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SEMI-ACTIVE CONTROL OF THE SEISMIC RESPONSE OF BUILDING FRAMES USING FUZZY CONTROL

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ABSTRACT

In this paper a fuzzy rule based semi-active control of building frames using semi-active hydraulic dampers (SHDs) is presented. The SHDs are installed between the top of a Chevron bracing and the upper beam on each storey to prevent damage to the structure from severe earthquakes. The set of Chevron brace and SHD is modeled as a Maxwell element that consists of a damping element in series with a spring. The rule extraction strategy for semi-active fuzzy control is done by genetic algorithms (GA). The objective is to minimize both the maximum inter-story drift and absolute acceleration responses of the structure. Interactive relationships between structural responses and damping coefficients of SHDs are established by using a fuzzy controller. GA is employed as an adaptive method to design the fuzzy controller, which is here known as a genetic fuzzy controller (GFC). To illustrate the efficiency of the proposed intelligent control strategy in application, numerical simulation for a 10-storey building frame equipped with multiple dampers is presented.

1. INTRODUCTION

The control of structure subjected to seismic excitation is a challenging task in the field of civil engineering. The traditional design approach was to mitigate earthquake and wind effects with sufficient strength capacity and the ability to have limited deformation (Symans and Constantinou 1997). In the last two decades, newer concepts of structural control, including both passive and active control systems, have been developed to enhance safety and reduce damage of structures during earthquakes. These alternative approaches aim to control the structural seismic response and increase energy dissipation in the structural members by modifying the dynamic properties of the system (Singh 2003). Semi-active control has received a lot of attention recently because it offers great adaptability without a large power requirement (Symans and Constantinou 1997).

Conventional control algorithms are based on mathematical model for the structure. Active control algorithms use complicated mathematical equations to mitigate structure responses. For such models, methods and procedures for the design of controllers, formal analysis and verification of control systems have been developed (Babuska 2004). Since buildings in civil engineering are getting much higher and bridges are getting much longer, finding an exact mathematical model to describe the behavior of these multi-degrees of freedom systems is very difficult (Choi 2004). Active and semi-active vibration control of structural systems using fuzzy

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logic control (FLC) theory has attracted the attention of researchers and engineers during the last few years. This is because of its inherent robustness, easiness to handle the uncertainties, nonlinearities and heuristic knowledge (Yan 2006).

A semi-active fuzzy control strategy for seismic response reduction using a magneto-rheological (MR) damper has been proposed by Choi et al (2004). A design strategy based on genetic algorithms (GA) to find the optimum voltage for MR dampers in establishing a fuzzy control of structures has already been presented by Yan and Zhou (2006).

A fuzzy sub-optimal bang-bang control method based on the fuzzy logic of the Takagi-Sugeno (T-S) model and the bang-bang control law has been presented by Li and Zhao (2006). Datta and Bhardwaj (2006) presented a simple fuzzy rule base control of the seismic response of building frames using multiple semi-active hydraulic dampers (SHDs). Their fuzzy controller for SHDs was designed for the bottom storey. Controllers placed at other storeys were assumed to provide control command in certain proportion to that obtained for the bottom most SHD.

In recent years, genetic algorithms have received considerable attention regarding their potential as a novel optimization technique. The reason is their simplicity, ease of operation, minimal requirements and parallel and global perspective (Sivanandam 2008).Kim and Ghaboussi (2001) used GA for design of an optimal FLC for wind excited vibration mitigation of a 76 story tall building.

Faruque and Ramaswamy (2009) developed an optimal fuzzy logic control algorithm to mitigate the vibration of buildings using magneto-rheological (MR) dampers. A micro-genetic algorithm (μ-GA) and a particle swarm optimization (PSO) are used to optimize the FLC parameters.

Here in this paper, a fuzzy rule based semi-active control of building frames using semi-active hydraulic dampers (SHDs) is presented. The SHDs are installed between the top of a Chevron bracing and the upper beam on each storey to protect building under severe earthquakes hazards. GA is used as an adaptive method to extract the most suitable rules which establish the fuzzy correlation between inputs (selected structural responses) and outputs (damping coefficients of SHDs).

