Semi-active Outrigger Damping System for Seismic Protection of Building Structure

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Abstract

The outrigger structural system is one of the most widely used lateral load-resisting structural systems for high-rise buildings. To increase the energy dissipation capacity of the outrigger system, an outrigger damping system has been proposed as a novel energy dissipation system. In this system, the outrigger and perimeter columns are separate and vertical viscous dampers are equipped between the outrigger and perimeter columns. In this study, the control performance of a semi-active outrigger damping system for the seismic protection of a building structure was investigated. Semi-active damping devices, such as magnetorheological (MR) dampers instead of passive dampers, are installed vertically between the outrigger and perimeter columns to achieve large and adaptable energy dissipation. A fuzzy logic control algorithm was used to generate a command voltage sent to the semi-active MR dampers. A genetic algorithm was used to optimize the fuzzy logic controller. An artificial earthquake load was generated for the numerical simulation and a simplified numerical model of a damped outrigger system was developed. Numerical analyses showed that the semi-active damped outrigger system could effectively reduce both the displacement and acceleration responses of the tall buildings compared to a passive outrigger damper system.

Keywords: damped outrigger system; MR damper; seismic response control; fuzzy logic controller; multi-objective optimization

1. Introduction

The outrigger and belt truss system is commonly used as a structural system that can effectively increase the lateral resistance of high-rise buildings to either wind or earthquake loads (Choi et al., 2012). In total, 73% of tall buildings constructed in the 2000s have adopted an outrigger structural system, and approximately 50% of them are constructed with concrete (CTBUH, 2010). The conventional outrigger is cantilevered from the core and connects to the perimeter columns directly. This can improve the efficiency of the core system by simply engaging the exterior columns to aid in resisting a part of the overturning moment resulting from the lateral loads (Smith and Salim, 1981; Chung and Sunu, 2015).

An innovative approach for the outrigger damping system consisting of vertical dampers between the outrigger walls and perimeter columns in a frame-core tube structure was proposed to protect high-rise buildings from various excitations induced by natural hazards (Jeremlah, 2006). Smith and Willford (2007) proposed a similar outrigger damping system to Jeremlah (2006) and applied the outrigger damping system successfully to a high-rise building in the Philippines (Willford et al. 2008).

The outrigger hydraulic jack damper system was installed from the outrigger to the perimeter column/belt truss joint of a 68-story North-East Asia Trade Tower (NEATT) in Songdo, Korea (Park et al., 2010). In this case, the outrigger damping system was used to automatically adjust the differential column shortening...
Advantages and disadvantages of the three control types are listed in Table 1. Recently, a semi-active control device is widely used to utilize the control performance benefits while seeking to solve the lack of stability of active systems.

One of the most promising semi-active devices is a magnetorheological (MR) damper. Because of its mechanical simplicity, high dynamic range and low power requirements, they are considered good candidates for reducing structural vibrations and have been studied by a number of researchers for the seismic protection of civil structures (Kim and Roschke, 2006; Dyke et al., 1996; Spencer et al., 1997). In recent years, the concept of a smart outrigger damping system was proposed by replacing passive dampers in the damped outrigger system by semi-active dampers, such as MR dampers (Chang et al., 2013; Asai et al., 2010). In these studies, the control performance of the smart outrigger damping system was investigated by experimental and numerical simulations. The clipped optimal control with the linear-quadratic Gaussian (LQG) acceleration feedback was adopted in previous research. These studies showed that the semi-active damped outrigger system effectively reduced the dynamic responses of high-rise buildings subjected to earthquake loads. Semi-active control devices, such as MR dampers, were applied successfully to conventional base isolation systems and tuned mass dampers, resulting in improved control performance. On the other hand, research on semi-active outrigger damping systems is relatively new with only several papers published thus far. Therefore, more studies on the control performance of a damped outrigger system with semi-active control devices will be needed to verify their applicability to practical tall buildings. In particular, the application of intelligent controllers, including fuzzy logic controllers (FLC) and genetic algorithms (GA), to a semi-active outrigger damping system has not been addressed.

