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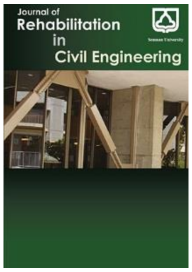

The Effect of Intelligent Semi-Active Thermal Exchange- Fuzzy Inference System in Structural Seismic Rehabilitation

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ABSTRACT

The effect of intelligent semi-active thermal exchange-fuzzy controller in structural rehabilitation by attenuating seismic responses of structural systems is investigated. In the suggested structural controller, MR dampers and their sensors are employed as a semi-active controller. Resultant control forces of MR damper are administrated by providing external voltage supply during the earthquakes and high intensity winds. Moreover, a novel evolutionary algorithm of thermal exchange (TE) is applied to compute the optimal location and the quantity of Magnetorheological (MR) dampers and their sensors with regard to minimizing resultant vibration magnitude. An optimal semi-active Thermal Exchange-Fuzzy Controller (TE-FC) has been suggested to administrate MR damper ingeniously. Results of numerical simulations illustrate the efficiency of suggested control system. The TE-FC can determine the optimal control arrangement and forces during a reasonable number of iterations. In comparison of the performance of various control strategies, the TE-FC demonstrates that economical cost and rehabilitation properties of the building could be optimized simultaneously. The TE-FC managed the optimal control forces online during strong ground motion, to attenuate the excessive responses in several rehabilitated buildings. Consequently, the TE-FC could improve the reliability of rehabilitated structure in comparison with passive and offline controllers. The significant efficiency of optimal arrangement of dampers and sensors over uniformly distribution of damper and sensors is presented as well.

1. Introduction

Intensive unforeseeable natural events including hurricanes and vigorous seismic excitations could cause undesirable damages, during the tall buildings lifetime. To ameliorate reliability and safety of structural systems, the rehabilitation of buildings is pursued. One of the best rehabilitation method is applying active structural control

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[1, 2]. For this objective, structural controllers are one of the novel solutions, which could be expressed as passive, active, semi-active, and hybrid control systems [3, 4]. However, active structural controller has been manufactured and utilized in full-scale structures, but it requires to develop in solving the reliability and robustness obstacles. Although passive control devices demonstrate suitable outcome in attenuating the undesired vibration magnitudes, but the deficiency of adaptability with online conditions of structural system is one of the main obstacles in robustness and reliability in passive controllers[5]. On the other hand, the idea came up that resistance effort could be inserted by applying smart materials in semi-active dampers. A semi-active damper is a controller device that cannot incorporate external energy into the structural building [6]. Magnetorheological (MR) damper was a novel semi-active device that has a great impact to enhance the seismic vibration controllers. The MR dampers have the reliability of passive control devices beside of preserving the versatility and adaptability of active control devices[7, 8].

The first development of MR fluids and devices was accomplished in the late 1940s by Jacob Rabinow at the US National Bureau of Standards[9, 10]. Lately, several large capacity MR dampers have been introduced and examined [11, 12]. The Bouc–Wen hysteresis model has been lately utilized in order to demonstrate the MR-dampers dynamic behavior [13] Furthermore, in place results of numerous full-scale structures indicate the attenuation of structural responses which equipped with supplemental semi-active damping devices[14]. The application of semi-active MR devices in structural system is more developing. Therefore, a huge requirement does exist to apply the optimal design scheme to increase the efficiency of structural semi-active controllers. In rehabilitation of buildings, optimal distribution of dampers and their sensors should be accomplished to achieve higher control efficiency. Moreover, it is vital to minimize the manufacturing set up and maintenance costs of the semi-active devices[15]. As a result to the importance of cost and performance optimization in control systems, several researches has been accomplished to compute the optimal distribution of dampers[16]. None of these studies has investigated to optimize the distribution of MR damper and their sensors as two separate issues.

In recent engineering problems, based on complex computational burden, the utilizing of meta-heuristic algorithm is wide spreading. Thermal exchange (TE) is a novel optimization strategy, which was introduced by relying on Newton's rule of cooling states. The thermal exchange rate of a solid body was related to the difference in temperatures between the solid body and its surrounding objects[17]. The following paragraph is the Newton's rule of heat cooling in his own textbook:

"The iron was laid not in a calm air but in a wind that blew uniformly upon it, that the air heated by the iron might been always carried off by the wind and the cold air succeed it alternately; for thus equal parts of air were heated in equal times, and received a degree of heat proportional to the heat of the iron", as illustrated in Figure 1, in references[18].