2. CONTROL STRATEGY

Consider a shear building equipped with some semi-active hydraulic dampers (SHDs) installed at different locations under earthquake ground excitation. The proposed control strategy is to integrate fuzzy logic and GA, as illustrate in Fig. 1. Fuzzy logic is used to establish a correlation between a set of inputs and outputs and GA is used to optimize the set of FLC. For the fuzzy logic controller (FLC), inputs are selected structural responses from relative velocity, displacement and acceleration and outputs are damping coefficients of SHDs. These damping coefficients are used to generate required control forces to reduce the responses of the seismically excited structure. Fuzzy mapping between structural responses and damping coefficients of SHDs is always involved in a multi-input-multi-output (MIMO) fuzzy controller. Instead of using conventional optimal control approaches which are based on mathematical models, typically differential equations, here in this study GA is employed as an efficient approach to optimally design a fuzzy logic controller.

GA is used as an adaptive method to extract suitable rules which maps the antecedents (structural responses) to consequents (damping coefficients of SHDs) of the fuzzy controller. For simplicity, other characteristics of the fuzzy controller such as shape and parameters of membership functions (MFs) are predefined and fixed. To simultaneously minimize both the peak inter-story drift and absolute acceleration responses of the structure, a multi-objective optimization problem is constructed and GA is employed to solve it.

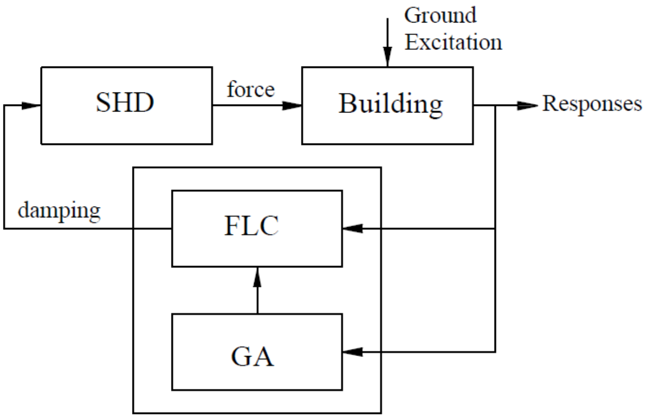


Figure 1.Integeratin of fuzzy logic and genetic algirithms for control strategy using SHD

3. FORMULATION OF THE PROBLEM

Consider an N-degree of freedom shear building model subjected to the ground excitation at the base with semi-active hydraulic dampers (SHDs) installed at different locations as shown in Fig. 2(a).

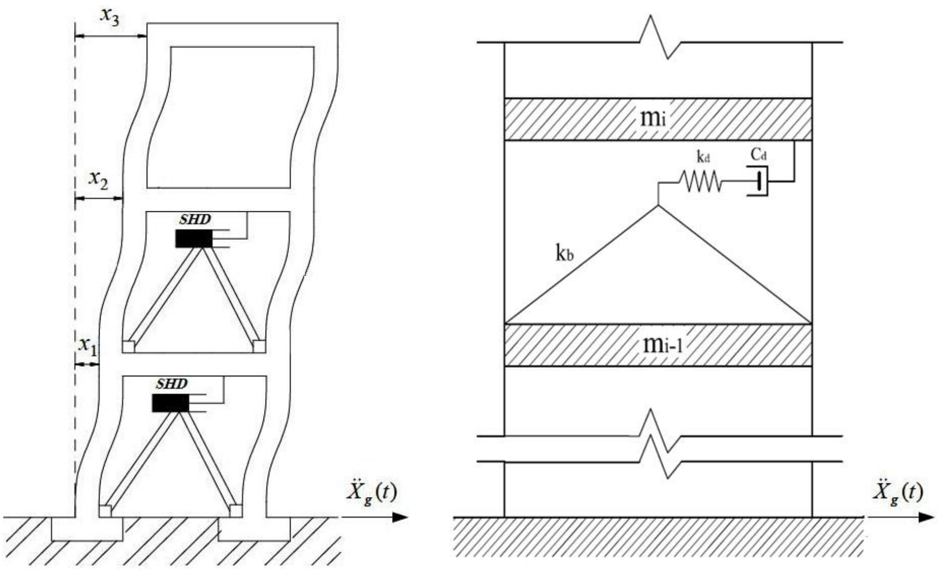


Figure 2 . (a) Building frame with dampers; (b) Maxwell damper on Chevron bracings

The equation of motion for this structure can be written as:

$$M_s\ddot{x}(t) + C_s\dot{x}(t) + K_s x(t) + \sum_{d=1}^{n_l} b_d P_d(t) = -M_s E\ddot{X}_g(t) \tag{1}$$