In this study, the lateral response reduction performance of a semi-active outrigger damping system for high-rise building structures subjected to seismic loads was investigated. MR dampers were used as semi-active dampers to compose a semi-active outrigger damping system instead of passive dampers. In the semi-active outrigger damping system, MR dampers were installed vertically between the outrigger and perimeter columns. As an example structure, a simplified finite element model representing the dynamic characteristics of a high-rise building was used for the numerical simulation. Artificial ground motion was generated for seismic time history analyses to examine the control performance of the semi-active outrigger damping system for the seismic protection of the building structure. One of the challenges in the application of the semi-active outrigger damper is the development of an appropriate control algorithm to determine the command voltages of MR dampers. A fuzzy logic controller (FLC) was used to operate an MR damper, which is a key component of the semi-active outrigger damping system. A genetic algorithm (GA) was applied to the optimal design of a FLC. Because a semi-active outrigger damping system has been lately proposed, the limited research cases were investigated. Therefore, the research methods selected in this study may not be the best option for development of the semi-active outrigger damping system. Accordingly, the objective of this study is not to develop the optimal semi-active outrigger damping system but to investigate the possibility of the semi-active outrigger damping system as a structural control method.

2. Simplified Model of an Example Structure with Semi-Active Outrigger Damping System

To efficiently evaluate the control performance of a semi-active outrigger damping system for high-rise buildings subjected to earthquake loads, a simplified finite element model with one outrigger in a frame-core tube structure, as shown in Fig.3., was adapted as an example structure. The deformation of the building core due to external horizontal loads, such as earthquakes or wind loads, normally shows similar characteristics to the cantilever beam. As a result, a simplified model of the core-to-perimeter-column outrigger system, proposed by Kim et al. (2011), was employed in this study. In this model, the building core was modeled as a uniform cantilever beam and lateral loads to this simplified model were resisted only by the shear wall core. The stiffness of the core was determined by the elastic modulus (E), moment of inertia (I) and height of the core (H). The outrigger with a length of L was assumed to be massless and...
infinitely rigid because the stiffness of the outrigger is much larger than that of slabs or beams. The intrinsic damping of the structure was omitted. The only damping source for the structural system was from the two dampers equipped between the outrigger and the perimeter columns. Fig.3.(a) shows a simplified model for a building with a conventional outrigger system having no additional dampers. Because the vertical stiffness of perimeter columns ($K_{col}$) is much stronger than the axial stiffness of the semi-active dampers, perimeter columns are assumed to be rigid vertically and the outrigger is connected directly to the ground through semi-active dampers, as shown in Fig.3.(b). An outrigger passive damper system is used for a comparative study. The semi-active outrigger damper model in Fig.3.(b) is used for the passive outrigger damper model by only replacing the semi-active dampers with passive dampers.

![Fig.3. Simplified Finite Element Model](image)

The material of the example structure was assumed to be reinforced concrete (RC) and the elastic modulus was set to be $2.8 \times 10^{11}$ N/m$^2$. The example building was assumed to have 50 stories with a uniform story height of 4 m. The width of the example building (L) and the width of the shear wall core were set to 40 m and 12 m, respectively. The story mass was 400,000 kg; thus, the total mass of the example building was 20,000,000 kg. Because a three-dimensional example building was simplified into a two-dimensional simple model, the thickness of the shear wall core was assumed to be 3 m by the sum of the thicknesses of every shear in a three-dimensional layout. Based on these assumptions, the first mode natural period of vibration of the example structure without the outrigger system was calculated to be 4.17 sec. The perimeter columns of the example structure with the conventional outrigger system were connected rigidly to the outrigger; thus, the vertical stiffness of perimeter columns ($K_{col}$) mainly affects the lateral stiffness of the analytical model, shown in Fig.3.(a). To calculate the vertical stiffness of the perimeter columns, it was assumed that the example structure has ten RC perimeter columns with a cross section of 1 m $\times$ 1m. As a result, the first mode natural period of vibration of the example structure with the conventional outrigger system was calculated to be 2.18 sec. Note that the natural period of vibration of the example structure was shortened because the lateral stiffness of the structure was increased significantly using the outrigger system.

A Bouc-Wen model was used to describe how the damping force is related to the velocity and applied voltage of the MR damper (Sues et al., 1988). The maximum capacity of the MR damper was approximately 2,000 kN, as shown in Fig.4. This passive-on damping force was determined by a trial and error process (iterative method) for optimal vibration control of the example structure. The damping force of the MR damper was controlled by the command voltage. When the maximum damping force was required (passive-on), 5 V was sent to the MR damper, and the minimum command voltage (passive-off) was 0 V. Two 2,000 kN MR dampers were used at both ends of the outrigger of the example structure.

