Top-story mass dampers for seismic control of asymmetric-plan buildings

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ABSTRACT: Using an inertial part of a building structure as a tuned mass damper (TMD) has been shown to have economic advantages in terms of required materials and space for installing and operating a TMD in a building. This study suggests either designing the top story of a new asymmetric-plan building or adding a purposely designed story atop an existing asymmetric-plan building as a TMD to protect the building against earthquakes. This novel TMD, called a top-story mass damper (TSMD), is formulated using the three-degree-of-freedom modal properties of the first triplet of vibration modes of the original two-way asymmetric-plan building. The so-called first triplet of vibration modes are the first dominant modes in each of the three directions, i.e. the two horizontal translations and one vertical rotation. The proposed TSMD is intended to suppress the vibrations resulting from the first triplet of vibration modes that are generally most significant in overall seismic responses. The effectiveness of the TSMD is verified by investigating the frequency response functions of one 20-story two-way asymmetric-plan building.

1 INTRODUCTION

The effectiveness of tuned mass dampers (TMD) in reducing structural vibrations caused by wind, earthquakes, and heavy industrial machinery has been validated in the literature (Tsai and Lin 1993, Lin et al. 2011). Some famous buildings with TMDs include Taipei 101 in Taipei, Citycorp Center in New York City, the John Hancock Building in Boston, and the Shanghai World Financial Center in Shanghai. The basic components of a TMD include a mass block, a damping system, and a spring system to provide the required mass, damping, and stiffness of the damper. Although the mass ratio of a TMD to the target building is typically very small (e.g. 1% to 5%), the mass of a TMD used in engineering practice is still quite large. For example, the masses of the TMDs installed in Taipei 101, Citycorp Center, and the John Hancock Building are 660 tons, 370 tons, and 2×300 tons, respectively. Besides the bulky mass, the space housing a TMD is relatively large as the stroke of a TMD's mass block is much larger in comparison with common inter-story deflections. The large space occupied by a TMD is very likely to become a substantial cost issue for a building owner.

In order to overcome the abovementioned disadvantages of employing a TMD, Villaverde (1998) proposed a roof isolation system to reduce the seismic response of buildings. The roof isolation system, which behaves likes a TMD, exploits the self-weight of the roof structure, including the roof's slab, girders, beams, and parapets as the TMD's mass. The stiffness of the roof isolation system is provided by rubber bearings installed beneath the roof's girders and atop the building's columns. Meanwhile, the damping of the roof isolation system is typically provided by linear viscous dampers. Thus, no additional huge mass block and space are required when using such a roof isolation system. Furthermore, the ratio of the weight of the roof to the total weight of a low- or medium-rise building is generally larger than the mass ratio of a conventional TMD. Hence, the performance of a roof isolation system is superior to that of a TMD with a small mass ratio. The roof isolation system is particularly ideal for retrofitting existing buildings because no additional mass is added to the buildings and the disruptions arising from their construction are limited to only a single story. Nevertheless, the research was limited to symmetric-plan buildings. Encouraged by promising roof isolation systems (Villaverde 1998), exploring the use of a segmented top story as a mass damper for suppressing the seismic responses of asymmetric-plan buildings appears to be in demand.

When the center of mass (CM) and the center of rigidity (CR) of a building are not aligned in one or two horizontal directions, this building is referred to as a one-way or a two-way asymmetric-plan building, respectively. The typical approach of using TMDs to control the translation-rotation coupled vibration of one-way asymmetric-plan buildings is to employ the multiple tuned mass dampers (MTMD). It is clear that a set of MTMD is composed of many TMDs vibrating in only one horizontal direction, but each vibration mode of a two-way asymmetric-plan building is translation–rotation coupled. Therefore, instead of using the conventional MTMD, Lin et al. (2011) proposed a very straightforward type of TMD, which itself is translation–rotation coupled, for controlling a single vibration mode of a two-way asymmetric-plan building. Nevertheless, to the author's best knowledge, it remains inevitable to use multiple TMDs for simultaneously controlling multiple modes of an asymmetric-plan building. Therefore, this study aims at developing a novel TMD so that multiple vibration modes of a two-way asymmetric-plan building can be controlled by using only one such TMD.