Where *Ms* , *Ks* , and *Cs* represent the *N*×*N* mass, structural stiffness, and inherent structural damping matrices, respectively; $\ddot{X}_g(t)$ represents the ground seismic excitation given at *l* intervals of time; *E* is *N*-dimensional ground motion influence vector ; x(t) is the *N*-dimensional relative displacement vector with respect to the base. A dot over a symbol indicates differentiation with respect to time. $P_d(t)$ represent the force in the SHD at the d^{th} location. The number and locations of semi-active devices is considered through the N-dimensional influence vector b_d. The structure is assumed to behave linear under earthquake induced ground excitation. As shown in Fig. 2, the SHDs are installed between the top of a Chevron bracing and the upper beam on each storey. The set of Chevron brace and SHD is modeled as a Maxwell element that consists of a damping element in series with a spring. The damping coefficient (C_d) in the model varies according to the commands that come from FLC. For the i^{th} floor, the equivalent stiffness of the Maxwell model (K_{ei}) can be obtained from the combination of K_{bi} and K_{di} , defined as:

$$K_{bi} = (k_{di}k_{bi})/(k_{di} + k_{bi}) \tag{2}$$

In which as shown in Fig. 2(b), K_d and K_b are stiffness of the damper and the stiffness of bracing, respectively. Fig. 3 shows Δ_1 and Δ_2 as the displacements of equivalent spring and damper respectively. Δ_d is the displacement of the total Maxwell element and it is the sum of Δ_1 and Δ_2.

$$\Delta_d = \Delta_1 + \Delta_2 \tag{3}$$

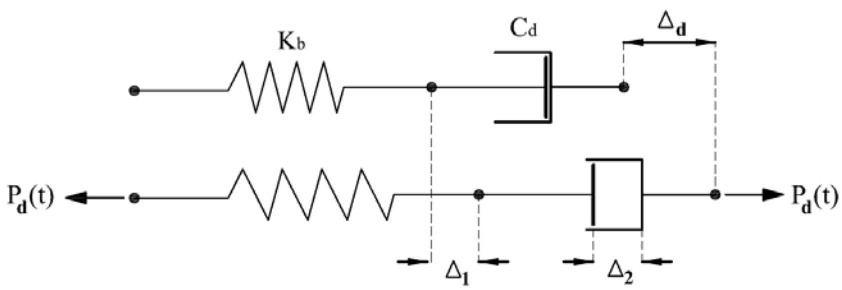


Figure 3. Maxwell model consist of the damper and spring in series

The force exerted by d^{th} damper is described by the following first-order differential equation:

$$\tau_d \dot{P}_d(t) + P_d(t) - C_d \dot{\Delta}_d(t) = 0 \qquad d = 1, \dots, n_l \tag{4}$$

Where $\tau_d = C_d/K_{ed}$, and $\dot{\Delta}_d$ is the relative velocity between the ends of the damper located in i^{th} floor. It can be related to the main structure by the following equation.

$$\dot{\Delta}_d = r_d^T \dot{x}(t) \tag{5}$$

Hatada et al.(1999) solved Eq. 4 in discrete time system with the assumption that $\dot{x}(t)$ varies linearly during each time increment Δt as follows:

$$\dot{x}_n(t) = \dot{x}_n + \frac{\dot{x}_{n+1} - \dot{x}_n}{\Delta t} t \tag{6}$$

They proved that the final solution of Eq. 4 can be expressed as follows in the discrete time intervals:

$$P_d^{n+1} = \alpha \dot{\Delta}_{n+1} + \beta \dot{\Delta}_n + \gamma P_d^n \tag{7}$$

Where:

$$\alpha = C_d\left[1+\frac{C_d}{K_b\Delta t}\left\{exp\left(-\frac{K_b\Delta t}{C_d}\right)-1\right\}\right]$$
$$\beta = -C_d\left[exp\left(-\frac{K_b\Delta t}{C_d}\right)+\frac{C_d}{K_b\Delta t}\left\{exp\left(-\frac{K_b\Delta t}{C_d}\right)-1\right\}\right]$$
$$\gamma = exp\left(-\frac{K_b\Delta t}{C_d}\right)$$

Now the equation of motion (1) can be written as:

$$M_s\ddot{x}(t)+C_s\dot{x}(t)+K_sx(t) = -M_sE\ddot{X}_g(t)-\sum_{d=1}^{n_l} b_dP_d(t) \tag{8}$$