![Fig.4. Force-velocity Relationship of the MR Damper](image)

To conduct numerical simulations of the semi-active outrigger damping system, the equilibrium equation of the simplified finite element model proposed by Kim et al. (2011) was used as follows:

$$
\begin{bmatrix}
12EI \\
6EI \\
6EI \\
4EI \\
H^3 \\
H^2 \\
H^2 \\
H \\
\end{bmatrix}
\begin{bmatrix}
u \\
\theta \\
f \\
T \\
\end{bmatrix}
= 0
$$

(1)

where $u$ and $\theta$ denote the lateral displacement and the rotation angle of the outrigger, respectively, $E$ is the elastic modulus, $f$ is the moment of inertia of the shear wall core, $H$ is the height of the structure, $f$ is the lateral force, and $T$ is the external moment. When the second row of Eq. (1) is expanded, the external moment, $T$, can be expressed as

$$
T = \frac{6EI}{H^2} u + \frac{4EI}{H} \theta
$$

(2)

This external moment ($T$) is equal to the resisting moment ($T_e$) induced by the outrigger dampers. The resisting moment can be expressed using the length (L) and rotation angle ($\theta$) of the outrigger, as shown in Eq. (3).

$$
T_e = -K_e \frac{L^2}{2} \theta - FL
$$

(3)
where $K_d$ is the stiffness of the perimeter columns and $F$ is the damping force caused by the outrigger dampers. In the case of the conventional outrigger system shown in Fig.3.(a), $F$ is equal to 0 and $K_d$ is equal to $K_{col}$ because there is no outrigger damper. In the semi-active outrigger damping system, $F$ is equal to $F_{MR}$, which is the damping force produced by the MR dampers. By equating $T$ in Eq. (2) with $T_d$ in Eq. (3), the relationship between the lateral displacement ($u$) and the rotation angle of the outrigger ($\theta$) can be expressed, as shown in Eq. (4).

$$u = \left( -\frac{K_d H^2 L}{12EI} - \frac{2}{3} H \right) \dot{\theta} - \frac{H^2 L}{6EI} F$$

(4)

The equation of motion of the example structure is shown in Eq. (5). When the lateral displacement ($u$) in Eq. (4) is substituted for $u$ in Eq. (5), the state space equation with respect to the rotation angle of the outrigger ($\theta$) can be obtained, as expressed in Eq. (6).

$$m \ddot{\theta} + c \dot{\theta} + \frac{6EI}{H^2} \theta = f$$

(5)

$$\begin{align*}
\begin{bmatrix}
\dot{\theta} \\
\theta
\end{bmatrix} = & \begin{bmatrix}
0 & \frac{1}{mX_a} \\
\frac{12EI}{H^2} & \frac{6EI}{H^2}
\end{bmatrix} \begin{bmatrix}
\theta \\
\dot{\theta}
\end{bmatrix} \\
+ & \begin{bmatrix}
0 & 0 \\
\frac{1}{mX_a} & \frac{1}{mX_a}
\end{bmatrix} \begin{bmatrix}
f \\
F
\end{bmatrix}
\end{align*}$$

(6)

where $X_a = \left( -\frac{K_d H^2 L}{12EI} - \frac{2}{3} H \right)$.

This state space equation for the simplified finite element model with the semi-active outrigger damper system was implemented using the SIMULINK and MATLAB 2011a version.

For seismic excitation, an artificial ground motion was generated to examine the control performance of the semi-active outrigger damping system for high-rise buildings for the numerical simulations. An artificial earthquake record was produced to fit the design response spectrum using the SIMQKE software program (Gasparini and Vanmarcke, 1976). As a baseline of the artificial earthquake, the design response spectrum for 5% damping was generated based on the 2009 edition of the Korean Building Code (KBC2009). The seismic zone factor and site class for the design response spectrum were selected to be 0.22 and SB, respectively. Fig.5. presents the acceleration response spectrum of the artificial earthquake produced along with the design response spectrum of KBC 2009. The response spectrum of the artificial earthquake represents the trend of the design response spectrum.