Recently, Lin and Tsai (2013) developed the effective one-story building (EOSB) that retains the dynamic characteristics of a pair of vibration modes of a multistory one-way asymmetric-plan building with supplemental damping. Because the EOSB retains the dynamic characteristics of several modes of an asymmetric-plan building, it appears likely to transform an EOSB into an additional top story for suppressing the seismic responses contributed by several modes of an asymmetric-plan building. This purposely added top story is hereafter called a top-story mass damper (TSMD). In order to achieve this purpose, this study first formulates the EOSB for two-way asymmetric-plan buildings, and then optimizes the parameter values of the EOSB that eventually becomes the TSMD for a target building. The properties of the first triplet of vibration modes of the original two-way asymmetric-plan building are used to construct the EOSB. The first triplet of vibration modes are the first translational-dominant vibration mode in each of the two horizontal directions and the first rotational-dominant vibration mode of the original building. In addition, the translational and rotational properties of each of the first triplet of vibration modes are obtained by exploiting the three-degree-of-freedom (3DOF) modal systems (Lin and Tsai 2008). Figure 1 illustrates the concept of developing the TSMD for seismic control of the first triplet of vibration modes of a two-way asymmetric-plan building.

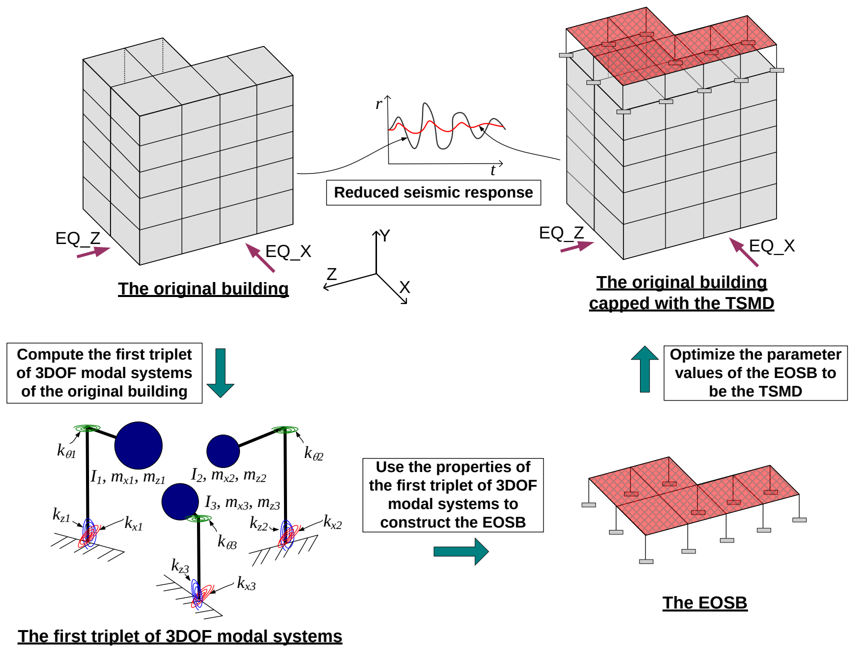

Figure 1. Concept sketch for constructing a TSMD.

2 THEORETICAL BACKGROUND

The two horizontal axes of the coordinate system used in this study are the x- and z-axes. The direction of the y-axis is opposite to the direction of gravity. The subscripts x, z, and θ used in the following

content refer to the quantities related to the *x*- and *z*-translational and the *y*-rotational components, respectively. The buildings are assumed to have proportional damping and rigid floor diaphragms. The CM and the CR of each story are not aligned with any one of the two horizontal coordinate axes. Additionally, the CMs and the CRs of all stories lie on two vertical lines, respectively.

