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Semi-active damped outriggers for seismic protection of high-rise buildings

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Abstract. High-rise buildings are a common feature of urban cities around the world. These flexible structures frequently exhibit large vibration due to strong winds and earthquakes. Structural control has been employed as an effective means to mitigate excessive responses; however, structural control mechanisms that can be used in tall buildings are limited primarily to mass and liquid dampers. An attractive alternative can be found in outrigger damping systems, where the bending deformation of the building is transformed into shear deformation across dampers placed between the outrigger and the perimeter columns. The outrigger system provides additional damping that can reduce structural responses, such as the floor displacements and accelerations. This paper investigates the potential of using smart dampers, specifically magnetorheological (MR) fluid dampers, in the outrigger system. First, a high-rise building is modeled to portray the St. Francis Shangri-La Place in Philippines. The optimal performance of the outrigger damping system for mitigation of seismic responses in terms of damper size and location also is subsequently evaluated. The efficacy of the semi-active damped outrigger system is finally verified through numerical simulation.

Keywords: semi-active damped outriggers; MR dampers; seismic control; high-rise buildings; LQG/clipped-optimal control

1. Introduction

Buildings have continued to soar skyward with the development of new materials and construction technologies. However, such flexible structures may fall victim to excessive levels of vibration caused by strong winds and earthquakes. As a result, structural modifications ranging from alternative structural systems and aerodynamic changes to utilization of passive and active control devices have been suggested for protecting flexible structures against external disturbances (Kareem *et al*. 1999).

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Passive supplemental damping systems for high-rise buildings, such as viscous dampers, viscoelastic dampers, and tuned mass dampers, have been studied extensively by researchers and engineers for mitigation of vibration response (Kareem *et al*. 1999, Spencer and Nagarajaiah 2003). These passive damping systems have also been considered for reduction of undesired vibration in some existing structures (Soong and Spencer 2002). However, the magnitude of the interstory drift typically decreases with increasing height of a building. Therefore, a number of response amplification systems have been created to improve performance, e.g., toggle braces (Constantinous *et al.* 2001), scissor-jacks (Sigaher and Constantinou 2003), and gear-type systems (Berton and Bolander 2005), the mega brace (Taylor 2003).

An innovative response amplification system developed specifically for high-rise buildings is found in the outrigger damping system, consisting of vertical dampers between outrigger walls and perimeter columns in a frame-core tube structure (Jeremlah 2006). A conventional outrigger cantilevers from the core to the perimeter columns, resulting in the resisting moment against static lateral loads (Smith and Salim 1981). Jeremlan (2006) and Smith and Willford (2007) proposed adding dampers to the outrigger to enhance structural dynamic performance against wind loadings. Willford *et al*. (2008) also report implementation of this technique in a high-rise building in the Philippines.

MR dampers are a class of semi-active control devices that have been shown to produce comparable performance to fully active control devices without many of the associated detractors (Spencer *et al*. 1997). Indeed, MR dampers have drawn extensive attention from the community due to the excellent performance in both laboratory testing and engineering practice (Dyke *et al*. 1996a, Spencer *et al*. 1997, Spencer and Nagarajaiah 2003, Chen *et al*. 2004, Yang *et al*. 2002, Fujitani *et al*. 2003). Such outrigger damping systems can employ the MR dampers to achieve high control performance. Moreover, MR dampers require little power to respond to external disturbances, i.e., seismic loadings. This type of smart damping devices generates different levels of resisting force in accordance to input currents. In addition to the conventional passive control devices, MR dampers can utilize semi-active control methods to maximize the capabilities of mitigating responses in structures (Dyke *et al*. 1996a, b).

In this study, a semi-active outrigger damping system employing magnetorheological (MR) dampers is proposed for protecting tall buildings against the strong winds and seismic excitations. First, a 60-story building is modeled to portray the St. Francis Shangri-La Place in Philippines (Willford et al.2008). An optimal damping coefficient in the damped outrigger is determined through the proposed evaluation that will be used as a baseline for comparison. The location of the outrigger system is also designed based on the evaluation criteria. Semi-active control design facilitates a reduce-order model to generate controllers, and a LQG/clipped-optimal control algorithm (Dyke *et al*. 1996a) derives the controller for the MR dampers in the outrigger system. Numerical simulation of the semi-active controlled outrigger system is performed under two different ground motions; the results are shown to be superior to the passive implementation of the MR dampers.

2. Problem formulation

A high-rise building can be idealized as a cantilevered beam in which the structural deformations are derived from the behavior of the core. Such an approach was employed to model a 76-story building in the ASCE benchmark control problem for the wind excited high-rise buildings (Yang *et al*. 2004). For a high-rise building with damped outriggers, the control devices (e.g., viscous dampers or MR dampers) are located between the outrigger walls and the perimeter columns. According to the model provided in Smith and Willford (2007), the perimeter columns are assumed to be axially very stiff, while the outrigger behaves as a rigid body. Nevertheless, neglecting the dynamics due to perimeter columns may overestimate performance of the damped outrigger system. Thus, analysis of high-rise buildings with damped outriggers should include the vertical deformation of the perimeter columns, as shown in Fig. 1. The numerical model of the structural system can be subsequently established by three components: a center core, the perimeter columns, and dampers. With an appropriate discretization, the equation of motion of the control problem can be written as

$$\begin{cases} \mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{\Lambda}\left(nef\right) - \mathbf{M}\mathbf{\Gamma}\ddot{x}_{\mathrm{g}} \\ \mathbf{M}_{\mathrm{c}}\ddot{\mathbf{u}}_{\mathrm{c}} + \mathbf{C}_{\mathrm{c}}\dot{\mathbf{u}}_{\mathrm{c}} + \mathbf{K}_{\mathrm{c}}\mathbf{u}_{\mathrm{c}} = \mathbf{\Lambda}_{\mathrm{c}}\left(nf\right) \end{cases} \tag{1}$$

where f is the force from a single control device; n is the total number of control devices; e is the distance of the control devices to the center of the core (see Fig. 1); f_{m} is the total moments; **M**, **C**, **K** are the structural mass, damping, stiffness matrices of the center core; $\mathbf{M}_{\mathrm{c}}$, $\mathbf{C}_{\mathrm{c}}$, $\mathbf{K}_{\mathrm{c}}$ are the structural mass, damping, stiffness matrices for the perimeter columns; **u** is the structural deformation vector considering the bending behavior; $\mathbf{u}_{\mathrm{c}}$ is the axial deformation of the perimeter columns; $\mathbf{\Lambda}$ presents the location of the outrigger system with respect to a specific rotational degree of freedom (DOF); $\mathbf{\Lambda}_{\mathrm{c}}$ indicates the connection of the outrigger system at the perimeter columns; $\mathbf{\Gamma}$ is a vector whose element with respect to the translational DOFs are all unity and zero for others; $\ddot{x}_{\mathrm{g}}$ is the ground acceleration.