In recent years, fuzzy control [19] is extensively applying in problems of civil engineering. The capability of Fuzzy controller (FC) has been taken into consideration in recent studies [20-22]. For structural systems with definitely known specification, instantaneous optimal control and classical optimal control have been proposed[23]. Further researches demonstrates that these controllers require some definitive previous knowledge or precise information about the specification of a structural system. To solve these problems, Linear Quadratic Gaussian (LQG) optimal control was proposed which requires a heavily constrained computational burden[24]. Many studies have been concentrated on soft-computing techniques, such as fuzzy controllers and neural networks[25] to eliminate these difficulties. Based on efficient performance, the application of fuzzy inference system in civil engineering problems are expanding[26-28]. Recent researches represented that smart adjustable structural controllers were more robust and efficient[29].

The main innovation of this research is representing a semi-active adjustable optimal controller for benchmark buildings under sever seismic excitation, based on the fuzzy controller (FC) and thermal exchange (TE). To improve the efficiency of controller, geometric and material linearity are both utilized in numerical simulations. The FC is applied to enhance the MR damper proficiency and to consume less energy during seismic strong motion. The fuzzy inference system administrates the MR damper specifications online by providing electrical inducing current.

In previous studies, input data were contemplated the relative displacement and velocity of damper's piston. Moreover, to increase efficiency of controller, separate sensors are applied separately to send the absolute velocity and displacement of structural system. Based on author's researched, there was no published study on semi-active structural controller by utilizing independently sensor installation to administrate the output damper forces. based on to the displacement and velocity of the floor, FC governs the magnetic field inducing electrical current. The inducing electrical current is transmitted to each semi-active devices. The suggested TE-FC represents its proficiency by utilizing less computational burden.

This point comes from the use of thermal exchange to optimally determine the distribution and the number of dampers and sensors, at the same time. In order to express the efficiency of the suggested TE-FC, the uniform dampers and sensors distribution is also applied in eight-story rehabilitated building. The simulation results demonstrate that TE-FC is superior in comparison with clipped optimal control or fuzzy uniformly distributed control in structural seismic rehabilitation.

2. Problem Statement and Formulation

During modelling of structural controllers, the main issue is which control scheme should be computed. If control scheme is complex and time-consuming, the precision and reliability of structural controller is mitigated based on the time delay issues. To examine the proposed controller three shear buildings were subjected to several strong seismic motions. Furthermore, the control system should be enhanced to optimally determine the peak force of dampers to reasonable magnitudes. For this purpose, a combinational optimization problem containing three objective functions to be minimized. These functions related to the responses of the building. A search-space is the location of dampers and their sensors. The magnitude of applied MR dampers and sensors were constraints for optimal distribution problem. In structural control engineering, calculation simplicity is mandatory to eliminate time-delay. To avoid solving a second-order differential equations of motion during seismic motion, state-space equation was used. A state space equation is a model of a physical control structural system as a set of input, output and state variables for first-order differential formulations. "State space" refers to the Euclidean space. The state of the system can be defined as vectors within control space. The most general state-space formulation of a n-story structure is expressed as following:

$$\begin{aligned}\dot{Z}(t) &= A.Z(t) + B.u(t)\\ y(t) &= C.Z(t) + D.u(t)\end{aligned} \qquad (1)$$

In these equations, parameters can be described as follows:

$$A = \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -M_S^{-1}.K_S & -M_S^{-1}.C_d \end{bmatrix}$$

$$B = \begin{bmatrix} 0_{n\times n} & 0_{n\times n} \\ -I_{n\times n} & -M_S^{-1}.D_p \end{bmatrix}$$

$$C = \begin{bmatrix} I_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & I_{n\times n} \\ -M_S^{-1}.K_S & -M_S^{-1}.C_d \end{bmatrix}$$

$$D = \begin{bmatrix} 0_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & 0_{n\times n} \\ -I_{n\times n} & -M_S^{-1}.D_p \end{bmatrix}$$

$$u(t) = \begin{bmatrix} \ddot{X}_{g\,n\times1} \\ F(t)_{n\times1} \end{bmatrix} \qquad Z(t) = \begin{bmatrix} X_{n\times1} \\ \dot{X}_{n\times1} \end{bmatrix}$$

