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Effectiveness of tuned mass damper system for steel frame building

Thanh Binh Pham and Van Tu Nguyen

Institute of Techniques for Special Engineering, Le Quy Don Technical University, Viet Nam.

E-mail: ptb@lqdtu.edu.vn

Abstract. The paper presents the analysis of using tuned mass damper system for reducing the response of structure subjected to lateral force, such as earthquake action. The assumed steel eight-story steel frame building is examined. The tuned mass damper system is modeled as 2 joint link in SAP2000, attached to top story of the building. The effect of tuned mass damper system for building under seismic excitation was evaluated by the results of maximum displacement and acceleration of the building. A sensitivity study was also performed to compare the structural response with different mass ratios. From the calculated results, discussions and conclusions are presented.

1. Introduction

Nowadays, the rushing development of economy and advanced construction technology bring to mankind the ability to build more and more high structure. The tall, supertall and mega tall buildings appear everywhere all over the world [3]. They are designed with additional flexibility, which lead to an increase in their response to external load. The flexible structures have fluctuations, i.e. vibrations that exceed the permissible limits. The problem of response mitigation of building has become important and practical in structural engineering. There are many applications [2] are being developed to do that task, such as: active control, passive control, semi-active control and hybrid control. Among them, tuned mass dampers (TMD) are widely used in many structures because of its reliability, simplicity and effectiveness.

TMD in the simple form consists of a mass on the spring moving along the direction of vibrations of the structure. The TMD was first proposed by Frahm [7], and then has been properly studied by Den Hartog [5], who found optimum frequency and damping of system under harmonic load. The frequency of the damper is tuned to a structural frequency so that the damper will resonate out of phase with the motion of structure. In [16], the natural frequency of the TMD is tuned in resonance with the fundamental mode of the structure. The vibration of building then will be transferred to the TMD and dissipated by damper.

This paper presented the analysis of dynamic structural response changing when using TMD. The objects are:



- Define the effectiveness of TMD to the fundamental period of the building;
- Define the peak acceleration and displacement of the top node of the building under seismic action;

- Define effectiveness of mass of TMD on the structural response;

2. Basic principle of TMD

The system with TMD [5][4] can be considered as two degree of freedom system with two mass and stiffness, damping properties of base structure and absorber respectively (see figure 1). In other words, the whole system can be single degree freedom and TMD system.

In figure 1: m_1 is the main structure mass, m_d is the damper mass, k_1 is the main spring stiffness, k_d is the spring stiffness of absorber, c_d is the absorber damping, $P_1(t)$ is the force acting on the main mass.

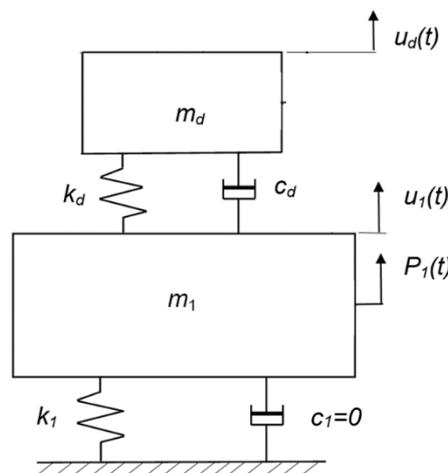


Figure 1. A damped vibration absorber according Den Hartog **Ошибка! Источник ссылки не найден..**

The equation of motion of the main mass is given here, as []:

$$m_1 \ddot{u}_1(t) + k_1 u_1(t) + k_d [u_1(t) - u_d(t)] + c_d [\dot{u}_1(t) - \dot{u}_d(t)] = P_1(t) \quad (1)$$

For the absorber:

$$m_d \ddot{u}_d(t) + k_d [u_d(t) - u_1(t)] + c_d [\dot{u}_d(t) - \dot{u}_1(t)] = 0 \quad (2)$$

3. TMD modelling

In order to simulate the TMD in tall building, a linear link was introduced in SAP2000 [8] **Ошибка! Источник ссылки не найден..** The TMD is considered as the pendulum absorber [13]. The link has the stiffness and mass assigned to it and is connected to a rigid joint.