In control applications, the state-space representation is usually employed to form a structural system and subsequently to develop control strategies. The overall structural system is converted from Eq. (1) and represented as

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}f + \mathbf{E}\ddot{x}_{\mathbf{g}} \\ \mathbf{y} &= \mathbf{C}_{\mathbf{y}}\mathbf{x} + \mathbf{D}_{\mathbf{y}}f + \mathbf{F}_{\mathbf{y}}\ddot{x}_{\mathbf{g}} + \mathbf{v} \\ \mathbf{z} &= \mathbf{C}_{\mathbf{z}}\mathbf{x} + \mathbf{D}_{\mathbf{z}}f \end{aligned} \tag{2}$$

where **x** is the state of the structure in terms of the bending and axial deformations from the center core and perimeter columns; **y** presents the measured structural responses including the relative displacements, the relative velocities, and the absolute floor accelerations; **v** is the measurement noise; **z** corresponds to the regulated structural responses.

3. Semi-active control designs

Most of previous studies were focused on the outrigger walls or passively damped outriggers. These approaches provide decent performance to resist external loadings. To surpass the conventional outriggers in capability of mitigating structural responses, this study adopts MR dampers to perform semi-active control strategies in the outrigger systems of high-rise buildings.

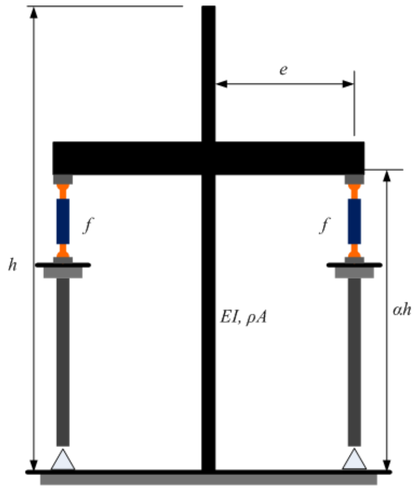


Fig. 1 Mechanism of outrigger systems

To facilitate semi-active control using MR dampers, a control method that derives the required force from adaptive input currents must be developed. Dyke *et al*. (1996a) proposed a LQG/clipped-optimal control method which had been verified through the experimental implementation with MR dampers. This study applies this control method for the semi-active outrigger system. In this control method, the outrigger system employs the H_2/LQG control algorithm to calculate the optimal control force and then switch on/off voltages for changing the input currents to the MR dampers. By reconsidering Eq. (2), the objective function of the H_2/LQG control can be written by

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} E\left[\int_0^{\tau} \left(\mathbf{z}^T \mathbf{Q} \mathbf{z} + r f^2 \right) dt \right] \tag{3}$$

where **Q** and *r* are the weighting parameters. By minimizing Eq. (3), the control force is a function of the structural state. As different semi-active control strategies may be developed, the matrix $\mathbf{C}_\mathbf{z}$ and $\mathbf{D}_\mathbf{z}$ should be formed accordingly. In the H_2/LQG control, the Kalman filter estimates (Nagarajaiah and Narasimhan 2006) the state based on the measured responses such that

$$\begin{aligned} \dot{\hat{\mathbf{x}}} &= \mathbf{A}\hat{\mathbf{x}} + \mathbf{B} f_\mathrm{m} + \mathbf{L}\left(\mathbf{y} - \mathbf{C}_\mathrm{y}\hat{\mathbf{x}} - \mathbf{D}_\mathrm{y} f \right) \\ f_\mathrm{d} &= -\mathbf{K}_\mathrm{c}\hat{\mathbf{x}} \end{aligned} \tag{4}$$

where **L** is the Kalman gain; f_d denotes the desired force; $\mathbf{K}_c$ is the optimal control gain; $\hat{\mathbf{x}}$ is the estimated state by the Kalman filter. To achieve the force calculated in Eq. (4), the clipped-optimal control approximates the command voltage by

$$v_i = V_{max} H\{(f_d - f) f\} \tag{5}$$

where $H\{\bullet\}$ is the Heaviside function; v_i is the input voltage to a MR damper; V_{max} is the maximum input voltage.

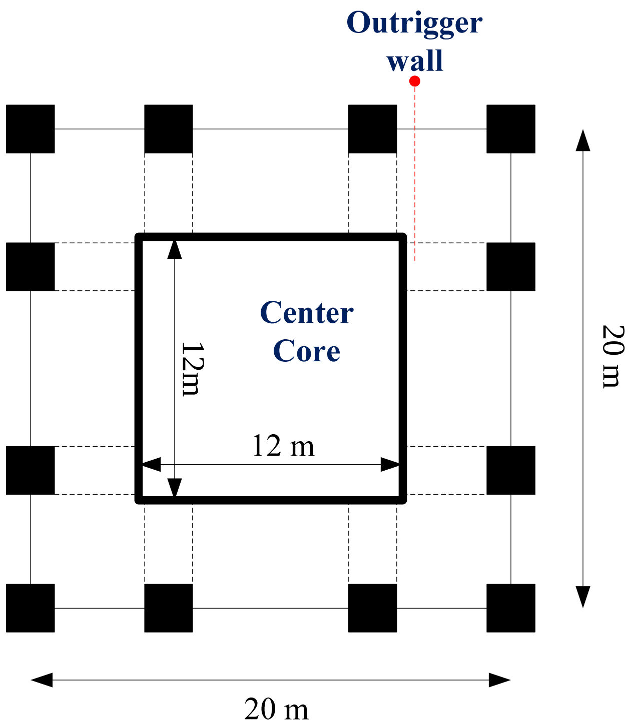


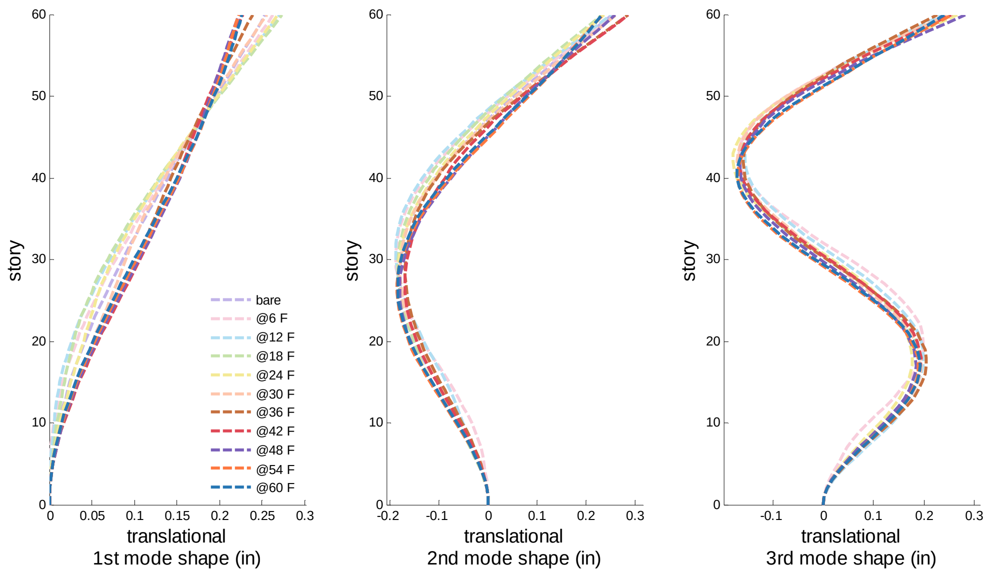
Fig. 2 Configuration of the building system with outrigger walls

4. St. Francis Shangri-La Place

The St. Francis Shangri-La Place in Philippines (Willford *et al.* 2008) employs a damped outrigger system and provides the inspiration of this study; this structural system is used to assess the efficacy of the semi-active outrigger system. The St. Francis Shangri-La Place is a sixty-story building with a height of 210 m (Infanti *et al.* 2008) and has 12 perimeter columns which are 20 m from the building centerline. As shown in Fig. 2, the concrete core is assumed to be 12 m x 12 m with a 0.5 m thickness, and the cross section of the perimeter columns are 2 m x 2 m. The total mass of this building reaches 30,000 tons. The outrigger system implemented in this building consists of sixteen viscous dampers, eight of which control the response in each of the two orthogonal directions. Note that this study only considers unidirectional excitations.