Fig.6. presents the acceleration time history graph of the artificial earthquake. The peak ground acceleration (PGA) of the artificially generated earthquake was 0.144g. The artificial ground motion was generated with a time step of 0.01 seconds and its duration was 30 seconds.

3. Development of Semi-active Control Algorithm

A passive damping device has the constant damping ($c_p$), while a variable semi-active damping device can be modulated between two damping values, which are referred to as on-status ($c_{on}$) and off-status damping ($c_{off}$), as shown in Fig.7.

Fig.7. On-off Controlled Damper

Fig.7. illustrates how a variable semi-active damping device can provide a wide range of damping forces. At a given velocity, $v_r$, the corresponding damping force for the passive damper is a constant force, $f_p$. On the other hand, the variable semi-active damping device offers a damping force ranging from $f_{off}$ to $f_{on}$. The variable semi-active damping device, which
provides a wide range of dynamic forces, improves the vibration control performance significantly compared to the passive damping device with the proper control methods.

Many control strategies for semi-active damping control have been reported. One of the first examinations of semi-active control is the skyhook damper control algorithm (Karnopp et al., 1974). The skyhook control policy is used favorably because of its simplicity and effectiveness. The algorithm has also shown good control performance for the vibration control of civil structures as well as vehicle applications (Liu et al., 2005; Koo et al., 2006). Feng and Shinozukah (1990) developed the bang-bang controller for a hybrid controller on a bridge. Leitmann (1994) proposed a control strategy based on the Lyapunov stability theory for ER (Electrorheological) dampers. The purpose of this algorithm was to reduce the structural responses by minimizing the rate of change of a Lyapunov function. A similar approach was proposed by McClamroch and Gavin (1995) to develop a decentralized bang-bang controller. This control algorithm was designed to minimize the total energy of the structure. Inaudi (1997) proposed a modulated homogeneous friction algorithm for a variable friction device. Recently, the clipped-optimal control algorithm was proposed and implemented for semi-active systems (Dyke and Spencer Jr., 1996). A clipped-optimal control strategy consists of a bang-bang (on-off) controller that causes a semi-active damper to generate a desirable control force determined by an ideal active controller. These control algorithms are bang–bang controllers (on–off controllers). The advantages and disadvantages of the bang-bang controller and fuzzy controller are listed in Table 2.

| Types                        | Description                                    |
|------------------------------|------------------------------------------------|
| Bang-bang controller         | Generate sub-optimal control force             |
|                              | May introduce local damage to the structure    |
|                              | Simple determination of control command        |
| Fuzzy controller             | Inherent robustness                            |
|                              | Control gradually and smoothly                 |
|                              | Easy handling nonlinear systems & uncertainties|
|                              | Time-consuming membership function creation    |

The bang-bang controller produces swift changes in the command voltage, which lead to a sudden rise in the external control force, which increases the structural responses and may introduce local damage to the structure. A fuzzy logic controller utilizes the entire range of damping capacities of the MR dampers by generating a continuous (not on-off) command voltage as shown in Fig.8. (Ali and Ramaswamy, 2009).

An FLC maps an input space to an output space. The primary mechanism for doing this is a list of if-then statements called fuzzy rules. In this study, the MR damper displacement and the MR damper velocity were selected for two input variables of the FLC and the output variable was the command voltage sent to the MR damper, as shown in Fig.9. The if-part of the rule is called the antecedent, while the then-part of the rule is called the consequent. As shown in Fig.9., interpreting an if-then rule involves distinct parts: first evaluating the antecedent (which involves fuzzifying the input and applying any necessary fuzzy operators), and second applying that result to the consequent (known as the implication).

The control performance of the FLC depends on a range of design parameters associated with the selection of membership functions and the definition of a rule base. The FLC needs to have an effective and reliable inference system to perform at the desired level. Even if the FLC is made up using a simple rule base, the tuning of the fuzzy controller is a more difficult and sophisticated procedure than that employed in bang-bang type semi-active control algorithms. The design of fuzzy control rules to optimize the MR damper voltage is quite challenging because it requires a good understanding of the dynamic response of the structure with the semi-active outrigger damping system, which exhibits highly nonlinear behavior. To overcome this difficulty, a multi-objective genetic algorithm (MOGA) was employed for the optimal design of FLC in this study.