The TMD consists of mass that is attached to a free point and connected to floor of building model by a spring of equivalent stiffness.

The parameter of TMD: natural frequency and the equivalent stiffness and effective damping are determined as following [8].

The natural period of the pendulum mass is calculated using formula below:

$$T_d = 2\pi \sqrt{\frac{L}{g}} \quad (3)$$

Where:

T_d - natural period of pendulum (TMD) in seconds;

L - length of pendulum in meters;

g - acceleration of gravity in m/s^2 .

The equivalent stiffness of damper is calculated using formula below:

$$k_{eq} = \frac{W_d}{L} \quad (4)$$

Where:

k_{eq} - Equivalent stiffness of damper in N/m;

W_d - weight of damper in Newtons;

L - length of pendulum in meters.

The effective damping is calculated using formula below:

$$C = 2\xi \sqrt{k_{eq} m_d} = 2\xi \sqrt{\frac{g}{L}} \quad (5)$$

Where:

C - effective damping;

ξ - coefficient of modal damping;

m_d - mass of damper.

4. Numerical examples and discussion

The dynamic behavior of 8-storey steel frame building without TMD (figure 2, a) is examined under seismic action by time history analysis. The model with TMD (figure 2, b) is also investigated to compare structural responses with those calculated from model without TMD.

The data of structure is: frame column with section W14x193, beam section W27x102; module $E=2.0e+8$ MPa; the modal damping $\xi = 0.05$. The frame is subjected to seismic action in the Imperial Valley in southeastern Southern California on May 18, 1940. The data of this earthquake is taken from time history functions of SAP2000. The fundamental period of building is 0.688 seconds.

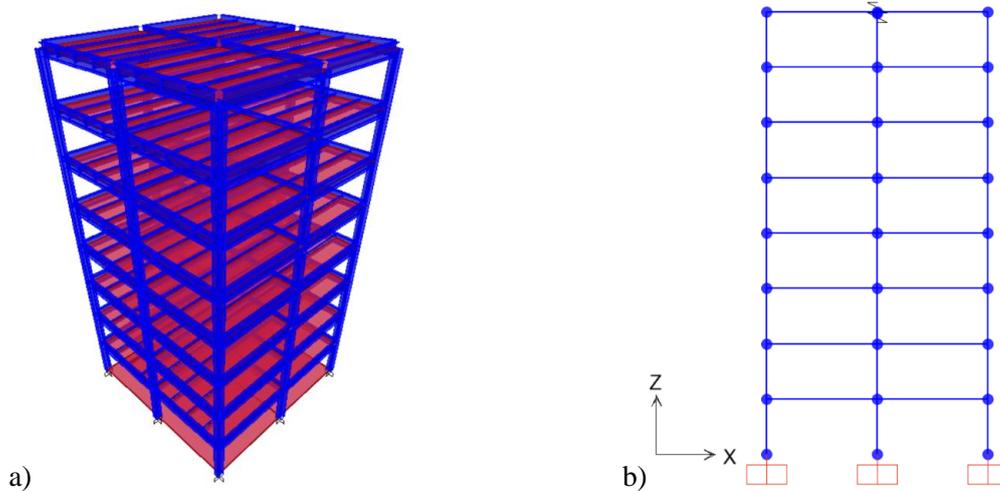


Figure 2. Eight-story steel frame building without and with TMD.

4.1. Effect of TMD on fundamental period of the building

TMD is attached in to the top story of the building with a mass of 30 kN-sec²/m, 5% of the structure mass. It has a length of 0.12 meters, which is calculated by formula (3), considering the period of TMD equals the fundamental period of building. So the effective stiffness k_{eq} is approximately 2500 kN/m according to formula (4).

The analysis results show that, with the TMD, the fundamental period of the building was increased from 0.688 seconds to 0.818 seconds, which is about 18.89 percentage. The difference in modal shapes of model without and with TMD was illustrated in figure 3 and figure 4, respectively. The present of TMD impacted only on the translation modes of system, but the torsional mode remained unchanged. This could be explained by the center location of TMD in the top floor of frame structure.