As the assumption made previously, this high-rise building itself is modeled as a cantilever beam. The finite element model is comprised of 60 beam elements with 120 DOFs, including 60 translational and 60 rotational DOFs. The perimeter columns are modeled by a single DOF system of which the mass term is composed of the partial weight of the building. The modal damping is assumed to be 2 % for each mode. The natural frequencies of the first five modes are 0.18, 1.15, 3.14, 6.00, and 9.61 Hz, respectively. As a convectional outrigger wall is considered at different heights, the dynamic characteristics vary in accordance with the resulting vertical stiffness of the perimeter columns. The study by Taranath (1988) indicated that the optimal location of the outrigger wall is at the middle height of the building, providing increased stiffness for the lateral deformations. Fig. 3 illustrates the high-rise building with an outrigger wall at different levels. In this figure, each mode shape has vector norm equal to one. In the context of stiffness, the building with a mid-height outrigger wall produces the largest natural frequency at the first mode. By investigating the 1st mode shapes, the outrigger wall at 0.8 of the height can provide smaller top displacements, while the outrigger wall at the top would efficiently reduce floor rotations. These results inform that outrigger locations will vary the structural responses in different objectives, and the additional damping devices placed along with the outrigger require further design in order to achieve the desired performance.

(a)



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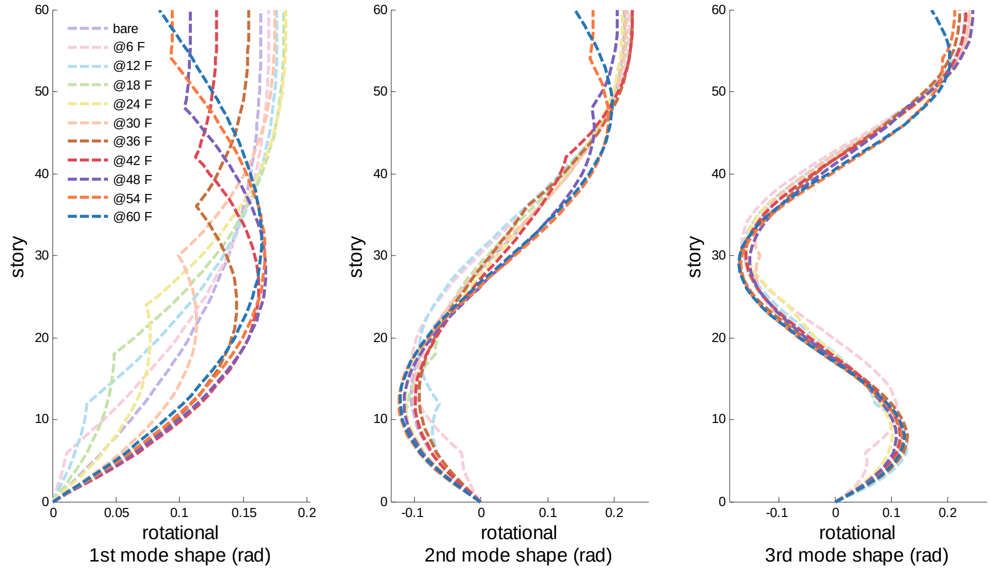
(b)



(c)

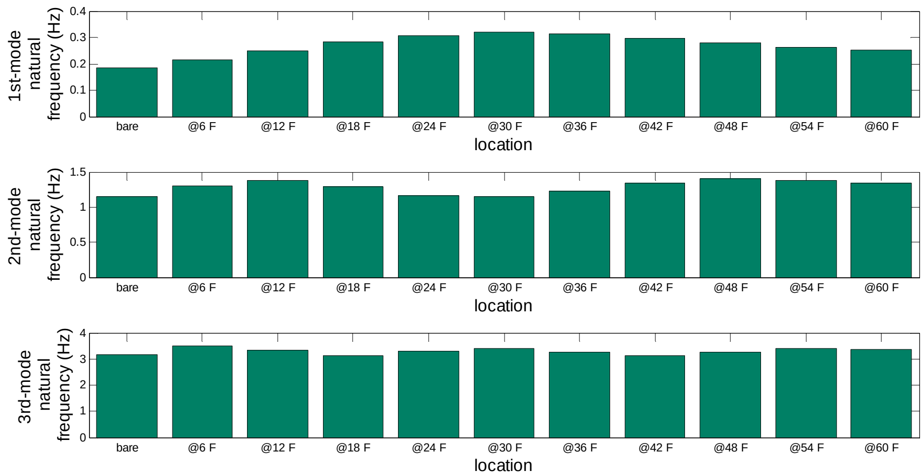


Fig. 3 Modal properties of the high-rise building with/without an outrigger wall: (a) translational, (b) rotational mode shapes, and (c) natural frequencies at the 1^{st}-3^{rd} mode

5. Evaluation of semi-active damped outrigger damping system

In this study, a semi-active outrigger system using MR dampers is developed and evaluated for a high-rise building subjected to seismic excitation. First, the location and size of the MR dampers are determined based on the proposed evaluation criteria. To demonstrate performance of the semi-active damped outrigger, various structural systems such as the bare building and buildings with the outrigger wall, viscously damped outrigger, and semi-active damped outrigger are investigated. As the focus of this study is the seismic protection of high-rise buildings, two historical earthquake records are selected for the assessment of building performance. By comparing the responses among these structural systems, the efficacy of the semi-active damped outrigger system is consequently verified.

Prior to exploring the performance of the semi-active damped outrigger system, the location and size of the MR dampers is determined. As illustrated in Fig. 3, changing the location of the outrigger wall will result in a different structural behavior. Similarly, performance of the semi-active damped outrigger system will vary with size of dampers and outrigger locations. Moreover, the damping forces provided by the smart damping devices will affect the building’s response against excitations. To further design the location and size, a stochastic analysis is conducted over a seismic spectrum which employs the Kanai-Tajimi spectrum with frequency $\omega_g = 12.6$ rad/sec and damping $\xi_g = 0.3$ (Ramallo *et al*. 2002). The analysis calculates the root-mean-square (RMS) responses of the building based on the assigned intensity of the ground motion. Because of multiple variables in this design, the locations are discretized by 0.1 of the building height from the mid-height to the top, and the damping coefficients per damper are increased by 5 MN-sec/m in a range of 5-800 MN-sec/m. The total number of dampers is 8, similar to the existing configuration in the St. Francis Shangri-La Place. Given a number of evaluation indices, the best design is defined by a weighted sum over all indices, including the root-mean-square (RMS) responses of the top displacement, top acceleration, base shear, and overturning moment. The design used in this study is determined my minimizing this composite evaluation index (see Fig. 4). Therefore, locating the semi-active damped outrigger system at the 54th floor provides the best performance, with the damping coefficients in a range of 80-90 MN-sec/m. For efficiency, the 80 MN-sec/m is chosen as the designed damping coefficient.