2.1 The EOSB for two-way asymmetric-plan buildings

The mass, damping, and stiffness matrices of an *N*-story two-way asymmetric-plan building are expressed as follows:

$$\mathbf{M} = \begin{bmatrix} \mathbf{m}_x & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{m}_z & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_0 \end{bmatrix}_{3N\times 3N}, \quad \mathbf{C} = \begin{bmatrix} \mathbf{c}_{xx} & \mathbf{c}_{xz} & \mathbf{c}_{x\theta} \\ \mathbf{c}_{zx} & \mathbf{c}_{zz} & \mathbf{c}_{z\theta} \\ \mathbf{c}_{\theta x} & \mathbf{c}_{\theta z} & \mathbf{c}_{\theta\theta} \end{bmatrix}_{3N\times 3N}, \quad \mathbf{K} = \begin{bmatrix} \mathbf{k}_{xx} & \mathbf{k}_{xz} & \mathbf{k}_{x\theta} \\ \mathbf{k}_{zx} & \mathbf{k}_{zz} & \mathbf{k}_{z\theta} \\ \mathbf{k}_{\theta x} & \mathbf{k}_{\theta z} & \mathbf{k}_{\theta\theta} \end{bmatrix}_{3N\times 3N} \tag{1}$$

Meanwhile, its undamped mode shapes are expressed as:

$$\boldsymbol{\varphi}_n = \begin{bmatrix} \boldsymbol{\varphi}_{xn} \\ \boldsymbol{\varphi}_{zn} \\ \boldsymbol{\varphi}_{\theta n} \end{bmatrix}_{3N\times 1}, \quad n = 1 \sim 3N \tag{2}$$

where $\mathbf{m}_x$, $\mathbf{m}_z$, and $\mathbf{I}_0$ are the *x*-directional mass matrix, *z*-directional mass matrix, and the mass moment of inertia matrix of the original building, respectively; $\boldsymbol{\varphi}_{xn}$, $\boldsymbol{\varphi}_{zn}$, and $\boldsymbol{\varphi}_{\theta n}$ are the $N\times 1$ sub-vectors of the *n*th undamped mode shape of the original building; and $\mathbf{0}$ is the $N\times N$ zero matrix. Each element of the $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ matrices shown in Eq. (1) is an $N\times N$ sub-matrix. In addition, the *j*th *x*-translational-dominant, the *j*th *z*-translational-dominant, and the *j*th rotational-dominant vibration modes of the two-way asymmetric-plan building are grouped together as the *j*th triplet of vibration modes. The mode shape of the vibration mode belonging to the *j*th triplet of vibration modes has *j* stationary points in each direction. The stationary points of the mode shapes are also designated as nodes. The first triplet of vibration modes appears to have the most substantial contribution to the seismic responses of an *N*-story two-way asymmetric-plan building. Therefore, the EOSB is created to retain the dynamic characteristics of the first triplet of vibration modes of the original multi-story building.

The displacement vector, mass matrix, damping matrix, and stiffness matrix of the EOSB are expressed as follows:

$$\mathbf{u}^* = \begin{bmatrix} u_x^* \\ u_z^* \\ u_\theta^* \end{bmatrix}_{3\times 1}, \quad \mathbf{M}^* = \begin{bmatrix} m_x^* & 0 & 0 \\ 0 & m_z^* & 0 \\ 0 & 0 & I^* \end{bmatrix}_{3\times 3}, \quad \mathbf{C}^* = \begin{bmatrix} c_{xx}^* & c_{xz}^* & c_{x\theta}^* \\ c_{zx}^* & c_{zz}^* & c_{z\theta}^* \\ c_{\theta x}^* & c_{\theta z}^* & c_{\theta\theta}^* \end{bmatrix}_{3\times 3}, \quad \mathbf{K}^* = \begin{bmatrix} k_{xx}^* & k_{xz}^* & k_{x\theta}^* \\ k_{zx}^* & k_{zz}^* & k_{z\theta}^* \\ k_{\theta x}^* & k_{\theta z}^* & k_{\theta\theta}^* \end{bmatrix}_{3\times 3} \tag{3}$$

Meanwhile, its undamped mode shapes are expressed as follows:

$$\mathbf{\Phi}^* = \begin{bmatrix} \phi_{x1}^* & \phi_{x2}^* & \phi_{x3}^* \\ \phi_{z1}^* & \phi_{z2}^* & \phi_{z3}^* \\ \phi_{\theta 1}^* & \phi_{\theta 2}^* & \phi_{\theta 3}^* \end{bmatrix}_{3\times 3} \tag{4}$$

