to both building so that the damage reduction is not defined. For PGA between 0.0116g and 0.0193g, although the damages of the building without TMD increase as the PGA increases, there is no damage to the building with TMD in this range of excitation. For PGA between 0.0193g and 0.043g, TMD can reduce the damage of the building, however it effectiveness in damage reduction becomes smaller as the PGA increases. For PGA is greater than 0.054g, the building with TMD also collapses and therefore TMD provides no benefit to the building. In term of roof displacement reduction, TMD can suppress the roof displacement whenever the building vibration is within elastic range or slightly inelastic range.

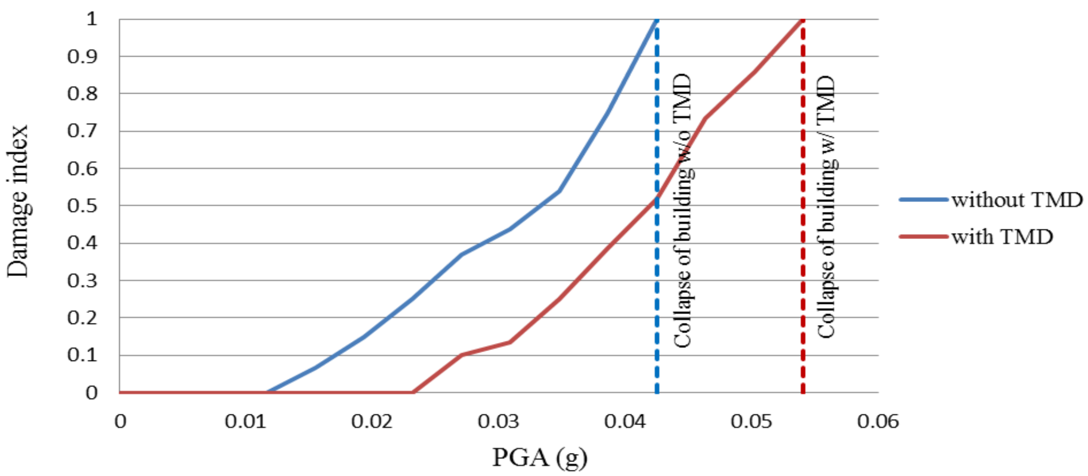


Fig. 11. Damage index of the building against PGA under Chi-Chi earthquake

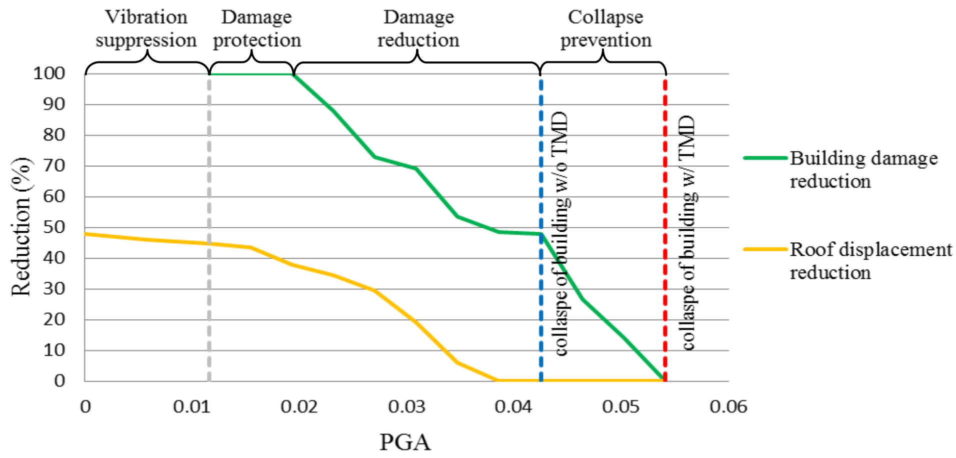


Fig. 12. Vibration and damage reduction of the building with TMD under Chi-Chi earthquake

Fig. 13 shows the seismic performance of critical frames and walls of the building with and without TMD under the input earthquake having PGA = 0.042g. Frames along grid A and F in the top floor are the most damaged zones of both structures. Fig.13a shows the damage scenario of the building without TMD. Similar to the case of harmonic ground motion, it can be seen that the damages occur in only upper story and the most damaged columns in the story are the corner columns. While the shear wall damage occurs only at the first story where the CP performance limit is observed. Fig. 13b shows the damage scenario of the building with TMD under the same magnitude of PGA. Obviously, the damages are not severe comparing with the collapse of the building without TMD. In particular, there is no column and shear wall gets damage of CP performance limit