Where:

$$y(t) = \begin{bmatrix} X_{n\times1} \\ \dot{X}_{n\times1} \\ \ddot{X}_{n\times1} \end{bmatrix} \qquad (2)$$

In the above equations, $\ddot{x}$, $\dot{x}$ and x are acceleration, velocity and displacement of stories in structural syste,, respectively. F(t) is expressing the output force of dampers and u(t) is output vector of the formulated state space. Cd , MS and KS expressed the damping, mass and stiffness matrices of the structural system, respectively. Dp exhibits the distribution of damper in location matrices. Y(t) and Z(t) were the state-space and output-vector, respectively. In the proposed controller, the output force of damper is designed as a function of velocity and displacement of the structural system in closed-loop control. The TE_FC manages the force of installed MR dampers. The main objective is proposing a structural controller to specify the optimal number and distribution of MR dampers and their sensors. These sensors are indepandant from state sensors of central computer control.

3. The Mechanical Specification of MR Damper and Fuzzy Inference System

Magneto-rheological liquid is a type of manageable hydraulic fluids that can react to a magnetic field with a rapid transition in its rheological behavior in pistons. The unique novelty of MR fluid was its capability to reversibly transmission to free-flowing, linear viscous liquid from semi solid fluids. These characteristics can grant a manageable strength in milliseconds while exposing to a magnetic field. MR hydraulic damper demonstrates reliability, robustness, high dynamic-range and large-force capacity, simultaneously. Several 200-kN MR-dampers have been examined and applied since 1998 [30].

Lately generated models are capable to simulate the response of MR damper over a wide-range of loading situations and electrical commanding currents.

In present research, to optimize the cost efficiency only finite number of 200-kN dampers were used. These dampers were utilized as adaptive semi-active actuators. The mechanical model of Spencer et al. [10]is utilized for MR-damper. This model was utilized to construct the output force of the MR-damper, in each time intervals. The formulation of the proposed as below:

$$
\begin{aligned}
&f = C_1.\dot{y} + K_1.(x - x_0) \\
&\dot{y} = \frac{1}{C_0 + C_1}\left[\alpha.Z + C_0.\dot{x} + K_0(x - y)\right] \\
&\dot{Z} = -\gamma\left|\dot{x} - \dot{y}\right|Z\left|Z\right|^{n-1} - \beta.(\dot{x} - \dot{y})\left|Z\right|^{n} + A.(\dot{x} - \dot{y})
\end{aligned}
\tag{3}
$$

Where:

$$\alpha(\mathrm{i}) = 16566.\mathrm{i}^3 - 87071.\mathrm{i}^2 + 168326.\mathrm{i} + 15114$$

$$\mathrm{C}_0(\mathrm{i}) = 437097.\mathrm{i}^3 - 1545407.\mathrm{i}^2 + 1641376.\mathrm{i} + 457741$$

$$\mathrm{C}_1(\mathrm{i}) = -9363108.\mathrm{i}^3 + 5334183.\mathrm{i}^2 + 48788640.\mathrm{i} - 2791630$$

In the above equations, the internal displacement the displacement of MR-damper in the piston direction are expresses by y and x, respectively. ‘I’ is the inducing electrical current, in each time window. α(i), C0(i) and C1(i) parameters of MR-damper are empirically examined and computed by Yang[31]. During seismic excitation, the additional parameters are applied to verify the empirically data. xo, k1, ko, A, γ, β and n assumed to be 0.18 meter, 617.31 N/m, 37810 N/m, 2679 m-1, 647.46 m-1 and =10, respectively. Researches demonstrate that the time-delay closed-loop responses and MR damper together is less than 10 milliseconds[32]. Therefore, the effect of time-delay could be relinquished because time-delay was away from the first period of benchmark structures which is discussed in this research. The governing rules will be inspected in the section 4. The schematic configuration and flowchart of MR-damper were given in Figure.1.

