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Seismic effectiveness of top-story mass dampers for inelastic two-way asymmetric-plan buildings

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A R T I C L E I N F O

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A B S T R A C T

Self-mass dampers, which use intrinsic parts of structures as tuned mass dampers, are economically advantageous in terms of the materials and space required. Previous research proposed using the top story of a two-way asymmetric-plan building as a self-mass damper, referred to as a top-story mass damper (TSMD), for suppressing the seismic response of an elastic building. In light of the promising results of that research, this study further explores the seismic effectiveness of TSMDs when two-way asymmetric-plan buildings become inelastic under earthquake loads. Furthermore, this study explores the possibility of using a pair of elastic TSMDs to alleviate the detuning effects caused by yielding of the main structure. One TSMD of the pair is designed according to the previous research and is responsible for suppressing the vibrations of the target building in elastic states. The other TSMD is designed based on the properties of collective force–deformation relationships and is responsible for suppressing the vibrations of the target building in inelastic states. The collective force–deformation relationships are the pushover curves of the target building when subject to the collective modal inertia force vectors of the first triplet of vibration modes of the building. This study looks at one single-story building and one 20-story building, which are shaken into various damage states, as the numerical examples for evaluating the seismic effectiveness of TSMDs for inelastic two-way asymmetric-plane buildings.

1. Introduction

Tuned mass dampers (TMDs) have been widely recognized as an effective approach to reducing displacement demands of elastic buildings that are subject to earthquake loads. Nevertheless, this advantage generally diminishes as detuning progresses. Conventional TMDs, which need no additional power source or sophisticated sensors/instruments, can be regularly and elaborately adjusted to address detuning caused by the alteration of usage or aging of materials. For instance, removing/adding a part of the TMD mass blocks or changing the length of the ropes suspending them can adjust the TMD's dynamic properties. However, adjusting conventional TMDs to address detuning caused by structural yielding during ground motions is not easily achievable. As a result, the effectiveness of a TMD on reducing displacement demands generally decreases as seismic damage to the main structure increases. Nevertheless, some researches [1–3] have noted that seismic damage is still mitigated by TMDs because the hysteretic energy dissipated from the main structures, which are controlled by using elastic TMDs, is less than that without any control device. This is because the damage index of a structure is usually a combination of the normalized peak deformation and the normalized hysteretic energy [4]. The less hysteretic energy dissipated through a main structure, which generally yields a smaller value of the damage index, denotes less seismic damage in the main structure [4]. This means that elastic TMDs are beneficial for buildings that not only remain elastic but also experience inelastic excursions during severe seismic events. It would be desirable for conventional TMDs to also effectively mitigate the displacement demands of inelastic buildings.

Due to their complex translation-rotation coupled seismic responses, one-way and two-way asymmetric-plan buildings—where the center of mass (CM) and center of rigidity (CR) are not aligned in one or two horizontal coordinate axes, respectively—have been the subject of a significant amount of research [5,6]. As for using TMDs to reduce the displacement demands of elastic asymmetric-plan buildings, a single translation-only TMD is obviously insufficient for addressing the translation-rotation coupled vibrations of asymmetric-plan buildings. The common approach for dealing with this issue is to employ multiple TMDs (MTMDs) [7–9]. Alternatively, Lin et al. [10,11] proposed using a single translation-rotation coupled TMD to suppress both the translational and rotational vibrations resulting from a target vibration mode of an asymmetric-plan building. Recently, Lin [12] further proposed using the top story of a two-way asymmetric-plan building as a TMD, referred to as a top-story mass damper (TSMD), for the simultaneous control of the first triplet of building vibration modes. The first triplet of

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vibration modes of a two-way asymmetric-plan building is composed of the first translational dominant mode in each of the two horizontal directions and the first rotational dominant mode in the vertical direction. The self-weight of the top story is designed to provide the needed mass and mass moment of inertia for the TSMD. The required damping and stiffness matrices of the TSMD are achieved by installing viscous dampers and springs/bearings between the bottom of the top story and the top of the stories below. Thus, additional heavy mass blocks are not needed, nor is a permanently occupied huge space for the installation and operation of a mass damper. The economic benefits of the building are thereby improved because of the increased available space. In addition, when remodeling the top story or adding a purposely designed story atop an existing building as a TSMD, the occupancy of the other stories need not to be suspended during the retrofit period. Therefore, TSMDs are very suitable for the seismic retrofit of existing two-way asymmetric-plan buildings. The mathematical formation of a TSMD [12] is briefly stated in Appendix A. In addition, Fig. A1 in Appendix A illustrates the concept of constructing a TSMD.