A multi-objective optimization problem occurs because multi-objective functions are in conflict, i.e., none of the feasible solutions allows simultaneous optimal solutions for all objectives. When a trade-off among the objectives exists, an improvement in one objective cannot be achieved without a detriment to another. In the case of structural control of a high-rise building with a semi-active outrigger damper system subjected to earthquake excitation, some trade-
off exists between the displacement response and the acceleration response of the building structure. For example, if the command voltages sent to the MR dampers in a semi-active outrigger damper system are increased, the connection force between the outrigger and perimeter columns are increased, resulting in an increase in lateral stiffness of the high-rise building. Consequently, lateral displacements of the high-rise building structure are reduced but the acceleration responses of the building structure show a concomitant increase. On the other hand, acceleration responses can be reduced by decreasing the MR damper forces, but this can lead to increased lateral displacements of the high-rise building structure. Therefore, it is impossible for minimum displacement and minimum acceleration of the building structure to occur simultaneously. In this study, the reduction of the peak displacement and RMS acceleration of the example building were selected as two objectives for a multi-objective optimization process, as shown in Table 3.

As shown in Table 3., the structural responses of the example building structure with a semi-active outrigger damper system were normalized by the corresponding responses of the conventional outrigger system in each objective function. Therefore, if the objective function values are less than 1, it means that the control performance of the semi-active outrigger damper system controlled by the NSGA-II optimized FLC is superior to that of the conventional outrigger system. The peak displacement of the example structure without an outrigger system can be reduced significantly from 17.3 cm to 8.7 cm using the conventional outrigger system. Conversely, the acceleration response is increased from 15.1 cm/s² to 37.0 cm/s² because of the conventional outrigger system. Therefore, the baseline responses of objective functions for J1 and J2 are 8.7 cm and 37.0 cm/s², respectively.

### Table 3. Multi-objective Functions

| Objective Function | Description |
|--------------------|-------------|
| J1                 | Peak displacement with semi-active outrigger damper system |
|                    | Peak displacement with traditional outrigger system |
| J2                 | RMS acceleration with semi-active outrigger damper system |
|                    | RMS acceleration with traditional outrigger system |

Among the many GA-based multi-objective optimization strategies available, the fast elitist Non-dominated Sorting Genetic Algorithm version II (NSGA-II) was used in this study (Deb *et al.*, 2002). The computational time in NSGA-II was reduced significantly compared to the existing multi-objective GAs and the crowding operator was introduced to maintain diversity without specifying additional parameters. Fig.10. presents the optimization procedure of NSGA-II.

### 4. Control Performance Evaluation

The population size, which is the number of chromosomes in each generation, was taken to contain 100 individuals in NSGA-II. An upper limit on the number of generations was taken to be 1000. Fig.11. shows the Pareto optimal solutions obtained by multi-objective optimization for MIMO FLC using NSGA-II.

The optimization results showed that the semi-active outrigger damping system can reduce both the peak displacement and RMS acceleration responses significantly compared to the conventional outrigger system. The J1 values of all individuals were between 0.6 and 0.8, as shown in Fig.11. This means that the semi-active outrigger damping system can reduce the peak displacements by 40% - 20% compared to the conventional outrigger system. The J2 values of most individuals were between 0.23 and 0.27, which shows that the RMS acceleration can be reduced considerably, by 77% - 73%. Among the Pareto optimal solutions in Fig.11., a FLC that can control both the displacement and acceleration responses appropriately was selected and marked with a solid circle. The J1 and J2 values of the selected FLC were 0.70 and 0.24, respectively.
For a quantitative evaluation of the control performance of the optimized FLC for the semi-active outrigger damper system, the structural responses of the example structure with three control cases were compared (Table 4.). Variations of the structural responses of each control case are shown as a percentage by assuming the example structure without an outrigger system to be a baseline (100%). In the case of the conventional outrigger system, the peak and RMS displacements were reduced by approximately 50% and 39%, respectively. On the other hand, the conventional outrigger system increases the acceleration responses approximately twofold. In the case of the semi-active outrigger damper system controlled by the selected FLC, the displacement responses were decreased by approximately 60% - 70% with an approximately 30% - 40% decrease in the acceleration responses.