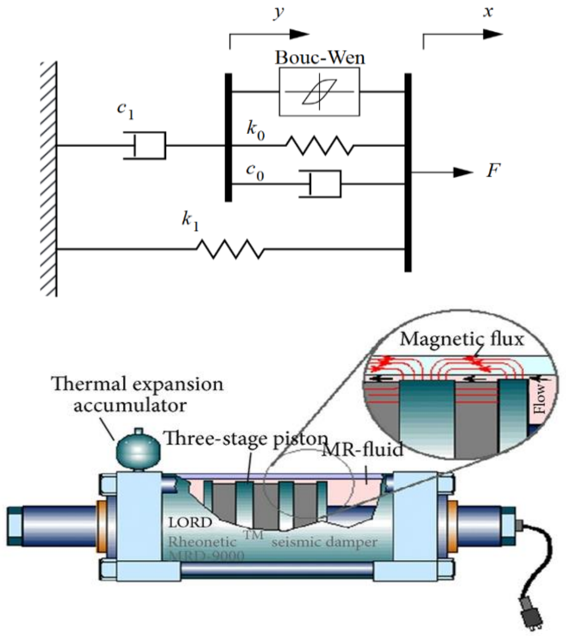


Fig.1. The schematic configuration and flowchart of MR-damper[33]

To enhance the reliability in rehabilitation process, the frequency and magnitude of the seismic excitation beside to uncertainties and nonlinearities in main structural characteristics. The next generation structural controller should tolerate the uncertainties and modeling imprecisions without necessitating any complex analysis requirements. Therefore, the FC (Fuzzy control) was applied to overcome these shortcomings. FC basically contains four ingredients to reproduce the logistic argumentation of human beings by using defuzzification interface, decision making, rule base and fuzzification interface. An intelligent FC has been introduced to tolerate the uncertainties and imprecisions which were not contemplated in the design rehabilitation procedure. A Fuzzy Inference System could be combined into a closed-loop structural controller as same as classical feedback structural controllers. Furthermore, each damper is considered to have an independent sensor to increase the efficiency of control system.

Table 1. The inference of fuzzy rules

		Velocity of story		
		N-V	Z-V	P-V
Displacement of story	N-D	L	S	Z
	Z-D	S	Z	S
	P-D	Z	S	L

The proposed Mamdani FIS (Fuzzy Inference System) had not output and two inputs. The FIS input parameters were the velocity and displacement of the sensors, and the output is inducing electrical current that administrates the MR-damper output forces. The input and output variables range for membership equations is determined to be [-1, 1] and [0,1], respectively. The fuzzy rule-bases applies a great inducing current to reproduce a significant damper force, if displacement and velocity of the damper's piston were in the same directions. Also no significant control force required if they are not in same directions. To produce reliable control force, gaussian curve membership functions were used. The transmitted signal from sensors convert into logical FC values by using the fuzzification process. The quantification and scale factors of FC were very vital to decide the output force of structural controller. By applying trial and error to carry out the reasonable structural responses, the determination of the fuzzyfication and de-fuzzyfication are selected. Figure.2, Figure.3 and Table.1 were exhibited the input and output variables, fuzzy Inference and the details of inference regulations for MR damper model, respectively. Furthermore, nine logical values are expressed in Table.1, output variables can be described as: N-D (Negative-Displacement), Z-D (Zero-Displacement), P-D (Positive-Displacement), N-V (Negative-Velocity), Z-V (Zero-Velocity) and P-V (Positive-Velocity). The input variables can be expressed by: Z (Zero), S (Small) and L (Large).