The analysis of a linear structure equipped with SHDs described by a set of linear differential equations can be done by expressing the Eq. 8 in the following state space format:

$$\dot{z}(t) = Az(t)+Bu(t) \tag{9}$$

$$z(t) = \begin{bmatrix}\dot{x}(t)\\ x(t)\end{bmatrix} \qquad u(t) = -M_sE\ddot{X}_g(t)-\textstyle\sum_{d=1}^{n_l} b_dP_d(t)$$

$$A = \begin{bmatrix}-M_s^{-1}C_s & -M_s^{-1}K_s\\ I_{N\times N} & 0_{N\times N}\end{bmatrix} \qquad B = \begin{bmatrix}M_s^{-1}I_{N\times N}\\ 0_{N\times N}\end{bmatrix}$$

Where z(t) is the state vector and $u(t)$ is the input vector which is the combination of earthquake and damper forces applied to the structure.
The output vector, y(t) is shown together with C and D matrices:

$$y(t) = Cz(t)+Du(t) \tag{10}$$

$$y(t) = \begin{bmatrix}\ddot{x}(t)\\ \dot{x}(t)\\ x(t)\end{bmatrix} \qquad C = \begin{bmatrix}-M_s^{-1}C_s & -M_s^{-1}K_s\\ I_{N\times N} & 0_{N\times N}\\ 0_{N\times N} & I_{N\times N}\end{bmatrix} \qquad D = \begin{bmatrix}M_s^{-1}I_{N\times N}\\ 0_{N\times N}\\ 0_{N\times N}\end{bmatrix}$$

4. DESIGN OF GENETIC FUZZY CONTROLLER (GFC)

As mentioned previously, fuzzy logic control is employed to describe a complex mapping between a set of inputs and a set of outputs. Since acceleration can be measured through accelerometers at arbitrary locations of the structure, acceleration of specific floors are taken as inputs for the FLC structure. The main goal of using a GA is to determine appropriate fuzzy rules of the FLC system that optimizes the outputs of the fuzzy controller. Other characteristics of the fuzzy controller such as membership functions shapes and parameters are predefined and fixed. Here, the following steps are pursued to design a genetic fuzzy controller (GFC).

4.1. Encoding membership function

To begin with the design of the FLC, the number of linguistic terms and corresponding membership functions of the inputs and outputs should be determined. Here, five membership functions are assumed for each input which are: Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Large (PL). Similarly four membership functions are assumed for each output which are: Zero (Z), Small (S), Medium (M), and Large (L). The acceleration input variables are normalized with respect to maximum uncontrolled acceleration over the discourse of [-1, 1]. A normalized damping coefficient rang of [0, 1] is also obtained from FLC. Since any shape can be assumed for membership functions, here, as shown in Fig. 4, a general bell shaped membership functions is used for all membership functions of the input and output variables.

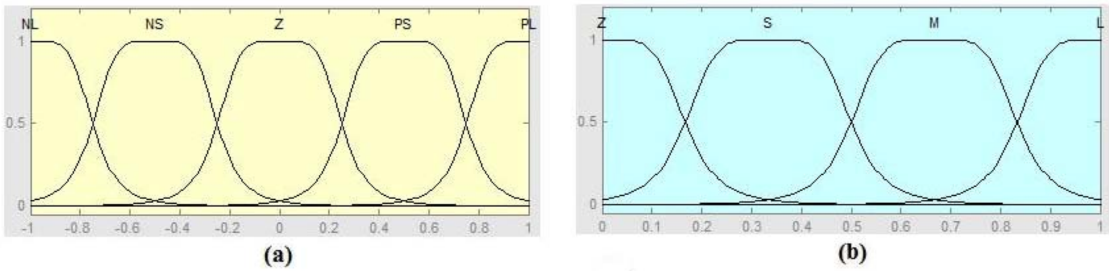


Figure 4.Input and output membership functions: (a) input membership function; and (b) output membership function

4.2. Encoding rules

The search process in GA works on a population of potential solutions to the problem. The individuals of the population are called chromosomes (Sivanandam 2008). In our case, each chromosome represents a complete potential solution, i.e. a set of fuzzy rules mapping fuzzy inputs to fuzzy outputs.

