A SEMI ACTIVE CONTROL STRATEGY FORSEISMIC TORSIONALLY COUPLEDBUILDING STRUCTURES

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ABSTRACT

This paper addresses the effects of different semi-active control strategies on seismic responses of one-story, asymmetric-plan systems. The Magneto-Rheological (MR) dampers have been used as a semi-active control device in numerous researches both for symmetric and asymmetric buildings due to their attractive characteristics. However, one can show that the level of reduction in seismic torsional responses of asymmetric buildings is strongly affected by the plan asymmetric parameters of the building. To examine the effect of asymmetry on the dynamic behavior of a controlled typical structure, a parametric study is performed using a mathematical model of a one-story building with an asymmetric stiffness distribution in one direction. The model is subjected to a uniaxial lateral disturbance, exciting both lateral and torsional motions. Due to the highly nonlinear dynamic behavior of MR dampers, existing uncertainty of seismic excitation and also torsional behavior of the systems, development of a robustness control algorithm is found as a significant challenge. Therefore application of optimal strategy to create an admissible control algorithm and attain the desired level of performance is also investigated in this study. In order to evaluate the effectiveness of the proposed methods, the performances of semi-active controllers are compared with some other control algorithms in a numerical example.

INTRODUCTION

It is well known that real responses of plane-asymmetric buildings with irregular mass or stiffness distributions can be affected by coupling of translational and rotational vibrations. This type of structures is likely to suffer more severe displacement demands at the corner elements under sever ground motions. Due to some architectural issues, employing traditional approaches to control seismic responses of these structures such as altering the stiffness and/or mass re-distribution is not usually practical choice. Structural control strategies represent relatively new and smart approaches to improve the performance of such systems(Yoshida and Dyke, 2005). Accordingly, supplemental damping devices have attracted growing worldwide interest as an innovative approach to protect structures against natural extreme events by enhancing the structural energy dissipation capacity. Depending on the level of energy dissipation required and the sensitivity related to the band control, a control system can be broadly categorized into various strategies such as passive, active, semi active and hybrid systems. Although, various devices have been proposed for these control systems, semi-active devices like MR dampers introducing the positive aspects of passive and active control devices have been given much consideration.On the other hand selection of a suitable control strategy guarantees desirable performance and reduction of the effective responses of the controlled system (Das et al., 2012). However, most of the past experiences have been conducted on planar (symmetric-plan) systems; whereas there are a few studies that have considered the effects of control strategy on seismic response of asymmetric buildings (Pnevmatikos, 2012). The paper presents an optimal fuzzy logic controller (FLC) algorithm design for vibration control of asymmetric-plan structures equipped with MR dampers considering coupling of translational and rotational vibrations. Active control strategies based on analytical approach define only target control forces (Jansen and Dyke, 2000); however, FLC systems due to their inherent robustness and their ability to handle nonlinearities of systems introduce nonlinear control strategy to interact relationships between structural responses and gradual changes in voltage of MR dampers(Das et al., 2012). Design of a classical FLC system for asymmetric-plan structuresdue to torsionally coupling of asymmetric building and also nonlinearity of dynamic behavior of MR dampers is computationally extensive and do not lead to an optimal controller.Accordingly, application of some tuning methods such as gain scheduling, self-tuning and genetic algorithm to create admissible FLC parameters and attain the desired level of performance is inevitable (Wilson and Makola, 2005).On the other hand, control vibration of plan-asymmetry buildings is highly dependenton reducing of displacement of plan edges and also floors rotation. Therefore,the optimal selection of fuzzy parameters with respect to simultaneous control of multi-point of the plan will be possible. In this study, an advanced multi-objective optimization, NSGAII(Deb et al., 2002), as a new design strategy due to improve torsional performance of asymmetric buildings is used to achieve an optimal and admissible parameters of FLC as an semi-active strategyand also Linear Quadratic Regulator (LQR) method as a comparative active control method. Effect of asymmetry on the performance of these proposed optimal strategies is evaluated by a set of parametric study. Numerical study showed that integration of the NSGAII and FLC or LQR is highly successful and provides an effective vibration control in reduction of the seismic responses of torsionally coupled building structures.