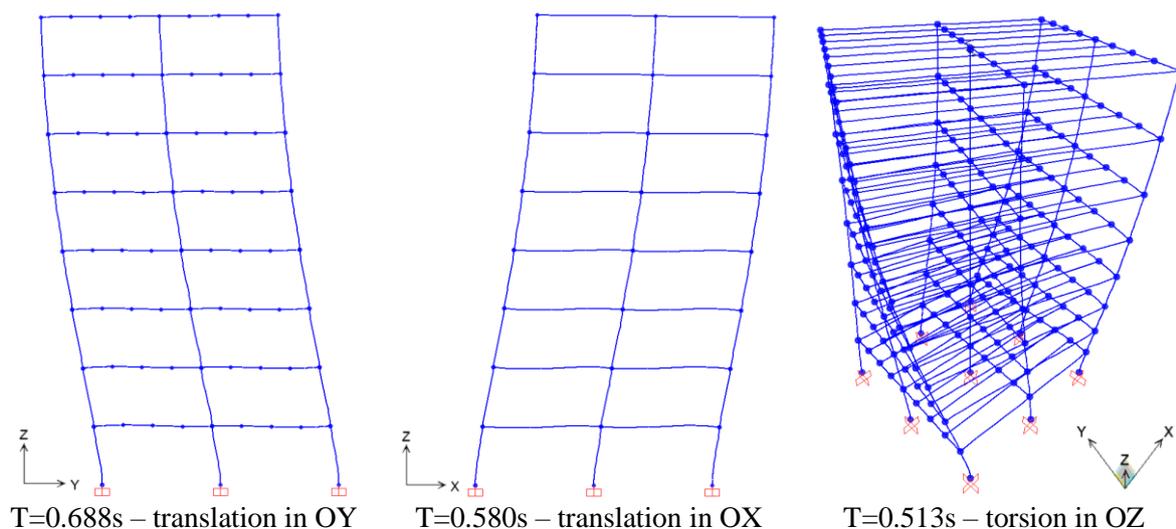


Figure 3. Modal shapes of building model without TMD.

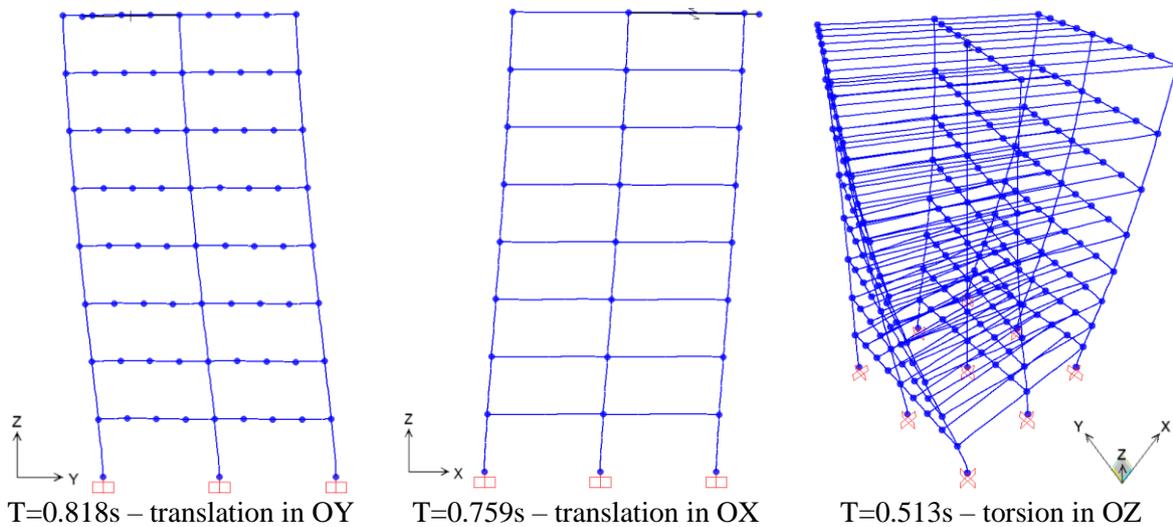


Figure 4. Modal shapes of building model with TMD.