Although the seismic effectiveness of a TSMD on an elastic two-way asymmetric-plan building has been validated [12], it is not clear whether the TSMD is beneficial or at least harmless for buildings that undergo inelastic excursions in rare/very rare earthquakes. Furthermore, it would be a significant advancement if the generally unremarkable effect of TMDs on mitigating displacement demands of inelastic buildings is improved. Therefore, this study has two goals: the first is to investigate the seismic effectiveness of TSMDs for inelastic two-way asymmetric-plan buildings with different extents of yielding that range from minor to severe damage; the second is to improve the effectiveness of TSMDs in reducing the displacement demands of inelastic asymmetric-plan buildings. It is common to employ MTMDs to control a wide band of vibration frequencies of a main structure [13]. This wide band of vibration frequencies may be due to considering the possible discrepancy between the actual and the designed dynamic properties of a building, or the possible yielding of a building subjected to large ground motions. Therefore, analogous to the idea of employing MTMDs to control a wide band of vibration frequencies, this study proposes an approach to design a pair of elastic TSMDs to counter the detuning caused by the building deforming from an elastic state to a damaged state. Assuming that the collective force–deformation relationships of the first triplet of vibration modes of the target building are bilinear, one of the pair of elastic TSMDs is responsible for suppressing the vibrations of the building in elastic states and unloading states. The second TSMD is designed to suppress the vibrations of the building in inelastic states. The second goal of this study is thus achieved. One single-story and one 20-story two-way asymmetric-plan building are investigated to verify this approach.

2. Investigation approach

2.1. A pair of elastic TSMDs for seismic control of inelastic asymmetric-plan buildings

To mitigate the detuning effect that results from the yielding of two-way asymmetric-plan buildings, a pair of elastic TSMDs, individually denoted as TSMD1 and TSMD2, are designed based on the bilinear force–deformation relationships of the first triplet of vibration modes of the target building. TSMD1, which is responsible for suppressing the vibrations of the target building in elastic states and unloading states, is directly obtained from the design method proposed previously [12]. TSMD2 is responsible for suppressing the vibrations of the target building in inelastic (i.e., softened) states. The method for determining the bilinear force–deformation relationships of the first triplet of vibration modes of the target building are stated below.

The equation of motion of an N-story, two-way asymmetric-plan building with each floor represented as a rigid diaphragm with three degrees of freedom (DOFs) is expressed as follows [14]:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = -\mathbf{M}\iota_x \ddot{u}_{gx}(t) - \mathbf{M}\iota_z \ddot{u}_{gz}(t) = -\sum_{n=1}^{3N} \mathbf{s}_{xn}\ddot{u}_{gx}(t) - \sum_{n=1}^{3N} \mathbf{s}_{zn}\ddot{u}_{gz}(t) = -\sum_{n=1}^{3N} \Gamma_{xn}\mathbf{M}\boldsymbol{\varphi}_n \ddot{u}_{gx}(t) - \sum_{n=1}^{3N} \Gamma_{zn}\mathbf{M}\boldsymbol{\varphi}_n \ddot{u}_{gz}(t) \quad (1)$$

Here, $\ddot{u}_{gx}(t)$ and $\ddot{u}_{gz}(t)$ are the x- and z-directional ground accelerations, respectively; $\boldsymbol{\iota}_x$ and $\boldsymbol{\iota}_z$ are the x- and z-directional influence vectors, respectively. The displacement vector $\mathbf{u}$, the nth mode shape $\boldsymbol{\varphi}_n$, the mass matrix $\mathbf{M}$, the damping matrix $\mathbf{C}$, the stiffness matrix $\mathbf{K}$, and the nth modal participation factors Γ_{xn} and Γ_{zn} are given as follows:

$$\mathbf{u} = \begin{bmatrix} \mathbf{u}_x \\ \mathbf{u}_z \\ \mathbf{u}_\theta \end{bmatrix}_{3N\times1}, \quad \boldsymbol{\varphi}_n = \begin{bmatrix} \varphi_{xn} \\ \varphi_{zn} \\ \varphi_{\theta n} \end{bmatrix}_{3N\times1}, \quad \Gamma_{xn} = \frac{\boldsymbol{\varphi}_n^T\mathbf{M}\iota_x}{\boldsymbol{\varphi}_n^T\mathbf{M}\boldsymbol{\varphi}_n}, \quad \Gamma_{zn} = \frac{\boldsymbol{\varphi}_n^T\mathbf{M}\iota_z}{\boldsymbol{\varphi}_n^T\mathbf{M}\boldsymbol{\varphi}_n}$$
$$\mathbf{M} = \begin{bmatrix} \mathbf{m}_x & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{m}_z & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_0 \end{bmatrix}_{3N\times3N}, \quad \mathbf{C} = \begin{bmatrix} \mathbf{c}_{xx} & \mathbf{c}_{xz} & \mathbf{c}_{x\theta} \\ \mathbf{c}_{zx} & \mathbf{c}_{zz} & \mathbf{c}_{z\theta} \\ \mathbf{c}_{\theta x} & \mathbf{c}_{\theta z} & \mathbf{c}_{\theta\theta} \end{bmatrix}_{3N\times3N}$$
$$\mathbf{K} = \begin{bmatrix} \mathbf{k}_{xx} & \mathbf{k}_{xz} & \mathbf{k}_{x\theta} \\ \mathbf{k}_{zx} & \mathbf{k}_{zz} & \mathbf{k}_{z\theta} \\ \mathbf{k}_{\theta x} & \mathbf{k}_{\theta z} & \mathbf{k}_{\theta\theta} \end{bmatrix}_{3N\times3N} \quad (2)$$

$\mathbf{s}_{xn}$ and $\mathbf{s}_{zn}$, which, respectively, represent the x- and z-directional nth modal inertia force vectors, are

$$\mathbf{s}_{xn} = \Gamma_{xn}\mathbf{M}\boldsymbol{\varphi}_n \quad \mathbf{s}_{zn} = \Gamma_{zn}\mathbf{M}\boldsymbol{\varphi}_n \quad (3)$$

The TSMD properties are obtained from the optimization of the effective one-story building (EOSB), which retains the dynamic properties of the first triplet of vibration modes of the target building [12]. This indicates that the dynamic response of the EOSB reflect the collective dynamic response of the first triplet of vibration modes of the target building in the modal space. This study further proposes the collective modal inertia force vectors of the first triplet of vibration modes as:

$$\mathbf{s}_x = \sum_{i=1}^{3} \Gamma_{xi}\mathbf{M}\boldsymbol{\varphi}_i, \quad \mathbf{s}_z = \sum_{i=1}^{3} \Gamma_{zi}\mathbf{M}\boldsymbol{\varphi}_i, \quad \mathbf{s}_\theta = \sum_{i=1}^{3} \Gamma_{\theta i}\mathbf{M}\boldsymbol{\varphi}_i \quad (4)$$

In which, $\Gamma_{\theta i} = \boldsymbol{\varphi}_i^T\mathbf{M}\iota_\theta/\boldsymbol{\varphi}_i^T\mathbf{M}\boldsymbol{\varphi}_i$ and $\iota_\theta = [\mathbf{0}^T \ \ \mathbf{0}^T \ \ \mathbf{1}^T]^T$. Note that the subscript, i = 1–3, used in Eq. (4), denotes the parameters belonging to the three modes constituting the first triplet of vibration modes, which are not necessarily the first three vibration modes of the target building. It is worth noting that according to the assumption of the modal pushover analysis (MPA) approach [15], applying the nth modal inertia force to a structure triggers only the nth modal deformation of the structure, even though the structure is underwent inelastic excursions. Likewise, assume that applying the collective modal inertia force of the first triplet of vibration modes to the target building triggers only the collective modal deformations of its first triplet of vibration modes. Neither using the nth modal inertia force in the MPA approach nor using the collective modal inertia force of the first triplet of vibration modes in this research definitely activate all the nonlinear elements. By subjecting the target building to $\mathbf{s}_x$, the relationship between the x-directional roof translation, $u_{x,r}$, and the x-directional base shear, V_{bx}, is obtained. By subjecting the target building to $\mathbf{s}_z$, the relationship between the z-directional roof translation, $u_{z,r}$, and the z-directional base shear, V_{bz}, is obtained. In addition, by subjecting the target building to $\mathbf{s}_\theta$, the relationship between the y-directional roof rotation, $u_{\theta,r}$, and the base torque, T_b, is obtained. Note that in the pushover analysis procedure [16], the roof displacement and base shear are divided by $\Gamma_1\varphi_{1,r}$ and $\Gamma_1^2 M_1$, respectively, to convert the force–deformation relationship into the format of acceleration-displacement response spectrum (ADRS). $\phi_{1,r}$ represents the roof component of the first mode shape. In addition, Γ_1 represents the modal participation factor of the first