OPTIMAL CONTROL SCHEME

A fuzzy controller is composed of the following principal elements(Yan and Zhou, 2006): 1)Fuzzification module (fuzzifier) that converts the crisp values of the control inputs into fuzzy; 2)The knowledge base that defines membership functions, fuzzy set representation of the input–output variables and the mapping functions between the physical and fuzzy domain; 3) The rule baseexpressed as a set of IF-THEN rules that uses expert knowledge or heuristics of the system. The rules are based on the fuzzy inference concept and the antecedents and consequents are associated with linguistic variables values; and 4) The mathematical procedure of converting fuzzy values into crisp values known as 'defuzzification'.Normalization is performed on input variables which is part of the control system. There are usually two types of normalization stages: one maps the physicalvalues of the control inputs onto a normalized universe of discourse and the other mapsthe normalized value of the control output variables back onto its physical domain.

The process of determining the fuzzy controller parameters including rule bases and membership functions based on an understanding of the behavior of a system will be a trial and error method. Using this method,especially for multi-input multi-output systems will be a very time consuming and tedious process and not necessarily lead to an optimal design. Computation search technique like genetic algorithmis a suitable method for determining the optimal parameters of a classic fuzzy control. Genetic algorithm is based on the principle of survival of Darwin. This means that the chromosomes that are more elegance, more likely to survive and have participated in the production of the next generation.In fact, by integrating the fuzzy control system and genetic algorithm parameters,an optimal control system will beobtained.Using this procedure, GA used a set of potential solutions, called a population, to evaluate the objective of the problem. During a number of natural operations including selection, mating, mutation, optimized solution will be obtained.

The buildings with asymmetry due to the coupling of translational and rotational vibrations had shown undesirable performances. To compensate the torsional effect, one approachisthe reduction of the existed irregularities by controlling the displacement ofstiffness and flexible edges of the plan. Thereby simultaneous reduction ofbothedges as two important objectives will be led to a multi-objective optimization problem in the process of FLC design.Non-dominated Sorting Genetic Algorithm –II (NSGAII) is one of the most successful and fastest elitist algorithms for multi objective optimization. In this algorithm the initial random population is generated and evaluated with random values. Then individual in this population is sorted based on non-domination into each front. This means thatthe individual in the first front is completely non-dominated by any other front and the second front are dominated only by the first front. Other fronts are sorted based on this method. Finally two parameters including rank and crowding distance represented their position in the front they belong are assigned to each individual in each front.Crowding distance as a new parameter maintains the diversity of the external archive and also leads to facilitate the convergence to the Paretooptimal solutions.In the next step the parents with lower rank and higher crowding distance during binary tournament are selected. Following that, through natural operation including crossover and mutation on the selected parents the new individual (offspring) are generated.Finally selection process from the parents and the offspring other for inclusion in the next iteration are done.

STRUCTURAL LAYOUT

The structure studied in this paper is a one-way asymmetric one-story building having non-compliance of the center of mass and stiffness (Fig.1). For such buildings, lateral and torsional motions under seismic excitations are coupled in one way. Thereby, torsionalmodel of structure has two coupled degreesoffreedoms at the floor including translation in the x-direction and a rotation about the vertical axis.Therefore, the equation related to the motions of the 3D asymmetric building structure with MR damper subjected to seismic excitations can be written as (Eq.1):

$$M\ddot{U} + C\dot{U} + KU = -Mr\ddot{u}_g + \eta F_{MR} \tag{1}$$

where M, C and K represent 2×2 mass , damping and stiffness matrices of the structure, respectively given in Eq. 2. U=$< u_x, u_\theta >^T$is the displacement vector with respect to the mass center, $\ddot{U}_g$ is the earthquake acceleration and r= <1 0 >^{T} is the influence vector with the order of 2×1defined for auni-directional excitation.