To understand the importance of considering the response perimeter columns, a comparison is made between the simplified model in Smith and Willford (2007) and the one proposed in this study (see Fig. 1). The simplified model proposed by Smith and Willford (2007) neglected the contribution of the perimeter columns, while this study models these columns in the building system. Fig. 5 shows the top displacement and acceleration for these two models, which are derived from the RMS response analysis as mentioned earlier. As shown in this figure, the top displacements between the simplified and current models are similar; however, the simplified model overestimates top floor accelerations in this damped outrigger, as the damping coefficients remain large. In the context of design, considering the dynamics of the perimeter columns can be critical to performance assessment.

In simulation, the semi-active damped outrigger employs a model for a prototype MR damper (Spencer *et al*. 1997, Phillips *et al*. 2011). This model is derived from the Bouc-Wen hysteretic model in which the damper force is a function of the damper displacement and velocity and input current. In this study, the coefficients in the model of the MR dampers are referred to Spencer *et al*. (1997), while some modifications are applied to this model in order to meet the design. For example, the coefficients are appropriately adjusted for the semi-active damped outrigger system, i.e., the force (KN) applies a multiplier equal to 100 and the coefficients with respect to the damper velocity (m/sec) and displacement (m) are multiplied by 5, as compared to the original model (Chang *et al*. 2008). Moreover, the maximum voltage used in the clipped-optimal control is set to be 5.0V, and the equivalent damping coefficient in the semi-active damped outrigger is approximately equal to the designed value.

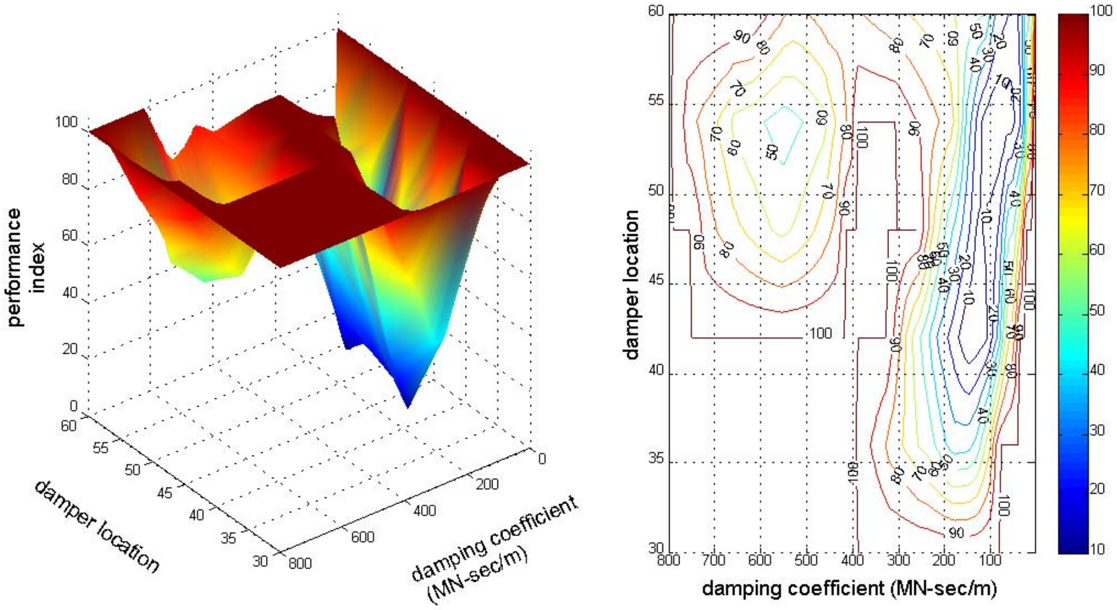
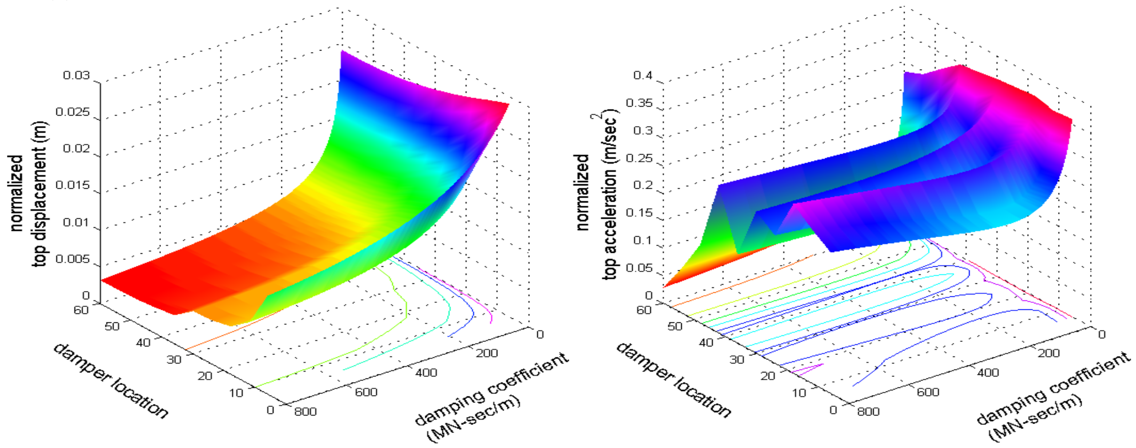


Fig. 4 Design of the damping coefficient used in the semi-active damped outrigger

(a)



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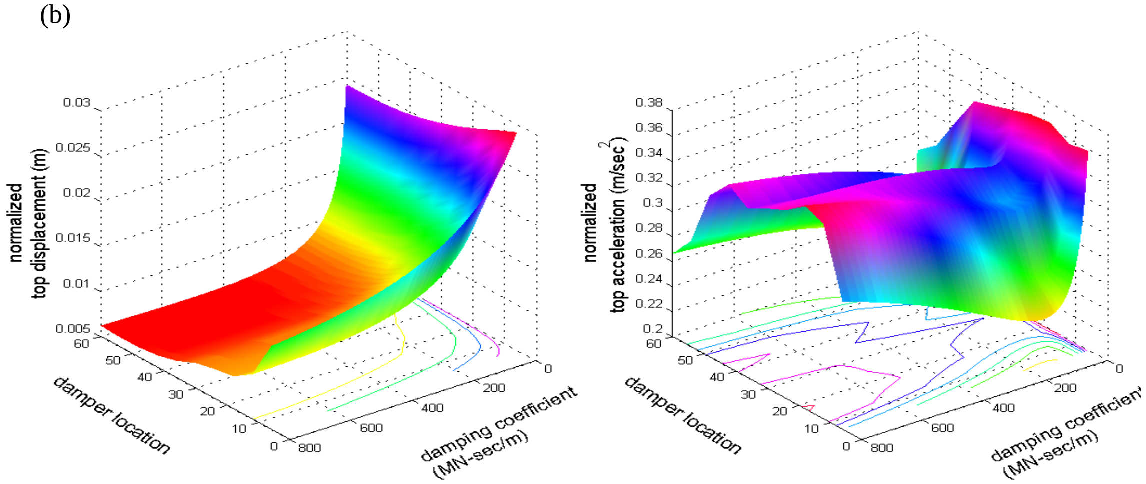