Table 4. Comparison of Dynamic Responses

| Response       | w/o outrigger system | w/ outrigger system | w/ semi-active outrigger damper |
|----------------|----------------------|---------------------|-------------------------------|
| Peak Displacement | 17.3 cm (100%)       | 8.7 cm (50.3%)      | 6.0 cm (34.7%)                |
| RMS Displacement  | 6.7 cm (100%)       | 4.1 cm (61.2%)      | 1.9 cm (28.4%)                |
| Peak Acceleration  | 39.2 cm/s² (100%)   | 78.3 cm/s² (199.7%) | 25.0 cm/s² (63.8%)           |
| RMS Acceleration  | 15.1 cm/s² (100%)   | 37.0 cm/s² (245.4%) | 10.7 cm/s² (70.9%)           |

Figs.12. and 13. present the displacement and acceleration time histories for the cases of w/o outrigger, w/ outrigger and w/ semi-active outrigger to investigate the variation tendency of the dynamic responses in the entire earthquake excitation range. Although the conventional outrigger system can reduce displacement response of the structure effectively, it may increase the acceleration response. On the other hand, the semi-active outrigger damper system can provide good control performance for the reduction of the displacement and acceleration responses. If the other FLC is selected, as shown in Fig.11., the control performance of the semi-active outrigger damper system is changed by the engineer's preference.

The analysis results obtained in this study (Figs.11.-13. and Table 4.) are limited to the simplified finite element model of outrigger damper system and the artificial earthquake load. Therefore, additional studies are required to be conducted in order to objectively verify control performance of the semi-active outrigger damper system.

5. Conclusions

The control performance of the semi-active outrigger damping system for the seismic protection of a building structure was investigated. MR dampers were used as semi-active control devices. A fuzzy logic controller was used to generate the command voltage sent to the MR dampers. The FLC was optimized using a multi-objective genetic algorithm (NSGA-II).

When the conventional outrigger system was applied to a high-rise building subjected to earthquake loads, the lateral stiffness of the building was increased. Because of the increased lateral stiffness, the lateral displacements were reduced but the structural accelerations were increased. On the other hand, the semi-active outrigger system can reduce both displacement and acceleration responses considerably compared to the conventional outrigger system. The FLC optimized by NSGA-II can effectively control the MR damper forces, which are located between the outrigger and perimeter columns. By controlling the MR damper forces, the lateral stiffness of the example building structure with the semi-active outrigger damping system was varied promptly based on the structural dynamic responses. Because a number of Pareto optimal solutions for the FLCs were obtained by the NSGA-II optimization process, control performance of the semi-active outrigger damping system controlled by the FLC can be changed conveniently to satisfy the desired performance requirements. In this research, a simplified finite element model for a high-rise building and only one set of artificial earthquake load data were used to develop and evaluate the semi-active outrigger damping system. Accordingly, additional studies using other earthquake or wind loads and more complicated...

Fig.12. Comparison of the Displacement Time Histories

Fig.13. Comparison of the Acceleration Time Histories
building structures need to be conducted in order to derive more generalized conclusions. Because only numerical experiment was conducted in this study, proper control operation of the semi-active outrigger damper system under the practical situation cannot be guaranteed. Therefore, experimental studies are required for practical application of the proposed control method in the future work.