$$M = \begin{vmatrix} m & 0 \\ 0 & I \end{vmatrix} \;,\; K = \begin{vmatrix} K_x & K_{x\theta} \\ K_{\theta x} & K_\theta \end{vmatrix} \;,\; C = \alpha M + \beta K \;,\; K_\theta = \sum k_{yi} x_i{}^2 + \sum k_{xi} y_i{}^2 \tag{2}$$

where ‘m’ is the mass of system and ‘I’ is the mass moment inertia at the center of mass.$k_{yi}$and k_{xi}refer to the lateral stiffness ofthe ithelement in y and x direction,respectively. xi and yi are the coordinate distance of ith element with respect to CM.K_x is the total translation stiffness of system in x–direction. Due to asymmetric assumption, K_θ is the torsional stiffness at the center of mass.The damping matrix is assumed inthe form of Rayleigh’s damping in which αand β are the coefficients obtained based on the damping ratios of two vibration modes. For the present study, 5% damping is considered for both modes of vibration of system.In order to vibration suppression and to avoid additional undesirable torsional effects, two pairs of MR dampers are installed at stiff and flexible edges along x direction. Thereforη is the vector of MR damper locations. This vector for one-story building, due to the position of damper is in the form of equation (3). d_1 and d_2 represent distance between location of each damper and center of mass. Finally, F_{MR} represents the damper force produced in each edge (Eq.3).

$$\eta = \begin{vmatrix} 1 & 1 \\ d_1 & d_2 \end{vmatrix} \;\&\; F_{MR} = \begin{Bmatrix} f_{MR1} \\ f_{MR2} \end{Bmatrix} \tag{3}$$

MR DAMPER CHARACTRISES AND DYNAMIC

The dynamic behavior of the prototype shear-mode MR damper has been modeled using the simplified Bouc-Wen hysteresis model [Yoshida and Dyke, 2005]. The governing equations for the damper force “F” predicted by the present Bouc-Wen model can be written as (Eq.4):

$F = c_0 x + \alpha z \& z = -\gamma|x|z|z|^{n-1} - \beta x|z|^n + Ax$ (4)

where x is the velocity of the device and z is the hysteresis parameter. The hysteresis effect follows from the evolutionary variable "z"' controlled by the Bouc-Wen equation (Eq.4). By adjusting the parameters of the model, γ, β and the value of n, one can control hysteresis behavior and amplitude of the produced force.The effect of gain parameters on the hysteresis and also viscous effect are in the present case described by linear functions of the input voltage. Due to the mechanical properties of the damper, it has value in the absence of a magnetic field. Dynamics introduced into the system by MR damper are typically accounted for by the first order filter as the following function shows (Eq.5), where v and u are input and output voltages and $\frac{1}{\varphi}$ is a time constant. All the constant parameters are evaluated during a nonlinear optimization process.

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \quad \& c_0 = c_0(u) = c_{0_a} + c_{0_b} u \quad \& u = -\varphi(v - u) \qquad (5)$$