Fig. 5 Comparison of top displacements and accelerations between (a) simplified model and (b) current model

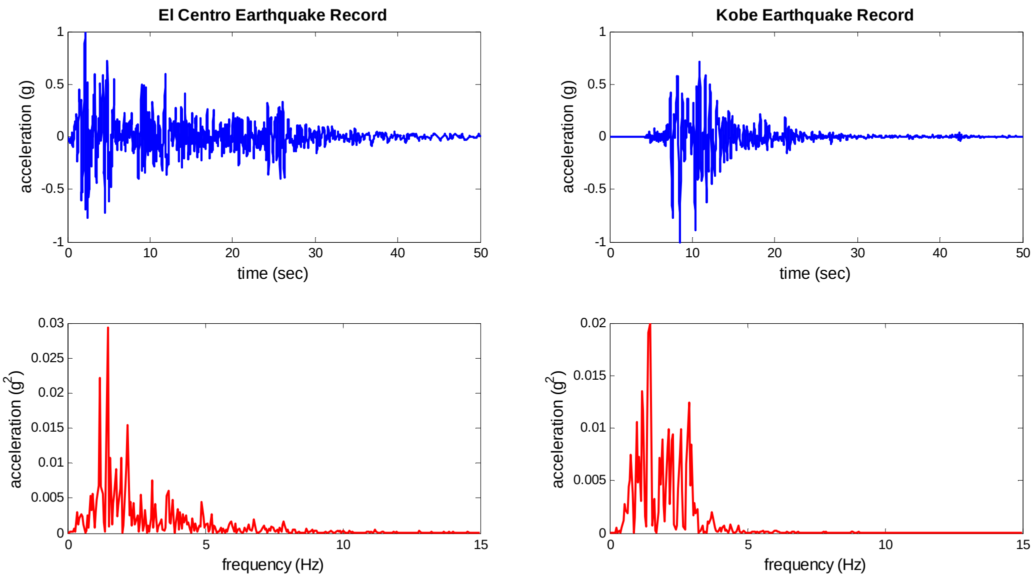


Fig. 6 Two historical earthquake records: El Centro and Kobe earthquakes

Fig. 7 shows the maximum and RMS displacement responses of the uncontrolled building and building with an outrigger wall that is fixed to the perimeter columns. These responses are normalized to those from the building with a viscously damped outrigger. The translational displacements of the building with an outrigger wall vary with the seismic events. In the case of the Kobe earthquake, the responses of this structural system are significantly increased as compared to the uncontrolled building, indicating the necessity of additional damping devices for resisting seismic loadings.

For the semi-active system, the semi-active damped outrigger produces RMS displacements superior to the viscously damped outrigger, as shown in Fig. 8. The responses in this figure are normalized to those from the viscously damped outrigger. The averaged reductions on RMS displacements are about 20% for both earthquake cases. As for the maximum displacements, the semi-active damped outrigger still produces better performance than the outrigger with viscous dampers in the El Centro earthquake case.

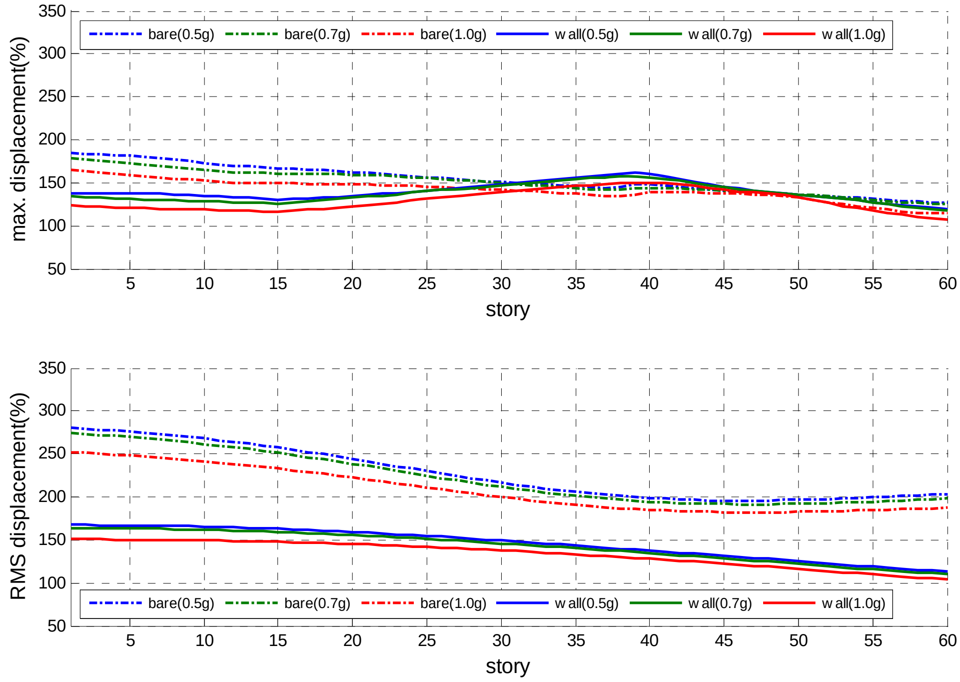
Fig. 9 demonstrates the acceleration responses of the semi-active damped outrigger which are normalized by the responses from the viscously damped outrigger. Using the control objective of minimizing the floor accelerations, the semi-active damped outrigger produces smaller accelerations than the viscously damped outrigger. With the PGA increase, the RMS accelerations from the semi-active damped outrigger are better mitigated. Moreover, the normalized base shears and overturning moments to the viscously damped outrigger are shown in Fig. 10. Despite some maximum floor accelerations exceeding the viscously damped case, most semi-active damped outrigger cases still generate lower maximum base shears and overturning moments. As a result, the semi-active damped outrigger can effectively decrease the overturning moments up to 30% under the 1.0-g Kobe earthquake, as compared to the outrigger with viscous dampers.

To further investigate the resulting damping in the semi-active approach, Fig. 11 illustrates the equivalent damping coefficient under the 0.5-g El Centro earthquake. As can be seen, the equivalent damping is slightly smaller than the designed value but still provides a higher capability of mitigating structural responses. In sum, minimizing the translational floor accelerations from first thirty modes in the LQG/clipped-optimal control design performs a semi-active damped outrigger system better for this tall building against earthquakes.

6. Conclusions

This study developed and evaluated a semi-active damped outrigger system using MR dampers for a high-rise building. A building model was developed to portray the St. Francis Shangri-La Place in Philippines, and the semi-active damped outrigger system with a feasible configuration was determined. In the context of the damper design, this study developed a method that evaluated the outrigger location and damper size through the stochastic analysis. By applying the proposed criteria, an optimal design was determined. To achieve high efficiency in the semi-active damped outrigger with MR dampers, the LQG/clipped-optimal control method was employed to design the semi-active control. The numerical results showed that the semi-active controller provided high control performance against two historical earthquake loadings. The semi-active damped outrigger with the semi-active control strategies effectively generated sufficient dissipating energy through the outrigger arms as well as significantly created the high capability of mitigating the building displacements and overturning moments.