Consider a building frame that is controlled by k SHDs. The number of rules (R) required for the control of the structure can be calculated from the following equation:

$$R = m^I \tag{11}$$

Where I is the number of inputs and m is the number of membership functions defined for each input. The length of chromosome (l) for any individual in GA is then found from the following equation:

$$l = kR = km^I \tag{12}$$

4.3. Optimization of FLC using GA

As mentioned before, GA is employed as an adaptive method to optimally design the FLC system. In this study, GA has been used with the following specifications:

1) Since the objective of the control in this study is to minimize both peak inter-storey drift and absolute acceleration responses of the structure, a multi-objective fitness function is

defined here. It is assumed to consist of the weighted sum of the normalized maximum floor drift and normalized peak floor absolute accelerations as follows:

$$\varphi(t) = w \times max_{i,t}\left|\frac{d_i(t)}{d_{unc}}\right| + (1-w) \times max_{i,t}\left|\frac{\ddot{x}_i(t)}{\ddot{x}_{unc}}\right| \qquad (13)$$

Where $d_i(t)$ is the drift of the i^{th} floor and $\ddot{x}_i(t)$ is the absolute acceleration of the i^{th} floor at the time t. They are normalized by the uncontrolled maximum drift (d_{unc}) and the maximum uncontrolled floor absolute acceleration response($\ddot{x}_{unc}$), respectively.

2) The initial population is often generated by the GA. However because of GA's solution structure and procedure, a primary knowledge in the form of fuzzy rules can help produce a fairly good initial population which in turn results in faster convergence of the algorithm.

3) Tournament selection is used as an ideal selection strategy. The best individual from the tournament is the one with the highest fitness.

4) To produce children, single point crossover with probability of 0.8 is considered.

5) To prevent the GA from falling into local extremes, mutation probability of 0.01 is adopted.

5. NUMERICAL SIMULATION AND RESULTS

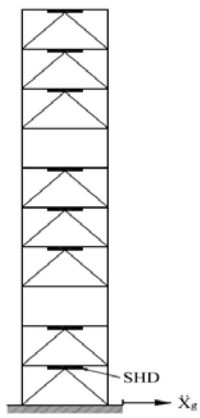
To demonstrate the effectiveness of the proposed semi-active control strategy, numerical simulations is carried out for a 10-storey building frames equipped with multiple dampers. The simulation is done by MATLAB 2008 and SIMULINK (MATLAB 2008).

10-storey building

To show the effectiveness of proposed control strategy in reducing seismic responses of tall buildings, a 10-stoery building frame equipped with 24 SHDs is considered in this section. There are three dampers in each story except in 3 and 7 stories. Table 1 illustrates the structural model and its properties for this example.

Table 1 .Structural properties of 10-storey building frame

Storey Mode	Mass $[kg \times 10^3]$	Stiffness $[N/m \times 10^7]$	Frequencies $[rad/\sec]$
1	100	9.26	3.97
2	100	8.57	10.52
3	100	7.88	17.05
4	100	7.20	23.17
5	100	6.51	28.74
6	100	5.83	33.65
7	100	5.14	38.17
8	100	4.45	42.80
9	100	3.77	47.90
10	100	3.08	54.00



Note: 2% modal damping ratio is assumed for all modes

To construct damping matrix (C), as defined in Eq. 14, we consider Rayleigh damping using 2% modal damping in all modes. The Rayleigh coefficients (a_0, a_1) are determined based on the first and second eigen frequencies (ω_1, ω_2) of the system (Chopra 2004).

$$C_s = a_0 M_s + a_1 K_s \tag{14}$$

$$a_0 = \xi \frac{2\omega_1\omega_2}{\omega_1 + \omega_2} \qquad a_1 = \xi \frac{2}{\omega_1 + \omega_2}$$

The ground excitation adopted in this study is North-South component of the 1940 El Centro. The maximum damping coefficient of Maxwell element in each floor is C_d=1000KN.s/m.
Based on the complex damping theory, the loss factor of the viscous damper–brace component, η_{vb}, is obtained from the following equation: (J.P. Ou 2007)

$$\eta_{vb} = \frac{K''_{vb}}{K'_{vb}} = \frac{K_b}{C_d\omega_0} \tag{15}$$

Where η_{vb} is an important parameter which reflects the damping characteristic of the Maxwell element; K'_{vb} represents additional stiffness when the Maxwell element is added to the structure; K''_{vb} is associated with the energy dissipation capacity of the Maxwell element. Thus K''_{vb}/K'_{vb} is generally expressed as: (J.P. Ou 2007)