The three degrees of freedom of the EOSB are the x-translation, z-translation, and y-rotation defined at the CM of the EOSB. The superscript * used in Eqs. (3) and (4) represent the quantities belonging to the EOSB, in order to differentiate these notations from the commonly used notations for the original building. The damping matrix of the EOSB is assumed as Rayleigh damping, i.e. $\mathbf{C}^* = a_0\mathbf{M}^* + a_1\mathbf{K}^*$, where a_0 and a_1 are obtained from assuming the first two damping ratios of the EOSB equal to

those of the original building. Thus, only the mass matrix and the stiffness matrix of the EOSB are to be determined. That is to say, there are nine unknowns for constructing an EOSB, which are the three diagonal elements of the mass matrix and the six elements of the upper (or lower) triangle of the stiffness matrix. The three diagonal elements of the mass matrix $\mathbf{M}^*$ are equivalently considered as m_x^*, $\mu^* = \sqrt{m_z^*/m_x^*}$, and $r^* = \sqrt{I^*/m_x^*}$. Since the EOSB is expected to retain the dynamic properties of the first triplet of vibration modes of the original multi-story building, the values of μ^* and r^* should be the same as the counterparts (denoted as μ and r) of the first triplet of vibration modes of the original multi-story building. When considering the first triplet of vibration modes of the original multi-story building, the parameter μ is the square root of the ratio of the summation of its three effective modal participation z-directional mass to the summation of its three effective modal participation x-directional mass. Similarly, when considering the first triplet of vibration modes of the original multi-story building, the parameter r is the square root of the ratio of the summation of its three effective modal participation y-directional mass moment of inertia to the summation of its thee effective modal participation x-directional mass. It assumes that the value of m_x^* is equal to one. As a result, it remains six unknowns of the EOSB, which are to be determined by using the following two conditions. The first condition is that the three modal vibration frequencies of the EOSB are required to be equal to the three vibration frequencies of the first triplet of vibration modes of the original multi-story building. The other condition is that the ratio of the x-directional mass to the z-directional mass, and the ratio of the x-directional mass to the y-directional mass moment of inertia in each vibration mode of the EOSB are required to be equal to those in the corresponding mode of the original multi-story building. That is to say, the following equalities must exist:

$$\left(\phi_{xi}^* m_x^* \phi_{xi}^*\right) : \left(\phi_{zi}^* m_z^* \phi_{zi}^*\right) : \left(\phi_{\theta i}^* I^* \phi_{\theta i}^*\right) = m_{xi} : m_{zi} : I_i, \quad i = 1,2,3 \tag{5a}$$

where:

$$m_{xi} = \boldsymbol{\varphi}_{xi}^T \mathbf{m}_x \boldsymbol{\varphi}_{xi}, \quad m_{zi} = \boldsymbol{\varphi}_{zi}^T \mathbf{m}_z \boldsymbol{\varphi}_{zi}, \quad I_i = \boldsymbol{\varphi}_{\theta i}^T \mathbf{I}_0 \boldsymbol{\varphi}_{\theta i}, \quad i = 1,2,3 \tag{5b}$$

Note that the subscript i, which is equal to 1, 2, and 3, when used for the quantities associated with the original building, represents the lowest, intermediate, and highest vibration modes, respectively, in the first triplet of vibration modes of the original building. In comparison, the subscript i, which is equal to 1, 2 and 3, when used for the quantities associated with the EOSB, represents its 1st, 2nd, and 3rd vibration modes, respectively. By using these conditions, the equation of motion of the EOSB, which excludes $\mathbf{C}^*$, is expressed as follows:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \ddot{u}_x^* \\ \mu^* \ddot{u}_z^* \\ r^* \ddot{u}_\theta^* \end{bmatrix} + \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ & k_{22} & k_{23} \\ sym. & & k_{33} \end{bmatrix} \begin{bmatrix} u_x^* \\ \mu^* u_z^* \\ r^* u_\theta^* \end{bmatrix} = - \begin{bmatrix} \ddot{u}_{gx}(t) \\ \mu^* \ddot{u}_{gz}(t) \\ 0 \end{bmatrix} \tag{6a}$$