(a)



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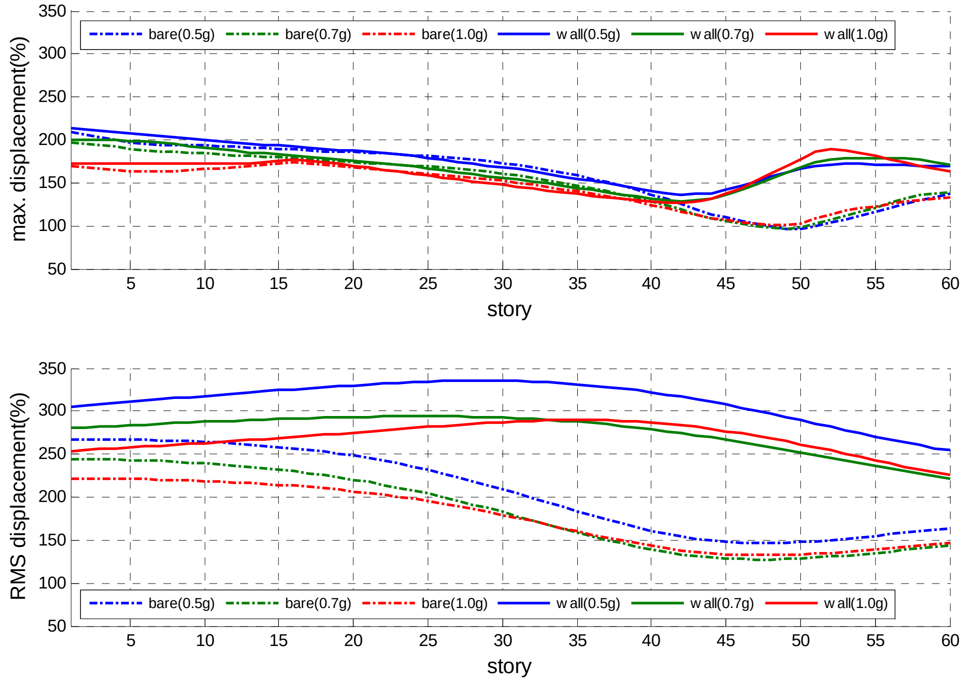

Fig. 7 Comparison of control performance between the uncontrolled building and building with an outrigger wall under (a) El Centro earthquake and (b) Kobe earthquake

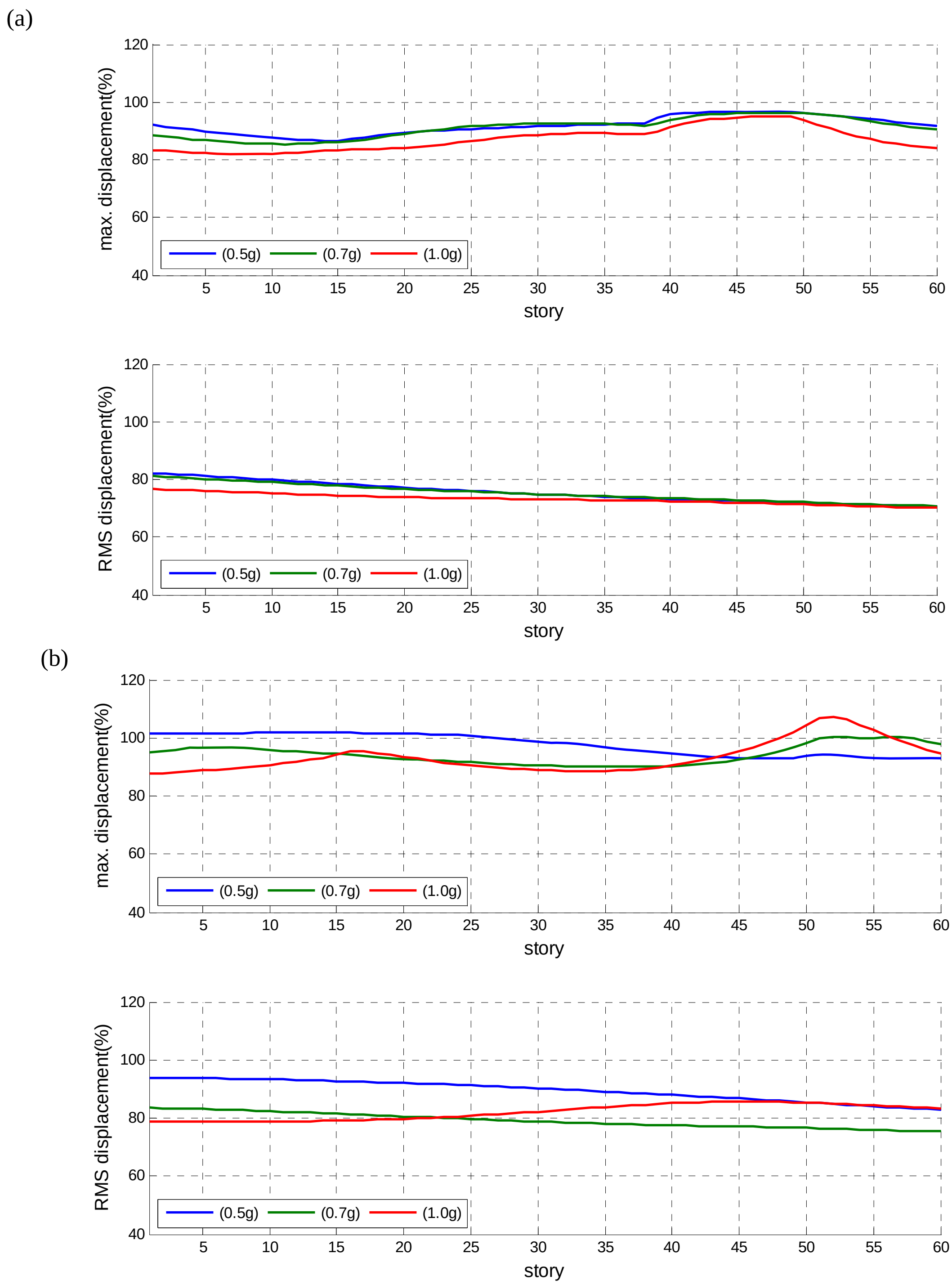

Fig. 8 Displacements of the semi-active damped outrigger under (a) El Centro earthquake and (b) Kobe earthquake