$$\frac{K''_{vb}}{K''_{v}} = \frac{1}{1 + \frac{1}{\eta_{vb}^2}} \tag{16}$$

Where, $K''_v = C_d\omega_0$, is the damper loss modulus. It is found from the Eq. 16 that when η_{vb}= 10, K''_{vb}/K'_{vb} = 0.99, indicating that the viscous damper–brace component achieves 99% of the energy dissipation capacity of the viscous damper–brace component. Selecting η_{vb}= 10 to achieve the best energy dissipation capacity of the viscous damper–brace component, the stiffness of the brace to each floor is obtained $K_b = 39.65\times10^6$ N/m.
The damping coefficients of all 3 dampers in each storey are considered the same; therefore the problem has 8 outputs for the FLC system. The accelerations of the 7th, 9th and 10th floors are considered as inputs. Since there are three inputs for each rule, to optimally design the fuzzy controller in this MIMO (3-input 8-output) system, we need $R = 5^3 = 125$ rules. The length of chromosome of each individual member of GA is $l = 8 \times 5^3 = 1000$. The population size is taken 100 members, and the stopping criteria are set on 100 for the number of generations and 0.005 for the tolerance of the function.
The solution process that is finding the most suitable FLC Rule Base, took about 40 hours on a Pentium IV core 2Duo 2.93 GHz computer. However the time required for issuing an output (8 commands) to given inputs (3 floor accelerations) were less than 1.8 milliseconds.
Fig. 6 shows the reduction in the absolute acceleration, inter-story drift and displacement to the El Centro earthquake for different values of w in the multi-objective fitness function. It is concluded from this figure that when w=0.75, the proposed method has been able to considerably reduce the lateral sway of the frame while it has also decreased the absolute accelerations in floors. Thus 0.75 is adopted as a proper value for w and the results are discussed about.

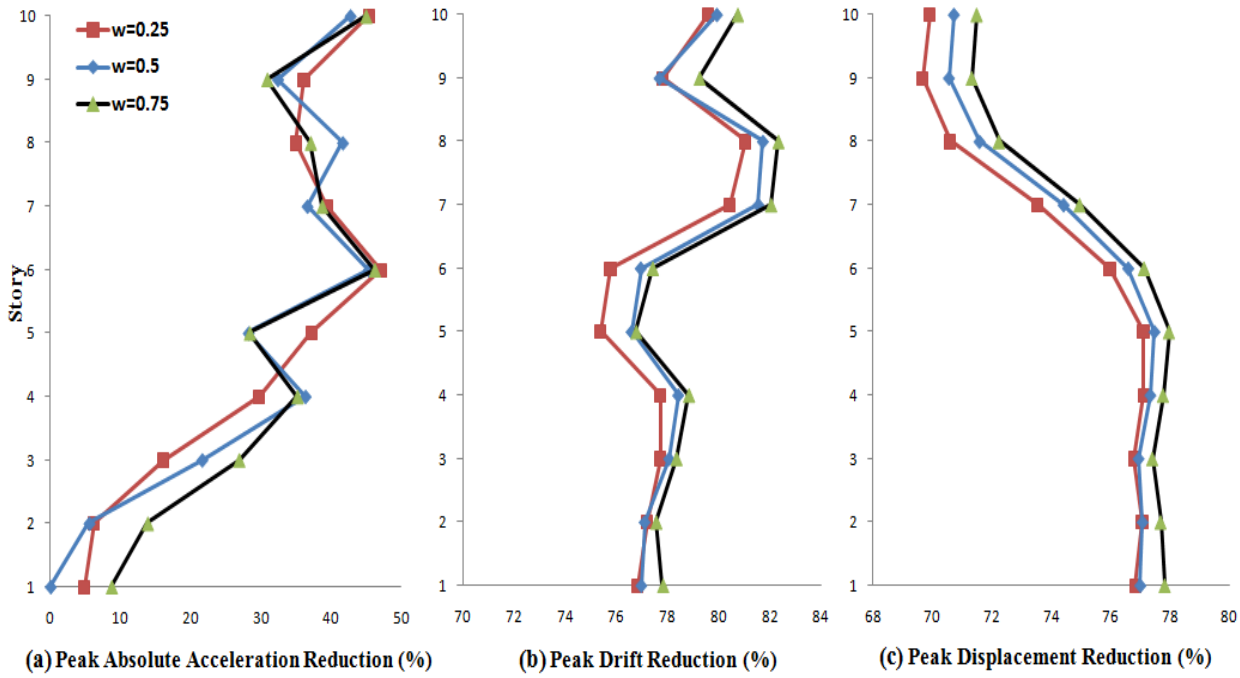


Figure 6.Peak responses reduction due to El Centro earthquake for different w
(a)Peak Absolute Acceleration ;(b)Peak Inter-storey Drift; (c)Peak Displacement