where

$$\begin{aligned}
k_{11} &= m_{x1}\omega_1^2 + m_{x2}\omega_2^2 + m_{x3}\omega_3^2 \\
k_{12} &= -\left[\left(s_2\sqrt{m_{x2}m_{z2}} + s_3\sqrt{m_{x3}m_{z3}}\right)\omega_1^2 + \left(s_1\sqrt{m_{x1}m_{z1}} + s_3\sqrt{m_{x3}m_{z3}}\right)\omega_2^2 + \left(s_1\sqrt{m_{x1}m_{z1}} + s_2\sqrt{m_{x2}m_{z2}}\right)\omega_3^2\right] \\
k_{13} &= -\left[\left(s_5\sqrt{m_{x2}I_2} + s_6\sqrt{m_{x3}I_3}\right)\omega_1^2 + \left(s_4\sqrt{m_{x1}I_1} + s_6\sqrt{m_{x3}I_3}\right)\omega_2^2 + \left(s_4\sqrt{m_{x1}I_1} + s_5\sqrt{m_{x2}I_2}\right)\omega_3^2\right] \\
k_{22} &= m_{z1}\omega_1^2 + m_{z2}\omega_2^2 + m_{z3}\omega_3^2 \\
k_{23} &= -\left[\left(s_2 s_5\sqrt{m_{z2}I_2} + s_3 s_6\sqrt{m_{z3}I_3}\right)\omega_1^2 + \left(s_1 s_4\sqrt{m_{z1}I_1} + s_3 s_6\sqrt{m_{z3}I_3}\right)\omega_2^2 + \left(s_1 s_4\sqrt{m_{z1}I_1} + s_2 s_5\sqrt{m_{z2}I_2}\right)\omega_3^2\right] \\
k_{33} &= I_1\omega_1^2 + I_2\omega_2^2 + I_3\omega_3^2
\end{aligned} \tag{6b}$$

and $\ddot{u}_{gx}$ and $\ddot{u}_{gz}$ are the x-directional and z-directional ground acceleration records, respectively. In Eq.

(6b), ω_1, ω_2, and ω_3 are the undamped circular vibration frequencies of the first triplet of vibration modes of the original building. Additionally, m_{xi}, m_{zi}, and I_i, where i = 1 to 3, are defined in Eq. (5b). The values of s_1 to s_6, which are either 1 or −1, are determined as below:

If the directions of $\boldsymbol{\varphi}_{zi}$ and $\boldsymbol{\varphi}_{xi}$, in which i = 1, 2, and 3, are the same, then the corresponding s_i is equal to 1. Conversely, if the directions of $\boldsymbol{\varphi}_{zi}$ and $\boldsymbol{\varphi}_{xi}$, in which i = 1, 2, and 3, are opposite, then the corresponding s_i is equal to −1. If the directions of $\boldsymbol{\varphi}_{\theta i}$ and $\boldsymbol{\varphi}_{xi}$, in which i = 1, 2, and 3, are the same, then the corresponding s_{i+3} is equal to 1. Conversely, if the directions of $\boldsymbol{\varphi}_{\theta i}$ and $\boldsymbol{\varphi}_{xi}$, in which i = 1, 2, and 3, are opposite, then the corresponding s_{i+3} is equal to −1.

Note that the abovementioned formulation of the EOSB is for an existing N-story building and that the corresponding TSMD is added atop the original building. As a result, it eventually becomes an (N+1)-story building. Alternatively, an existing N-story building can be retrofitted by remolding the original top story into the TSMD instead of adding a new story as the TSMD. In such a case, the abovementioned formulation of the EOSB will be based on the properties of the first triplet of vibration modes of the underlying (N−1)-story building, rather than those of the entire N-story building.

2.2 Optimization of the parameter values of an EOSB to serve as a TSMD

When optimizing an EOSB to act as a TSMD, the mass, damping, and stiffness matrices of the TSMD, which are respectively denoted as $\mathbf{M}_a^*$, $\mathbf{C}_a^*$, and $\mathbf{K}_a^*$, are expressed as follows:

$$\mathbf{M}_a^* = \alpha^* \mathbf{M}^*, \quad \mathbf{C}_a^* = \beta \alpha^* \mathbf{C}^*, \quad \mathbf{K}_a^* = f \alpha^* \mathbf{K}^* \tag{7}$$

where $\mathbf{M}^*$, $\mathbf{C}^*$, and $\mathbf{K}^*$ are the mass, damping, and stiffness matrices of the EOSB; and α^*, β, and f are the tuning parameters for the mass, damping, and stiffness matrices, respectively. Furthermore, the mass ratio of the TSMD, denoted as α, is defined as the ratio of the x-directional mass of the TSMD to that of the original building. Because the x-directional mass of the EOSB is one, α is equal to $\alpha^* / sum(diag(\mathbf{m}_x))$, where $sum(diag(\mathbf{m}_x))$ represents the total x-directional mass of the original building. Rather than using the tuning parameter α^*, using the mass ratio α directly shows how heavy the TSMD is relative to the original multi-story building. Just as the conventional TMD, the mass ratio α is chosen by the designers, and thus only the two parameters β and f need to be tuned for optimization.