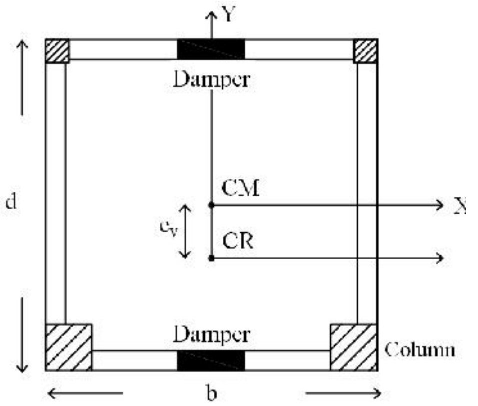

Figure1. Asymmetric building plan

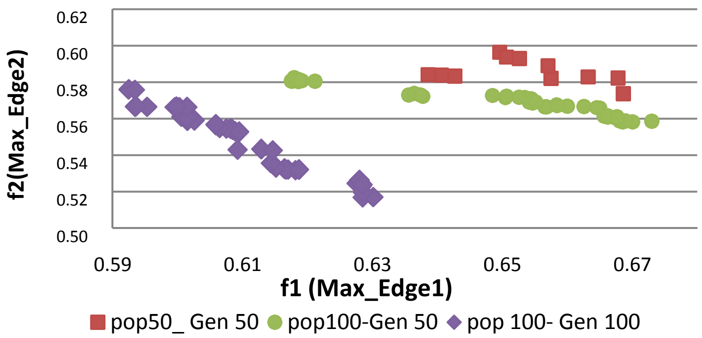

Figure 2. Optimized solutions

CLASIFICATION OF THE ASYMETRIC STRUCTURAL SYSTEMS

The structural systems depending on their torsional behavior under uni-directional seismic attack in the principal direction of the building can be categorized into three groups: the system with dominant lateral displacements motioncalled torsionally-stiff system, the system with dominant torsional rotation motion indicated torsionally-flexbile. These two systems have weak coupling between lateral and torsional motions whilethe third system will be referred to as a 'torsionally-similarly-stiff' system demonstrated that the lateral and torsional motions, are strongly coupled.
The key parameter defined these three groups is the lateraltorsional frequency ratio, Ω_θ.As defined by Goel and Chopra (1977)$\Omega_\theta$is the ratio of uncoupled torsional to lateral frequency (Eq. 6):

$$K_\theta = K_{\theta s} + K_x {e_y}^2 \& \omega_\theta = \sqrt{\frac{K_{\theta s}}{I}} \& \omega_x = \sqrt{\frac{K_x}{m}} \quad \rightarrow \quad \Omega_\theta = \frac{\omega_\theta}{\omega_x} \qquad (6)$$

where $K_{\theta s}$ is the torsional stiffness at the center of stiffness and e_y is the structural stiffness eccentricity, that is distance between the center of mass (CM) and center of stiffness (CS) along y direction. Considering this definition,if Ω_θ< 1, the structure is classified as torsionally-flexible and if Ω_θ> 1, the structure is classified as torsionally- stiff.

CONTROL SYSTEM DESIGN METHODOLOGY

In order to control an asymmetric building,a fuzzy controller due to inherent robustness and the ability to control of complicated system has been used. In this section an attempt is made to apply multi- objective

GAs to achieve satisfactory design of a FLC.In this traditional approach, designing an FLC can be led to an efficient process. Fuzzy controller used in this study has two inputs (displacement and velocity of each edge) and one output (required voltage of damper installed on the same edge). Gaussian shape function (Eq.7) respect to the ability of approximating almost all other types of membership functions is selected for both inputs and one output. The shape of Gaussian function is dependent on two parameters to be determined in the optimization process.

$$\mu = \exp\left(\frac{(\rho-b)^2}{2a^2}\right) \quad (7)$$

where b is the location of the center and a is the width of the function or standard deviation. To optimize rules base and map two input variables to a single output considered in this study, these rules are described as follows (Eq.8):

$$\text{Rule i : IF } \rho_1 \text{ is } A_i \text{ and } \rho_2 \text{ is } B_i \text{ then } \gamma \text{ is } C_i \;,\; i = 1,2,\ldots N \quad (8)$$

where N is the number of fuzzy rules, A_i, B_i and C_i are fuzzy sets characterized by membership functions.

To present a random complete fuzzy controller in this study, 10 IF-THEN rules are considered. In order to describe each rule six parameters, which are a_i and b_i for each input and output will be required. Finally, in order to encode random rule base with 10 rules totally sixty parameters are considered to be defined with NSGAII. In this study 100 initial population represented 100 random complete fuzzy controllersduring 100 evolutionary steps were optimized. In this step, building was excited with NS component of the 1940 El Centro ground acceleration and multi objectives included mitigation of peak displacement of both edges normalized by the uncontrolled peak displacement as the two objectives were considered.The set of Pareto resulted from NSGAII approach for various number of population and generations are shown in figure (2). Table(1) and figure (3) present an optimized rule base and its membership functions for one of the optimized solution.