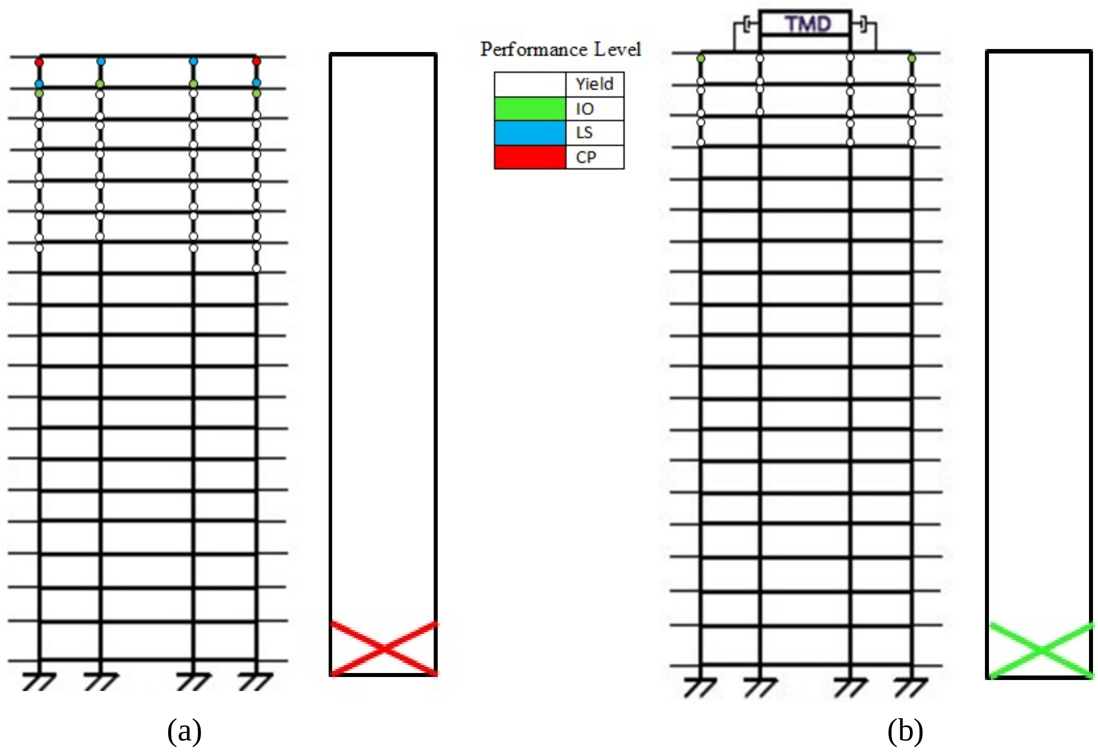


Fig. 13. Comparison of building performance level between (a) builiding without TMD
(b) building with TMD under Chi-Chi earthquake with PGA of 0.042g

7 CONCLUSIONS

In this study, the seismic effectiveness of TMD for a 20 story reinforced concrete building subjected to both harmonic and earthquake record ground motions with varying amplitudes until the building collapse is investigated. The inelastic modeling of the building according to ASCE 41 is employed to realistically represent the building behavior under strong ground motion. The dynamic inelastic analysis of the building with and without TMD is adopted. To evaluate the effectiveness of TMD, the damage index and building performance level are estimated. The obtained results indicate that, for these narrow band ground motions, TMD is effective in displacement reduction whenever the vibration of the building is within elastic or slightly inelastic ranges. When the building gets significant damages, the change in vibration frequency deteriorates its effectiveness due to de-tuning effect. Therefore, TMD cannot provide any significant displacement reduction in this high inelastic range. However, it is clearly found that TMD can protect or reduce the building damages induced by the ground motions. The damage protection and reduction are significant. In addition, it is also observed that TMD can prevent the building from collapse with a significant range of ground motion magnitude. Based on this investigation, the application of TMD to a tall building subjected to far-field ground motions seems to be an attractive alternative to other retrofitting techniques.

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