4.2. Structural response under earthquake

Using the TMD bring the structure better behavior under seismic action. The acceleration and displacement at the top-story node 200 of models without and with TMD is shown in figure 5 and figure 6, respectively. Comparing with responses of model without TMD, the maximum acceleration was decreased by 18% from 0.639 m/s^2 to 0.524 m/s^2 . The peak displacement was decreased by 5.97% from $7.974\text{e-}03\text{ m}$ to $7.590\text{e-}03\text{ m}$.

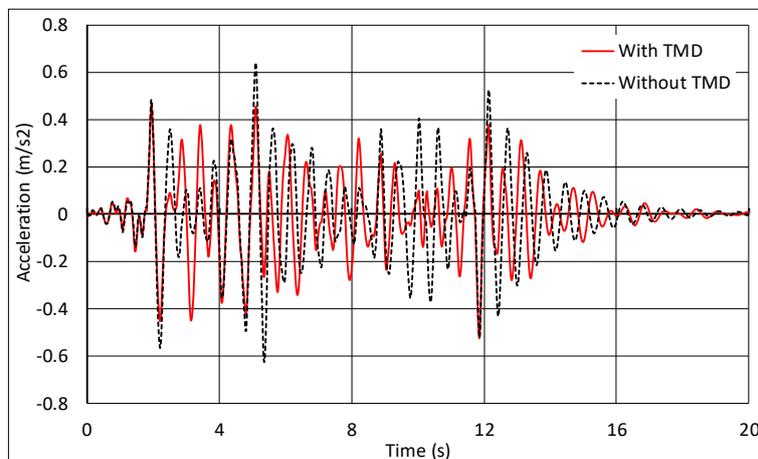


Figure 5. Acceleration of node 200 of models without and with TMD.

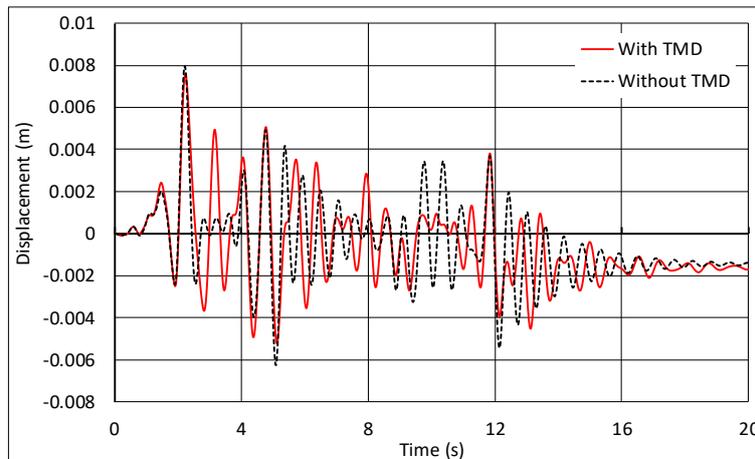


Figure 6. Displacement of node 200 of models without and with TMD.

4.3. Effect of mass ratio on structural response

To understand the effectiveness of TMD mass on the structural behavior, a sensitivity analysis was conducted to compare the structural response in cases with different mass ratio: 5%, 10% and 15%. The results, acceleration and displacement of top-story node 200 are shown in figure 7 and figure 8. It can be seen that the structural response is reduced relatively with the increase of mass ratio. However, increasing mass ratio produced negative effect on structure. Peak accelerations of node 200 in both cases with mass ratio 10% (0.614 m/s^2) and mass ratio 15% (0.661 m/s^2) were increased compared to the case with mass ratio 5% (0.524 m/s^2). Similarly, the maximum displacement of node 200 with mass ratio 10% was $7.46\text{e-}3 \text{ m}$, decreased compared to the case with mass ratio 5% ($7.59\text{e-}3 \text{ m}$). But in the case with mass ratio 15%, it was increased ($8.925\text{e-}3 \text{ m}$).

The effectiveness of TMD system was also studied by evaluating the story drift of frame in different cases of mass ratio. The results in figure 9 showed that, increasing mass ratio of TMD reduced the maximum story drift, which was beneficial for structure. However, system with exclusively increased mass ratio has negative effect on story drift. In examined cases, system with mass ratio 10% has decreased maximum story drift compared to the case with mass ratio 5%. But it was increased in the case with mass ratio 15%.