Table1. Parameter values of optimized fuzzy logic Controller (Ω=0.5 , ex/d=0.25)

	a1	b1	a2	b2	a3	b3
Rule1	0.35	0.53	0.10	0.43	0.79	0.07
Rule2	0.62	0.52	0.48	0.68	0.60	9.51
Rule3	0.35	0.30	0.73	0.20	0.50	7.76
Rule4	0.67	0.01	0.19	0.78	0.10	6.34
Rule5	0.10	0.51	0.28	1.00	0.79	5.02
Rule6	0.73	-0.41	0.10	-0.25	0.10	1.94
Rule7	0.69	-0.48	0.10	0.18	0.15	2.54
Rule8	0.75	0.03	0.33	-0.54	0.76	9.71
Rule9	0.10	-0.69	0.45	-0.28	0.10	5.46
Rule10	0.10	-0.38	0.53	-0.28	0.10	7.81

COMPARING ALGORITHMS

In order to evaluate the effectiveness of proposed control method two other strategy including classic FLC and Linear-Quadratic Regulator (LQR) method which is typical active control algorithms are used. Classic FLC used the displacement and the velocity of the same edge astwo inputs variables with common seven Gaussian membership function, and the voltage of damper will be as an output variable with four Gaussian membership function. Due to seven fuzzy sets for each input, there are totally 49 rules that form the fuzzy control rule bases in such a system. Fuzzy controller used in this study isMamdani based on the Max-Min approach and defuzzifying method will be the center of area method for obtaining the crisp value.
Using the state-space form (Eq.9 and Eq.10) considering equation (1), LQR method finds the optimal gain (K_lqr) based on the state feedback law (11). Such that the cost function is minimized (Eq.12).

$$Z = AZ + B_c F_{MR} + B_m \ddot{u}_g \& Z = \begin{Bmatrix} U \\ \dot{U} \end{Bmatrix} \quad (9)$$

$$A = \begin{vmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{vmatrix} \& B_m = \left\{ \begin{matrix} 0 \\ -r \end{matrix} \right\} \& B_c = \left\{ \begin{matrix} 0 \\ M^{-1}\eta \end{matrix} \right\} \quad (10)$$

$$F_{MR} = -K_{lqr} Z \quad (11)$$

$$J = \int \left(Z^T Q Z + F_{MR}{}^T R\, F_{MR} \right) dt \quad (12)$$

Where Q is a weighting matrix specifying the relative importance of each of the system states and similarly, R is a weighting matrix that specifies the relative importance of the inputs. By increasing each coefficient, the corresponding quantity of state can be shrunk. There for during multi objective optimization process Q and R matrixes were optimized. In this stage, multi objectives including displacement of stiff and flexible edges were considered.

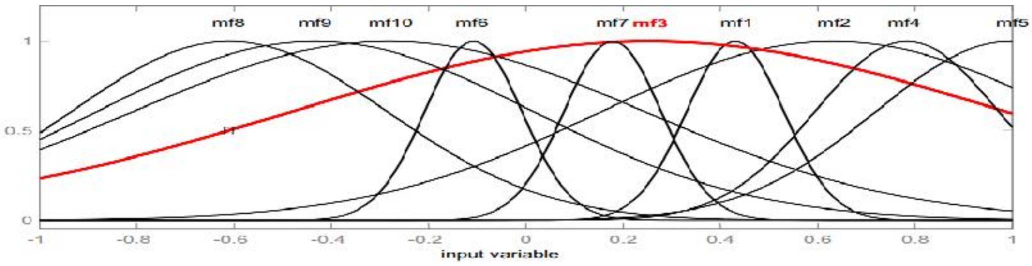

Figure3. Optimized input membership function (Ω=0.5, ex/d=0.25)