Fig. 7 shows the peak responses of each floor of the structure under the El Centro earthquake without control and with the GFC control strategy that is presented in Table 2 when w=0.75. In Fig. 8, the absolute acceleration, inter-story drift and relative displacement time histories of roof floor when controlled by the proposed control strategy (GFC) is compared to uncontrolled one.

Table 2 .Peak responses due to El Centro earthquake when w=0.75

Story	Drift (cm)		Displacement (cm)		Absolute Acceleration (cm/s^2)	
	Uncontrolled	Controlled	Uncontrolled	Controlled	Uncontrolled	Controlled
1	4.6965	1.0413	4.70	1.04	297.83	271.83
2	4.8109	1.0795	9.49	2.12	294.04	253.25
3	5.0991	1.1039	14.11	3.19	341.54	249.56
4	5.2130	1.1031	19.03	4.23	401.10	259.71
5	4.9227	1.1431	23.94	5.27	394.00	281.94
6	5.1338	1.1591	27.74	6.34	485.23	260.61
7	6.3578	1.1413	29.84	7.47	373.91	228.88
8	6.2179	1.0983	30.75	8.53	397.15	249.63
9	5.2438	1.0878	33.28	9.54	381.82	263.65
10	4.2033	0.8092	35.94	10.24	524.33	288.08

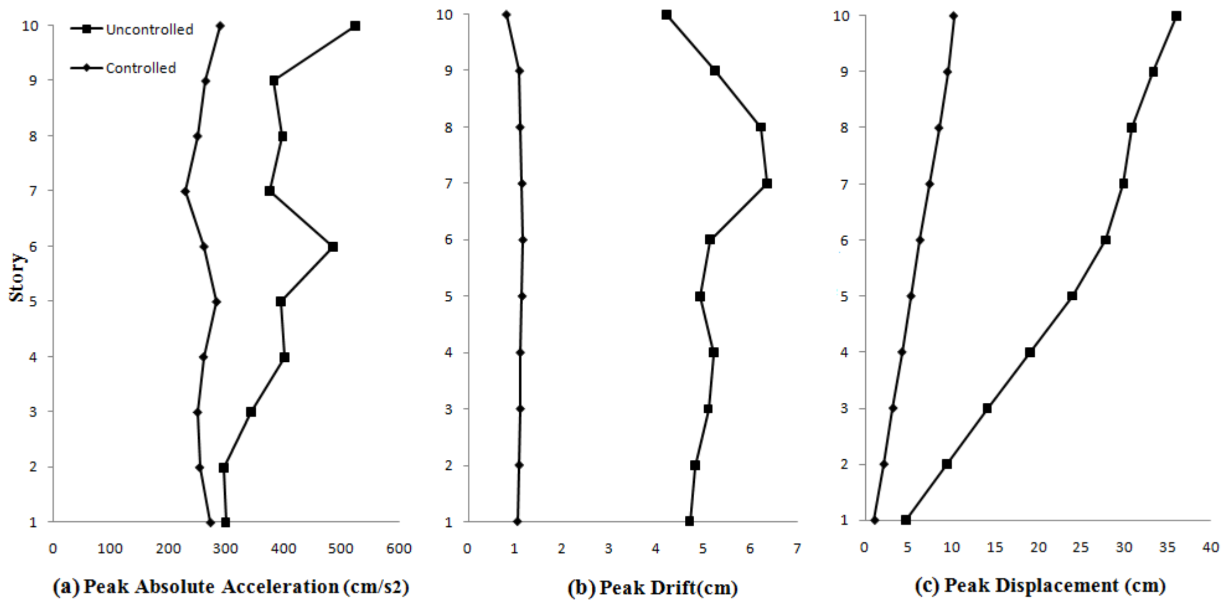


Figure 7.Peak responses due to El Centro earthquake without and with GFC when w=0.75
(a)Peak Absolute Acceleration ;(b)Peak Inter-storey Drift; (c)Peak Displacement