The Min-Min-Max approach (Randall et al. 1981), which is an iterative numerical process, is applied here to determine the optimum values of β and f. As the seismic responses of structures are dependent upon the input ground motions, the amplitude of the frequency response function, which is an intrinsic structural dynamic property independent of the ground excitation, is preferred in the Min-Min-Max approach. In addition, it is usually not possible to determine which direction of a two-way asymmetric-plan building is more important or more vulnerable than the other directions. Therefore, this study selects the controlled target, denoted as CT, used in the Min-Min-Max approach for searching the optimum values of β and f as follows:

$$CT = CT_x + CT_z + CT_\theta \tag{8a}$$

where:

$$CT_x = \frac{(H_{x,N})_{\max} - (H_{x,N}^a)_{\max}}{3(H_{x,N})_{\max}}, \quad CT_z = \frac{(H_{z,N})_{\max} - (H_{z,N}^a)_{\max}}{3(H_{z,N})_{\max}}, \quad CT_\theta = \frac{(H_{\theta,N})_{\max} - (H_{\theta,N}^a)_{\max}}{3(H_{\theta,N})_{\max}} \tag{8b}$$

In Eq. (8b), $H_{x,N}$, $H_{z,N}$, and $H_{\theta,N}$ denote the amplitudes of the frequency response functions of the three directional displacements at the Nth story of the original N-story building without the TSMD. In addition, $H_{x,N}^a$, $H_{z,N}^a$, and $H_{\theta,N}^a$ denote the amplitudes of the frequency response functions of the three directional displacements at the Nth story of the building capped with the TSMD. The operator

$(\bullet)_{max}$ indicates that the peak value of the corresponding amplitudes of the frequency response function, denoted as $\bullet$, is used.

3 NUMERICAL VALIDATION

In order to verify the effectiveness of the TSMD, one 20-story building (designated as ASY20) is investigated in this study. Figure 2 shows the typical floor plan and the elevation of ASY20, which is varied from the symmetrical 20-story SAC building located in Los Angeles (FEMA-355C 2000). The variation is that the CM of the original symmetrical building has been moved away from the CR, resulting in the eccentricity ratios being equal to 20% in both the *x*- and *z*-directions (Fig. 2). The detailed properties of ASY20, such as the member properties, floor mass, and mass moment of inertia of each floor, are available in the associated report (FEMA-355C 2000). In addition, Rayleigh damping with the damping ratios of the first and second vibration modes of ASY20 equal to 5% is adopted. The undamped mode shapes of the first thee vibration modes of ASY20 are shown in Figure 3. Note that the rotational components shown in Figure 3 are multiplied by a or 0.1a, where a is the *x*-directional length of the building, equal to 5×6096 mm. Figure 3 indicates that the 1st, 2nd, and 3rd vibration modes constitute the first triplet of vibration modes. The values of s_1 to s_6 for the first triplet of vibration modes, which are used to construct the EOSB of ASY20, are -1, 1, -1, 1, -1, and -1, respectively (Figs. 3a, 3b and 3c).

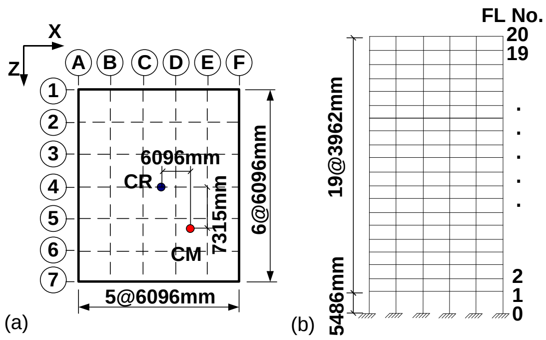

Figure 2. (a) The typical floor plan and (b) elevation of ASY20.