ASSESSMENT OF PROPSED STRATEGY

Optimal active and semi-active control methods are proposed in this study to control the torsional performance of an asymmetric structure equipped with MR dampers. The level of effectiveness of these control strategies is strongly affected by the asymmetric parameters including uncoupled frequency ratio ($\Omega_{\theta)}$ and stiffness eccentricity (e_y). Therefor a parametric study was performed using the numerical model proposed in the previous section by varying e_y from 0.1 to 0.25 as the ratio of the plan dimension along y direction (d),and Ω_θ as follows: Ω_θ = 0.5, 1.0, 1.5 representing various kind of torsional systems. The significant parameters used to assess the performance of the plan asymmetric structure are displacement and rotation of center of mass, displacement of stiff and flexible edges including displacement in x direction and also the root mean square (rms) displacement considering displacement in x and y directions due to rotational effect. The key design parameters such as base shear and torsion could be evaluated and compared. These criteria were calculated as a ratio of the controlled and uncontrolled responses. Control strategy can be evaluated by the number of control devices and the maximum force should be used to control the structure. Hence, the maximum level of control force provided by additional damper as the ratio of weight of building is also presented.Ability of various control strategies to control of asymmetric buildings with different Ω_θ and e_y/d are shown in tables (2) and (3).These results demonstrated the success of both designed controllers. It can be considered that GA_FLC are more successful to control of displacement while GA_LQR is better for control of torsion and base shear. But performance of both optimized controllers is better in comparison with classic FLC. Comparing two torsionally systems' responses showed that system with Ω_θ=1 could achieve higher reduction.The responses obtained for the systems with different Ω_θ and e_y/d, are presented in Table (4). The significant reduction in displacement and acceleration responses at CM, flexible and stiff edges as well as torsional response can be observed. These results reflected the success of the designed controller.This result are also observed in all tables for comparing systems with various Ω. GA_FLC, due to El-Centro excitation (ordinary excitation), was designed and optimized. Hereafter, the performance of this controller is assessed with Sanfernando as another ordinary excitation and also with two high intensity excitations (Kobe and Northridge). Results of these evaluations as presented in Table(5) indicated that GA_FLC was robustness enough to control of torsional coupled building under various excitations.

Table2. Comparison of Various Control Strategy on Seismic Responses of Different Eccentricity Building (Ω_θ=0.5)

GA_LQR	GA_FLC	FLC	e_y/d =0.15
0.59	0.55	0.76	U1
0.62	0.45	0.57	U2
0.68	0.57	0.77	Max_Edg1
0.31	0.61	0.73	Max_Edg2
0.44	0.69	1.39	Base Shear
0.49	0.55	0.6	Torsion
0.26	0.15	0.18	Fc_1/W
0.21	0.14	0.14	Fc_2/W

GA_LQR	GA_FLC	FLC	e_y/d =0.25
0.75	0.53	0.75	U1
0.68	0.5	0.69	U2
0.85	0.61	0.76	Max_Edg1
0.39	0.58	0.63	Max_Edg2
0.51	0.64	1.24	Base Shear
0.52	0.56	0.68	Torsion
0.21	0.18	0.22	Fc_1/W
0.16	0.13	0.1	Fc_2/W

Table3. Comparison of Various Control Strategy on Seismic Responses of Different Eccentricity Building (Ω_θ=1.5)

GA_LQR	GA_FLC	FLC	e_y/d =0.15
0.32	0.05	0.14	U1
0.37	0.06	0.15	U2
0.32	0.05	0.14	Max_Edg1
0.32	0.06	0.13	Max_Edg2
0.14	0.18	0.46	Base Shear
0.18	0.26	0.73	Torsion
0.31	0.32	0.43	Fc_1/W
0.21	0.19	0.18	Fc_2/W