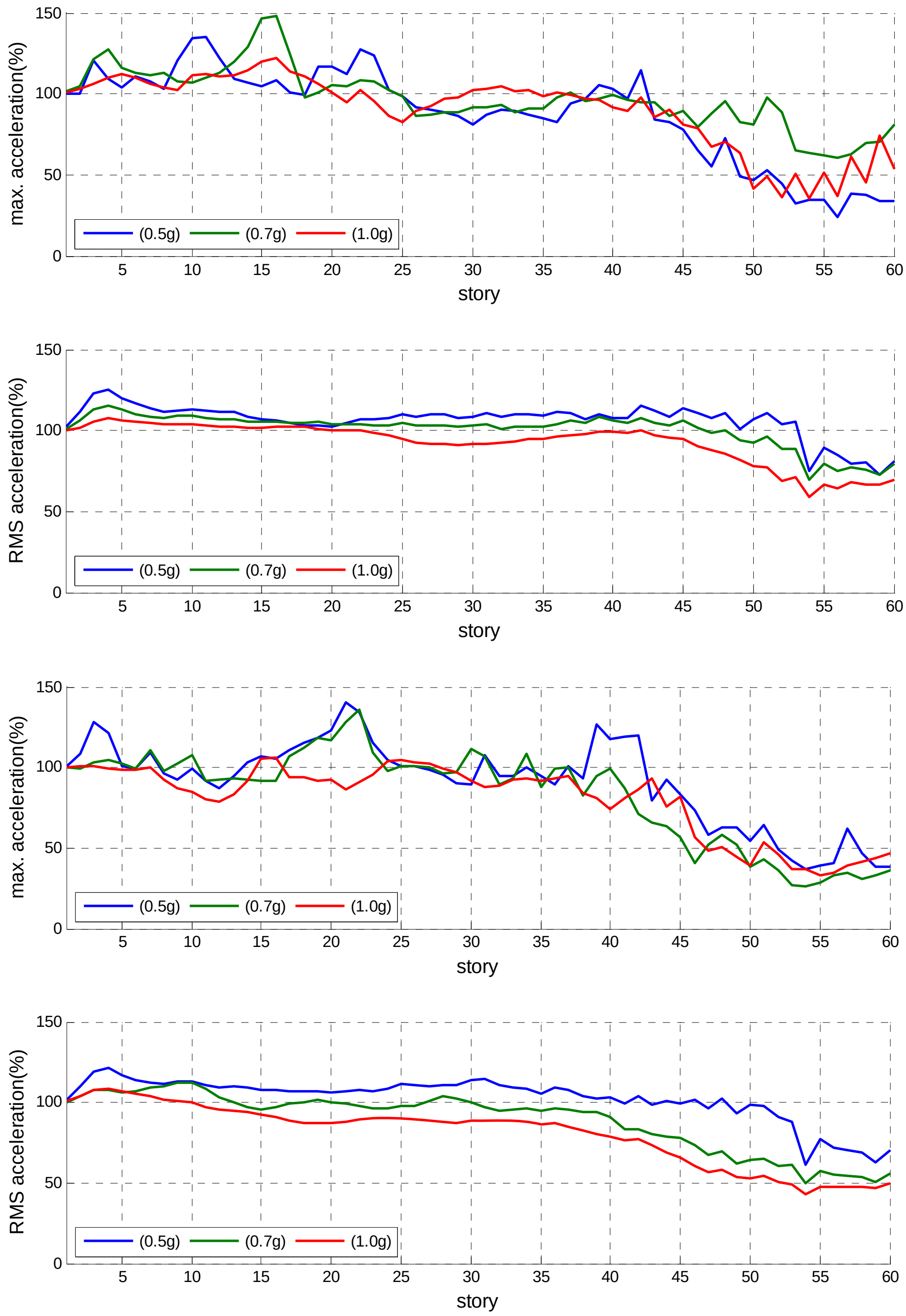

Fig. 9 Floor accelerations of the semi-active damped outrigger under (a) El Centro earthquake and (b) Kobe earthquake

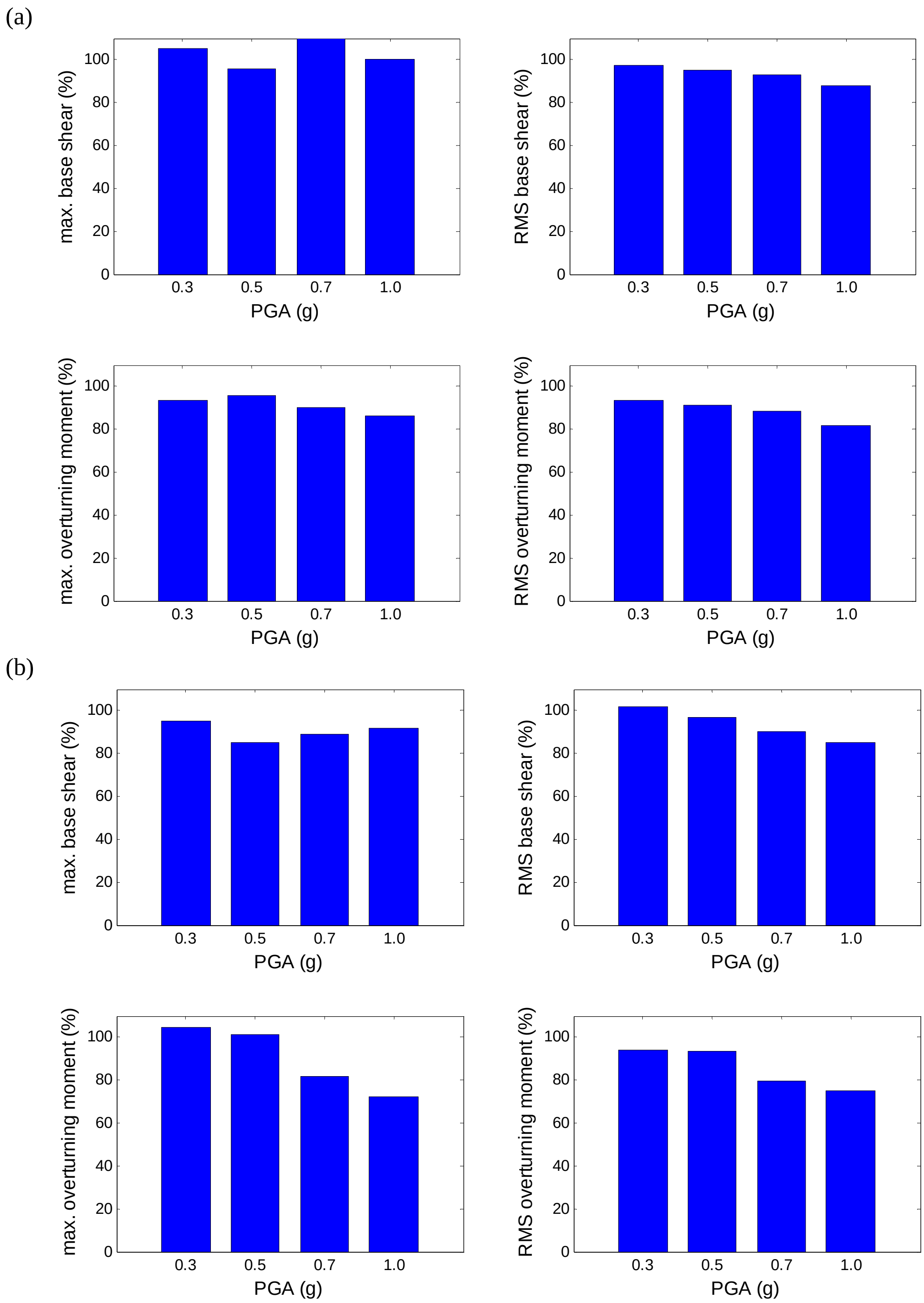

Fig. 10 Base shears and overturning moments of the semi-active damped outrigger under (a) El Centro earthquake and (b) Kobe earthquake