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References
1) Ali, S. F. and Ramaswamy, A. (2009) Optimal fuzzy logic control for MDOF structural systems using evolutionary algorithms. Engineering Applications of Artificial Intelligence, 22, pp.407-419.
2) Asai, T., Chang, C. M., Phillips, B. M. and Spencer, B. F. Jr. (2013) Real-time hybrid simulation of a smart outrigger damping system for high-rise buildings. Engineering Structures, 57, pp.177-188.
3) Chang, C. M., Wang, Z., Spencer, B. F. Jr., Chen, Z. (2013) Semi-active damped outriggers for seismic protection of high-rise buildings. Smart Structures and Systems, 11(5), pp.435-451.
4) Choi, H., HO, G., Joseph, L. and Mathias, N. (2012) Outrigger Design for High-Rise Buildings: An output of the CTBUH Outrigger Working Group. Council on Tall Buildings and Urban Habitat, Chicago.
5) CTBUH (2010) Tall Buildings in Numbers, The Council on Tall Buildings and Urban Habitat.
6) Chung, K. and Sunu, W. (2015) Outrigger systems for tall buildings in Korea. International Journal of High-Rise Buildings, 4(3), pp.209-217.
7) Deb, K., Pratap, A., Agrawal, S. and Meyarivan T. (2002) A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II. IEEE Transactions on Evolutionary Computation, 6(2), pp.182-197.
8) Dyke, S. J. and Spencer Jr. B. F. (1996) Seismic response control using multiple MR dampers. Proc. of the 2nd Intl. Workshop on Struc. Control, Hong Kong, pp.163-173.
9) Dyke, S. J., Spencer, B. F. Jr., Sain, M. K. and Carlson, J. D. (1996) Modeling and control of magnetorheological dampers for seismic response reduction. Smart Materials and Structures, 5, pp.565-575.
10) Feng, Q. and Shinozuka, M. (1990) Use of a variable damper for hybrid control of bridge response under earthquake. Proc. of U.S. Nat. Workshop on Structural Control Research USC Publ. No. CE-9013.
11) Gasparini, D. A. and Vanmarcke, E. H. (1976) SIMQKE: User's manual and Documentation. Dept. of Civil Eng. Massachusetts Institute of Technology.
12) Inaudi, J. A. (1997) Modulated homogeneous friction: a semi-active damping strategy. Earthquake Engineering and Structural Dynamics, 26(3), pp.361-376.
13) Jeremlah, C. (2006) Application of damping in high-rise building. Massachusetts Institute of Technology, Boston, USA.
14) Karnopp, D. C., Crosby, M. J. and Harwood, R. A. (1974) Vibration control using semi-active force generators. ASME Journal of Engineering for Industry, 96(2), pp.619-626.
15) Kim, B. J., Lee, S. H. and Chung, L. (2011) Design of outrigger damper system for wind-induced vibration control of building structures. Journal of the Wind Engineering Institute of Korea, 15(4), pp.163-171.
16) Kim, H. S. and Roschke, P. N. (2006) Design of fuzzy logic controller for smart base isolation system using genetic algorithm. Engineering Structures, 28(1), pp.84-96.
17) Koo, J. H., Ahmadian, M. and Setareh, M. (2006) Experimental robustness analysis of magneto-rheological tuned vibration absorbers subject to mass off-tuning. Journal of Vibration and Acoustics, Transactions of the American Society of Mechanical Engineers, 128(1), pp.126-131.
18) Leitmann, G. (1994) Semiactive control for vibration attenuation. Journal of Intelligent Material Systems and Structures, 5, pp.841-846.
19) Liu, Y., Waters, T. P. and Brennan, M. J. (2005) A comparison of semi-active damping control strategies for vibration isolation of harmonic disturbances. Journal of Sound and Vibration, 280, pp.21-39.
20) McClamroch, N. H. and Gavin, H. P. (1995) Closed loop structural control using electrorheological dampers. Proc. of the Amer. Ctrl. Conf., Seattle, Washington, pp.4173-4177.
21) Park, K., Kim, D., Yang, D., Joung, D., Ha, I. and Kim, S. (2010) A comparison study of conventional construction methods and outrigger damper system for the compensation of differential column shortening in high-rise buildings. International Journal of Steel Structures, 10(4), pp.317-324.
22) Smith, B. S. and Salim, I. (1981) Parameter study of outrigger-braced tall building structures. Journal of Structural Division (ASCE), 6, 2001-2014.
23) Smith, R. J. and Willford, M. R. (2007) The damped outrigger concept for tall buildings. The Structural Design of Tall and Special Buildings, 16(4), pp.501-517.
24) Spencer, B. F. Jr., Dyke, S. J., Sain, M. K. and Carlson, J. D. (1997) Phenomenological model of a magnetor-heological damper. Journal of Engineering Mechanics, 123(3), pp.230-238.
25) Sues, R. H., Mau, S. T. and Wen, Y. K. (1988) System identification of degrading hysteretic restoring forces. Journal of Engineering Mechanics, ASCE, 114(5), pp.833-846.
26) Willford, M., Smith, R., Scott, D. and Jackson, M. (2008) Viscous dampers come of age. Structure Magazine, 6, pp.15-18.