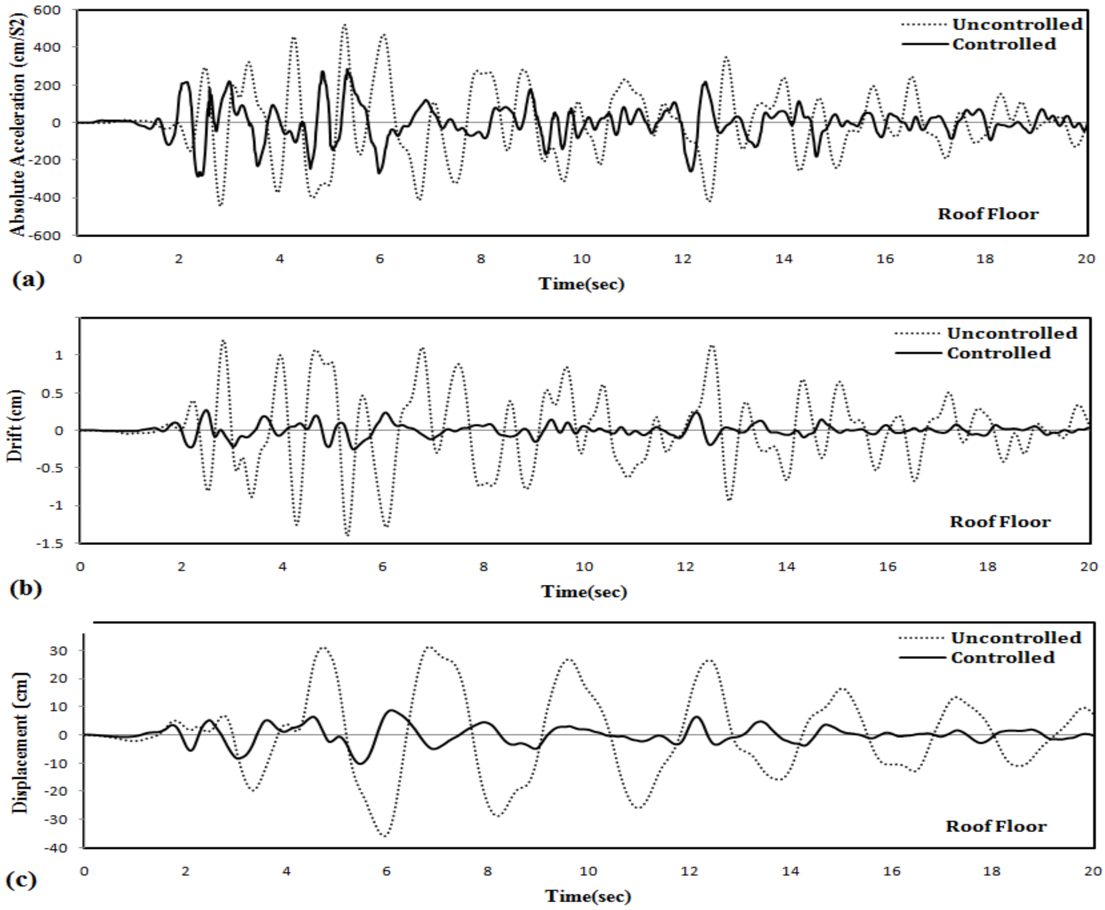


Figure 8.Roof floor responses time histories without and with GFC when w=0.75
(a) Inter-storey Drift ;(b) Displacement;(c) Absolute Acceleration

6. CONCLUSIONS

In this paper a fuzzy rule based control strategy for building frames equipped with SHDs was presented. The SHDs are installed between the top of Chevron bracings and the upper beams on each storey. The Maxwell model was adopted for the set of chevron bracing and SHD dampers and the corresponding formulation was presented. GA was used as an adaptive method to optimally design the fuzzy controller, which is here known as a genetic fuzzy controller (GFC). To simultaneously reduce the peak inter-storey drift and absolute acceleration, a multi objective fitness function was introduced for the GA. It was shown that the integration of fuzzy logic and GA algorithm is a highly adaptive and efficient control strategy. Although the establishment of FLC may take some time for any given frame, the response of this fuzzy controller to any input is very fast (a few milliseconds) such that it can be easily used in online control of any structure.

A 10-storey shear building example was presented to illustrate the capabilities of the GFC system in mitigating the responses of the building frames simultaneously. It was shown that the proposed algorithm is capable to reduce the inter-storey drift up to 80% and absolute acceleration up to 50%.

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