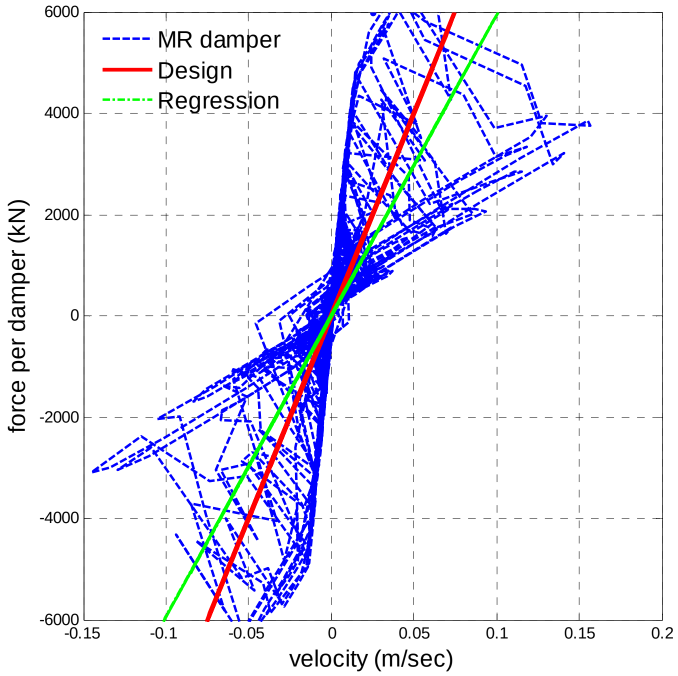

Fig. 11 Illustration of the damping coefficient in the semi-active damped outrigger

The results provided in this study showed superior performance using the semi-active damped outrigger in this high-rise building. For higher control efficacy, more MR dampers can be considered in the outrigger system. Alternatively, multiple outriggers located in different floors can be designed to outperform a single outrigger in a building. This study only emphasizes the acceleration feedback to fulfill the semi-active control strategy, and more control strategies focusing on different control objectives and different feedback measurements can be further investigated. Since the study verified the semi-active damped outriggers in high-rise buildings, similar strategies based on this control approach can be extensively explored to enhance building performance against strong winds and earthquakes.

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References

Berton, S. and Bolarnder, J.E. (2005), "Amplification system for supplemental damping devices in seismic applications", *J. Struct. Eng.*, **131**(6), 979-983.

Chang, C.M., Park, K.S., Mullenix, A.T. and Spencer, B.F., Jr. (2008), "Semiactive control strategy for a Phase II base isolated benchmark building", *J. Struct. Control Health Monit*., **15**, 673-696.

Chen, Z.Q., Wang, X.Y., Ko, J.M., Ni, Y.Q., Spencer, B.F., Jr., Yang, G. and Hu, J.H. (2004), "MR damping system for mitigating wind-rain induced vibration on Dongting Lake cable-stayed bridge", *Wind Struct*., **7**(5), 293-304.

Constantinou, M.C., Tsopelas, P., Hammel, W. and Sigaher, A.N. (2001), "Toggle-brace-damper seismic energy dissipation system", *J. Struct. Eng*., **127**(2), 105-112.

Dyke, S.J., Spencer, B.F., Jr., Sain, M.K. and Carlson, J.D. (1996a), "Modeling and control of magnetorheological dampers for seismic response reduction", *Smart Mater. Str*uct., **5**, 565-575.

Dyke, S.J., Spencer, B.F., Jr., Quast, P., Sain, M.K., Kaspari, D.C. and Soong, T.T. (1996b), "Acceleration feedback control of MDOF structures", *J. Eng. Mech*., **122**(9), 907-918.

Fujitani, H., Sodeyama, H., Tomura, T., Hiwatashi, T., Shiozaki, Y., Hata, K., Sunakoda, K., Morishita, S. and Soda, S. (2003), "Development of 400kN magnetorheological damper for a real base-isolated building", *Proceedings of the SPIE Conf. Smart Structures and Materials*, 5057, Bellingham, WA.

Infanti, S. and Robinson, J. and Smith, R. (2008), "Viscous dampers for high-rise buildings", *Proceedings of the 15th World Conference on Earthquake Engrg*., Beijing, China.

Jeremlah, C. (2006), *Application of damping in high-rise buildings*, Massachusetts Institute of Technology, http://hdl.handle.net/1721.1/34589

Kareem, A., Kijewski, T. and Tamura Y. (1999), "Mitigation of motion of tall buildings with recent applications", *Wind Struct*., **2**(3), 201-251.

Nagarajaiah S. and Narasimhan, S. (2006), "Smart base-isolated benchmark building. Part II: phase I sample controllers for linear isolation systems", *J. Struct. Control Health Monit*., **13**, 589-604.

Phillips B. and Spencer Jr., B.F. (2011), *Model-Based Servo-Hydraulic Control for Real-Time Hybrid Simulation*, Newmark Structural Engineering Report Series, Report No. NSEL-028, https://www.ideals.illinois.edu/handle/2142/25933.

Ramallo, J.C., Johnson, A.M. and Spencer, B.F., Jr. (2002), "Smart base isolation systems", *J. Eng. Mech*., **128**(10), 1088-1100.

Sigaher, A.N. and Constantinou, M.C. (2003), "Scissor-jack-damper energy dissipation system", *Earthq. Spectra*, 19(1), 133-158.

Smith, B.S. and Salim, I. (1981), "Parameter study of outrigger-braced tall building structures", *J. Struct. Division*, **6**, 2001-2014.

Smith, R.J. and Willford, M.R. (2007), "The damped outrigger concept for tall buildings", *Struct. Des. Tall Build*., **16**, 501-517.

Soong, T.T. and Spencer, B.F., Jr. (2002), "Supplemental energy dissipation: State of art and state of practice", *Eng. Struct*., **22**, 243-259.

Spencer, B.F., Jr. and Nagarajaiah, S. (2003), "State of the art of structural control", *J. Struct. Eng*., **129**(7), 845-856.

Spencer, B.F., Jr., Dyke, S.J., Sain, M.K. and Carlson, J.D. (1997), "Phenomenological model of a magnetorheological damper", *J. Eng. Mech*., **3**, 230-238.

Taranath, B.S. (1998), *Structural Analysis and Design of Tall Buildings*, McGrwa Hill, Inc.

Taylor, D.P. (2003), "Mega brace seismic dampers for the Torre Mayor project at Mexico city", *Proceedings of the 74th Shock & Vibration Symposium*, San Diego, CA.

Willford, M., Smith, R., Scott, D. and Jackson, M. (2008), "Viscous dampers come of age", *Struct. Mag*., **6**, 15-18.

Yang, G., Spencer, B.F., Jr., Carlson, J.D. and Sain, M.K. (2002), "Large-scale MR fluid dampers: Modeling and dynamic performance considerations", *Eng. Struct*., **24**, 309-323.

Yang, J.N., Agrawal, A.K., Samali, B. and Wu, J.C. (2004), "Benchmark problem for response control of wind-excited tall buildings", *J. Eng. Mech*., **130**(4), 437-446.