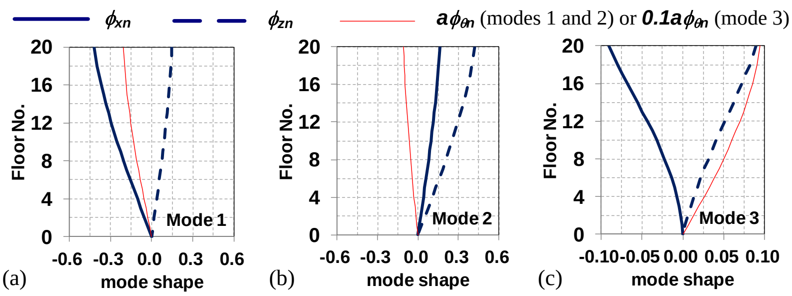

Figure 3. The mode shapes of the first three vibration modes of ASY20.

It is found that the first triplet of vibration modes takes 80%, 80%, and 82% of the total *x*-directional mass, *z*-directional mass, and *y*-directional mass moment of inertia of ASY20. The total *x*-directional mass, *z*-directional mass, and *y*-directional mass moment of inertia of ASY20 are 11072 kN×s²/m, 11072 kN×s²/m, and 2.089×10⁶ kN×s²×m, respectively. Therefore, μ^* and r^* are equal to 1 ($=\sqrt{(11072\times0.8)/(11072\times0.8)}$) and 13.9 m ($=\sqrt{(2.089\times10^6\times0.82)/(11072\times0.8)}$), respectively. The value of α of the TSMD for controlling ASY20 is considered as 0.05. That is α^* = 0.05 × 11072 = 553.6, where 11072 is the total *x*-directional mass of ASY20. By using the Min-Min-Max approach, the values of f_{opt} and β_{opt} are found as 0.735 and 3.75, respectively, and the corresponding *CT* value is 0.671. Consequently, the mass, damping, and stiffness matrices of the TSMD (i.e. $\mathbf{M}_a^*$, $\mathbf{C}_a^*$, and $\mathbf{K}_a^*$) are determined and presented in Table 1.

Table 1. The mass, damping, and stiffness matrices of the TSMD for ASY20 (units: kN, m, sec).

$\mathbf{M}_a^*$			$\mathbf{C}_a^*$			$\mathbf{K}_a^*$		
554	0	0	339	0	-1211	1091	2	-7807
0	554	0	0	376	1270	2	1330	8190
0	0	1.07×10^5	-1211	1270	1.64×10^5	-7807	8190	8.46×10^5

Figures 4a, 4b, and 4c show the amplitudes of the frequency response functions of the x-translational, z-translational, and y-rotational displacements, respectively, at the 20th story of ASY20 with and without the TSMD. Additionally, those of the TSMD itself are also shown in these figures. Figures 4a, 4b and 4c clearly show that the TSMD satisfactorily suppresses the amplitudes of the frequency response functions in the three directions. It is noted that the amplitudes of the frequency response functions of the TSMD itself are approximately equal to those of ASY20 without the TSMD. As frequency response functions are intrinsic dynamic properties of a structural system, Figures 4a, 4b and 4c confirm the effectiveness of the TSMD in suppressing the displacement responses of ASY20. For the purpose of comparison, two SDOF TMDs, each of which is placed in one of the two horizontal directions, are also designed to control ASY20. The mass ratio of each SDOF TMD is 0.05, which is the same as that used for the TSMD. The optimum frequency ratio and damping ratio of the SDOF TMDs are 0.9638 and 0.1410, respectively, which are the optimum parameter values proposed by Tsai and Lin (1993). Figures 4d, 4e, and 4f show the amplitudes of the frequency response functions of the x-translational, z-translational, and y-rotational displacements, respectively, at the 20th story of ASY20 with and without the SDOF TMDs. Additionally, Figures 4d, 4e also show the amplitudes of the frequency response functions of the x-directional and z-directional SDOF TMDs themselves, respectively. By comparing Figures 4d and 4e with Figures 4a and 4b, it indicates that using the two SDOF TMDs can result in similar effect on reducing the amplitudes of the frequency response functions of the two translational displacements. Nevertheless, the effectiveness of reducing the amplitude of the frequency response function of the rotational displacement by using the two SDOF TMDs (Fig. 4f) is not as substantial as that by using the TSMD (Fig. 4c). Moreover, the amplitudes of the frequency response functions of the two SDOF TMDs themselves (Figs. 4d and 4e) are much larger than those of the TSMD itself (Figs. 4a and 4b). That is to say, the necessary space for accommodating the displacement of the TSMD is much less than that of the two SDOF TMDs.