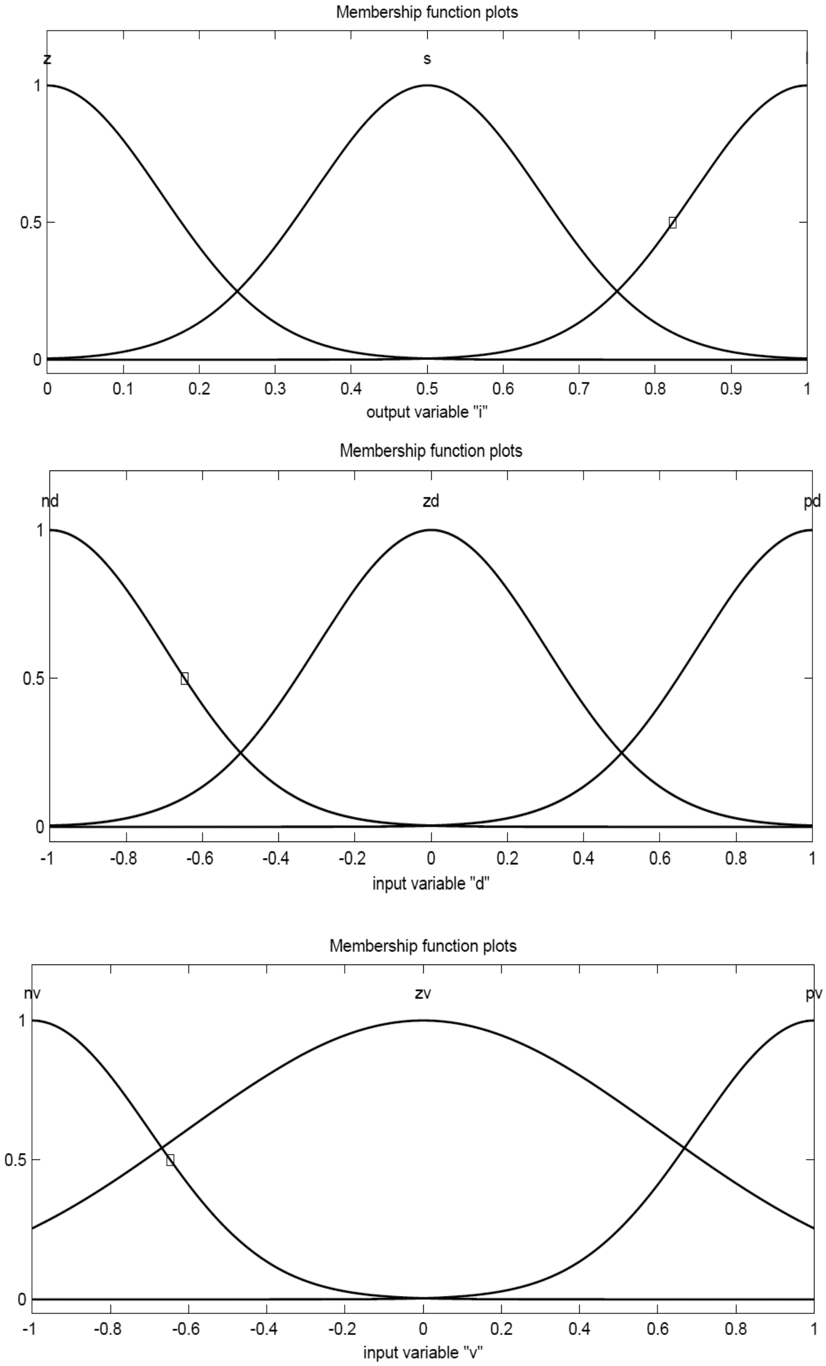


Fig. 2. The Membership figures for output (inducing current) and input (displacement and velocity) parameters of FC

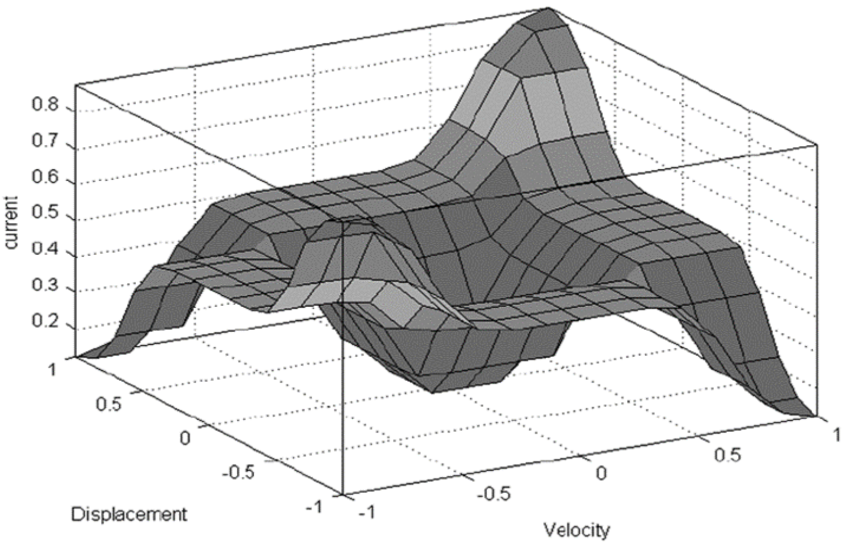


Fig.3. Proposed Fuzzy Inference System

4. Thermal Exchange Algorithm (TE)

Kaveh and Dadras developed a novel optimization algorithm, which was named thermal exchange (TE) algorithm. The modern simplified parameter to transient heat-cooling was proposed in recent researches[17, 18]. TE assumes the general coefficient of heat exchange to be h. Other physical properties can be assumed to be constant. The object begins from time of $t = 0$ with high temperature ($T0$). After that, it is quickly moved into another environment where it was refrigerated by utilizing heat exchange with surrounding area at a temperature (Tb). The surface area and volume of the solid are expressed with V and A, respectively. The heat-loss rate from the surrounding surface is expressed as follows:

$$dQ/dt = h.(Ta - Tb).A$$

$$V.\rho.c.dT = -h.A.(Ta - Tb).dt \quad (6)$$

$$T = Tb + (T0 - Tb).\exp(-\beta t)$$

Where A, T ,h and t are expressing the area for heat-flow in m2, temperature in K, the coefficient of heat-transfer in W, m−2K−1 and time in s, respectively. The heat-loss in time can be computed with $h(Ta-Tb).A.dt$ and this expresses the stored-heat exchange as the temperature modifies dT. Where V, ρ and c are demonstrated the volume in m3, density in kg.m−3 and specific heat-coefficient in J.kg−1.K−1, respectively. In an m-dimensional search-space, the temperature of objects at the beginning was determined by the following equation:

$$T0i = Tmin + random.(Tmax - Tmin) \quad (7)$$

Where T0i was solution vector of the i-th object at the first time. Also Tmin ,Tmax, n and random are demonstrated the bounds of design variables, the number of objects and a random vector which each components were in [0,1] , respectively. The fitness function computes the quantity of cost value of every solution. A memory has been applied to save historical-best solution T vectors and their related fitness function details. It could enhance the efficiency of the algorithm with less computational burden. For this reason, a Thermal Memory (TM) is utilized to remember a number of the best solutions so far. On that account, the solution vectors remembered in TM were combined to the population, and the same numbers of worst solutions were eliminated. At the end, solutions are listed based on their related fitness function. The flowchart of TE can be presented in Figure 4 and the steps involved are expressed. Solutions were detached equally into two groups. For instance, T1 was an environment solution for Tn/2+1 cooling solution and vice versa, when a solution had lower β-value, it transmits the temperature slowly. The β-value for each solution was calculated based on Eq. (8).

$$\beta = \frac{\text{Cost (object)}}{\text{Cost (worst object)}} \tag{8}$$

Time is a parameter is related to the iteration quantity. The quantity of t for each solution is expressed as follows:

$$\mathrm{t} = \frac{\text{Iteration}}{\text{Max Iteration}} \tag{9}$$

Meta-heuristic algorithms should be applied to escape from traps capability. It happens while solution gathers around to a local optimum location. Steps 7 and 9 were applied to escape from the local optimal solution or traps.