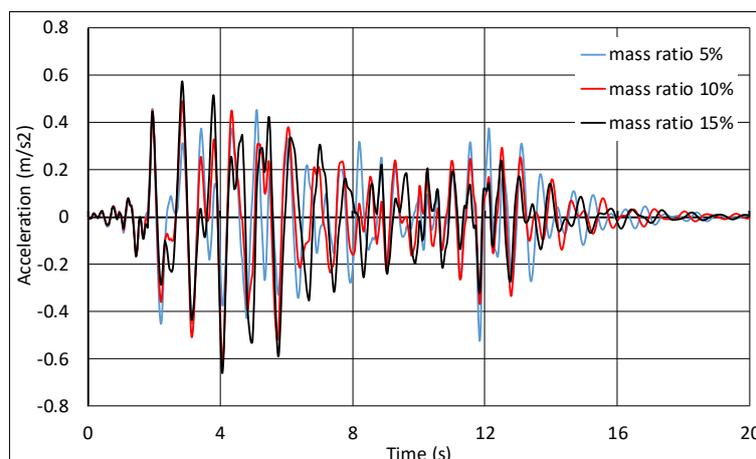


Figure 7. Acceleration of node 200 of models with different TMD mass ratios.

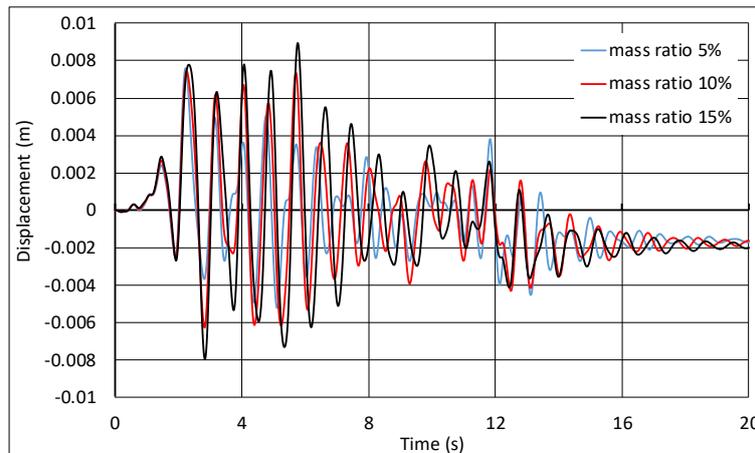


Figure 8. Displacement of node 200 of models with different TMD mass ratios.

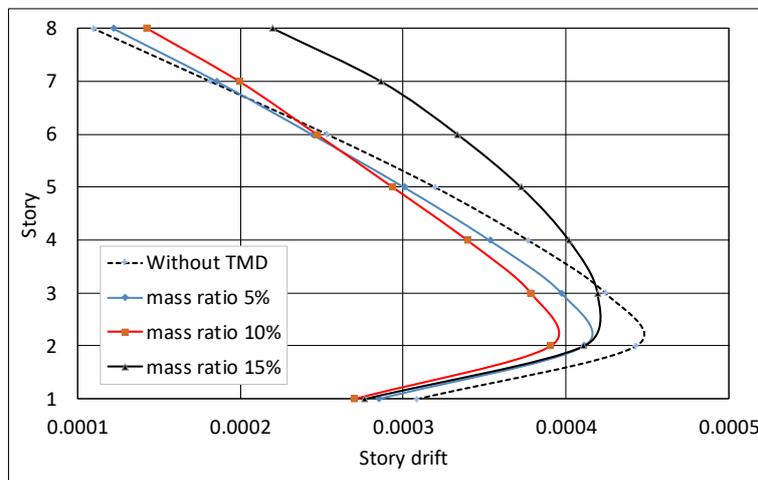


Figure 9. Story drift of structure with different TMD mass ratios.

5. Conclusions

When performing time history analysis of frame building under seismic action, the effect of TMD has been proven. The peak of acceleration and displacement of top-story node are reduced relatively. The investigation of effectiveness of TMD mass on structural response showed that, in some cases the increasing mass ratio may have negative effect on structure. Therefore, in each specific case, it is necessary to be cautious in choosing TMD mass to achieve beneficial effect of it.

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