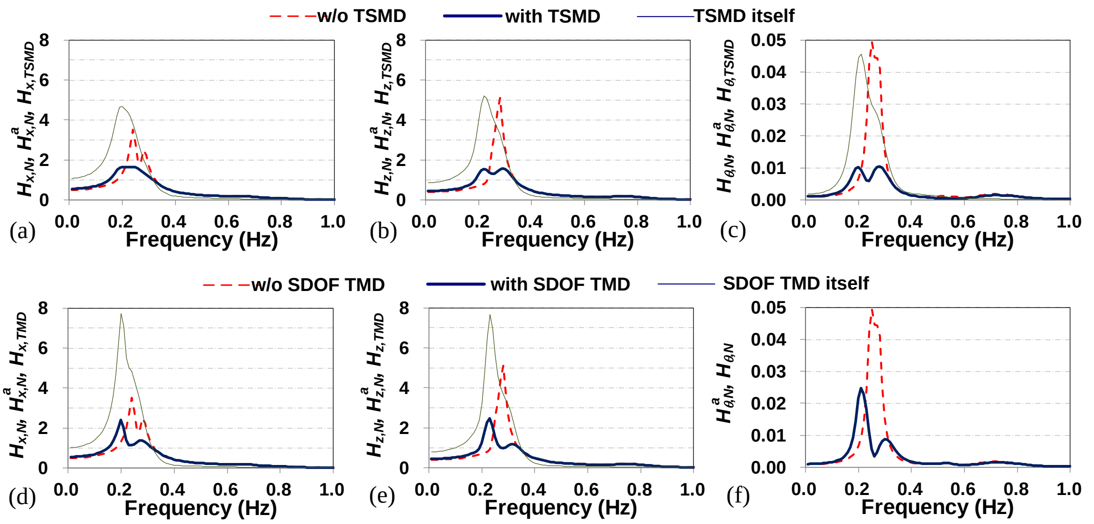

Figure 4. The amplitudes of the frequency response functions (a) $H_{x,N}$, $H^a_{x,N}$, and $H_{x,TSMD}$; (b) $H_{z,N}$, $H^a_{z,N}$, and $H_{z,TSMD}$; and (c) $H_{\theta,N}$, $H^a_{\theta,N}$, and $H_{\theta,TSMD}$ of ASY20 controlled by using the TSMD. The amplitudes of the frequency response functions (d) $H_{x,N}$, $H^a_{x,N}$, and $H_{x,TMD}$; (e) $H_{z,N}$, $H^a_{z,N}$, and $H_{z,TMD}$; and (f) $H_{\theta,N}$, $H^a_{\theta,N}$ of ASY20 controlled by using one x-directional and one z-directional SDOF TMDs.

4 SUMMARY

This study proposed a novel tuned mass damper, called a top-story mass damper (TSMD), aimed at suppressing the seismic responses contributed from the first triplet of vibration modes of a two-way asymmetric-plan building. The main challenge of this task is that each vibration mode of a two-way asymmetric-plan building is translation–rotation coupled and the three vibration modes, each of which is fundamental in one direction, are to be controlled simultaneously by using only one tuned mass damper. The TSMD was obtained from optimizing the EOSB, which was constructed in the subspace spanned by the first triplet of vibration modes of the original building. The approaches of constructing the EOSB and transforming the EOSB into the TSMD were shown in this paper. The effectiveness of the TSMD was numerically validated by designing the TSMD for one 20-story two-way asymmetric-plan building. The amplitudes of the frequency response functions of the three directional displacements at the tops of the original building were significantly reduced when the building were capped with the TSMD in comparison with those of the building without the TSMD. Hence, it is concluded that the TSMD is a promising alternative for seismic dampers for asymmetric-plan buildings.

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