GA_LQR	GA_FLC	FLC	e_y/d =0.25
0.32	0.05	0.18	U1
0.36	0.06	0.26	U2
0.32	0.05	0.15	Max_Edg1
0.34	0.04	0.13	Max_Edg2
0.15	0.16	0.38	Base Shear
0.19	0.23	0.41	Torsion
0.35	0.38	0.36	Fc_1/W
0.19	0.15	0.14	Fc_2/W

CONCLUSIONS

The effects of different semi-active control strategies on the seismic response of torsionally coupled building structures equipped with semi active MR dampers based on the parametric study investigated in this research. Considering the important parameters such as e_y/d and Ω_θ, three classes of asymmetric buildings are controlled by active and semi active control methods optimized with NSGAII. Comparing the controlled system's responses showed thatperformance of proposed controllers is highly dependent on Ω_θ. It was noted that the GA_FLC can effectively reduce responses of the structure compared to the ordinary FLC algorithm. Generally, the control performance of the GA_FLC is comparable to GA_LQR, while GA_ FLC as a nonlinear control strategy is more applicable for control of semi-active MR dampers. GA_ FLC can effectively reduce the displacement responses and could be successfully satisfy the design requirements by considerable reduction of base shear and torsion. The performance of optimized fuzzy controller was acceptable in a wide range of excitations. Therefore, GA_FLC system is quite effective in control of torsional systems.

Table 4. Effect of GA_FLC Strategy on Seismic Responses of Different Eccentricity Building

(Ω_θ=1)

0.1	0.15	0.2	0.25	e_y/d
0.50	0.55	0.65	0.53	U1
0.43	0.45	0.63	0.5	U2
0.49	0.57	0.71	0.61	Edge1
0.52	0.61	0.7	0.58	Edge2
0.46	0.48	0.65	0.51	Edge1rms
0.44	0.46	0.63	0.5	Edge2_rms
0.70	0.69	0.89	0.64	Base Shear
0.57	0.55	0.67	0.56	Torsion
0.11	0.15	0.15	0.18	Fc1/W
0.11	0.14	0.12	0.13	Fc2/W

(Ω_θ=0.5)

0.1	0.15	0.2	0.25	e_y/d
0.1	0.1	0.09	0.09	U1
0.74	0.42	0.31	0.35	U2
0.13	0.12	0.10	0.1	MaxEdge1
0.07	0.06	0.06	0.05	MaxEdge2
0.18	0.16	0.14	0.14	Edge1_rms
0.16	0.15	0.15	0.13	Edge2_rms
0.25	0.24	0.24	0.24	Base Shear
0.86	1.0	0.93	0.98	Torsion
0.32	0.32	0.38	0.36	Fc1/W
0.22	0.19	0.18	0.17	Fc2/W

Table 5. Performance of GA_FLC Strategy under Various Excitations (e_y/d =0.25)

Northridge	Kobe	Sanfernando	ElCentro	Ω_θ=1.5
0.06	0.11	0.05	0.05	U1
0.07	0.14	0.07	0.06	U2
0.07	0.1	0.06	0.05	MaxEdge1
0.04	0.09	0.03	0.04	MaxEdge2
0.07	0.1	0.06	0.06	Edge1_rms
0.07	0.1	0.07	0.06	Edge1_rms
0.17	0.1	0.3	0.16	Vb
0.18	0.21	0.42	0.23	Tm
0.45	0.4	0.27	0.38	Fc1/W
0.22	0.21	0.09	0.15	Fc2/W

Northridge	Kobe	Sanfernando	ElCentro	Ω_θ=0.5
0.51	0.71	0.56	0.53	U1
0.65	0.81	0.61	0.5	U2
0.49	0.73	0.56	0.61	MaxEdge1
0.56	0.55	0.57	0.58	MaxEdge2
0.64	0.81	0.61	0.51	Edge1_rms
0.65	0.81	0.61	0.5	Edge1_rms
0.59	0.53	0.83	0.64	Vb
0.92	1	0.87	0.56	Tm
0.22	0.21	0.12	0.18	Fc1/W
0.16	0.11	0.09	0.13	Fc2/W

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