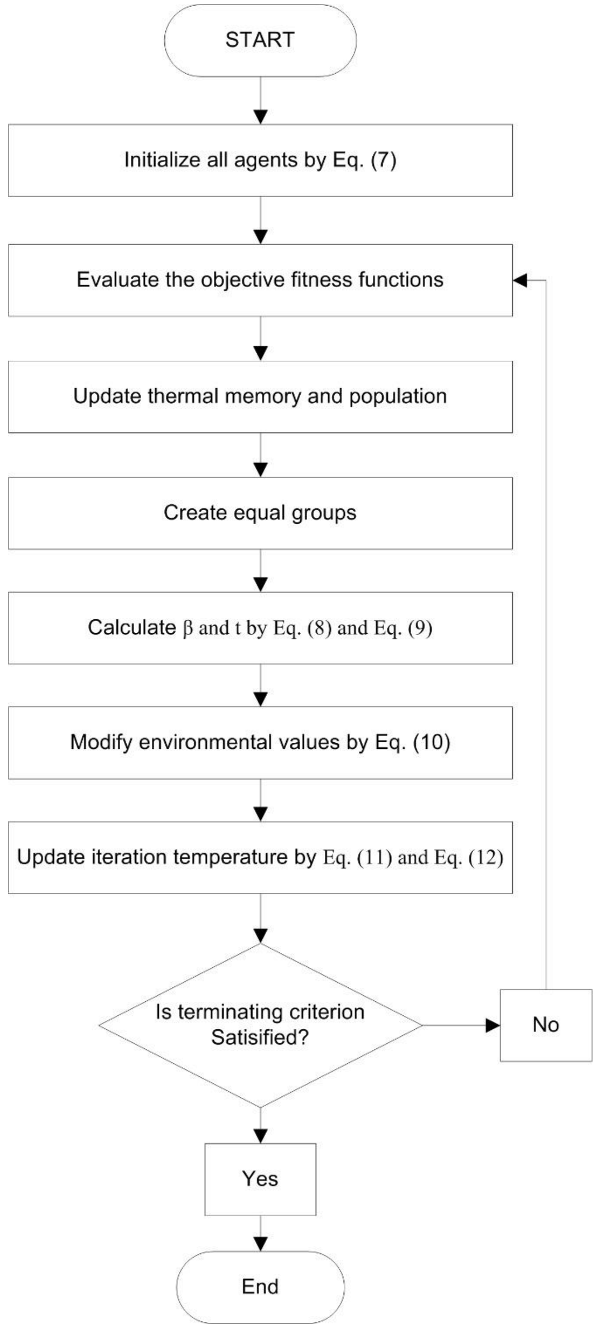


Fig.4. The structure of TE algorithm

The environmental temperature was expressed by Equation.10, where c1 and c2 parameters were the controlling items:

$$\mathrm{T_i^{env.}} = (1 - (\mathrm{c_1} + \mathrm{c_2} \times (1 - \mathrm{t})) \times \text{random.}) \times \mathrm{T_i^{`env.}} \tag{10}$$

Where c1 and c2 are the controlling variables. $\mathrm{T_i^{`env.}}$ was the temperature of the object in previous step, which is corrected to $T_i^{env.}$. $(1-t)$ parameter was applied to mitigate the stochasticity by closing to the previous iterations. By closing to the end of the procedure, t raises which leading to a linear decrease stochasticity and expanding exploitation. c2 and c1 administrate $(1-t)$ and size of the random intervals. In this research, c1 and c2 are chosen from [0,1]. New temperature of each solution can be updated by:

$$T_i^{new} = T_i^{env} + \left(T_i^{old} - T_i^{env}\right) \times e^{-\beta t} \tag{11}$$

One dimension of the i-th representative is selected randomly and its value is regenerated by the following equation:

$$T_{i,j} = T_{j,min} + \text{random}.\left(T_{j,max} - T_{j,min}\right) \tag{12}$$

Where $T_{i,j}$ is the j-th parameter of the i-th representative. $T_{j,min}$ and $T_{j,max}$ were the lower and upper margins of the j-th parameter, respectively. To maintain the formation of the representatives, only one dimension is adapted. This procedure prepares chances for the representatives to discover over the search-space to acquire better diversity. The optimization procedure will be ended after a finite number of iterations. While the criterion was not achieved, it goes to step-2 for a next round of iteration, in other respects the process will be suspended and the best-solution will be presented. The maximum number of sensor and damper placement is determined as the algorithm's stopping criterion. The terminating criterion is determined as a maximum iteration number, which is assumed to be 50 in this research. At the end, the population size of solutions is specified to be N=50. These values were selected based on trial and error to acquire required accuracy and most suitable convergence speed of TE. The objective function for each time-window is expressed as follows:

$$J_1 = \frac{\sum^n RMS(x_{FLC})}{\sum^n RMS(x_{Poff})} \qquad J_2 = \frac{\sum^n RMS(d_{FLC})}{\sum^n RMS(d_{Poff})}$$

$$J_3 = \frac{\sum^n RMS(\ddot{x}_{FLC})}{\sum^n RMS(\ddot{x}_{Poff})} \tag{13}$$

The POFF superscript describes the case where the MR-dampers were manipulated in the passive-off mode and no command voltage was transmitted to the MR dampers. Where x was the displacement matrix of stories, d is the inter-story drift matrix, $\ddot{x}$ was the absolute acceleration of the floor matrix and RMS exhibits the root mean square of parameters.

5. Numerical Modeling and Simulation Results

The components of Numerical modeling and simulation results include the benchmark building characteristics, MR devices and their sensors, structural controller and the ground seismic excitation. The State-space formulation is applied to simulate the dynamic behavior of structure in SIMULINK library and Fuzzy Toolbox of MATLAB [34].

5.1. The Thermal Exchange Fuzzy Controller (TE-FC)

To represent the proficiency of the suggested fuzzy controller, the state space model of benchmark buildings was assigned and the Bouc-Wen model of MR-damper is applied. While seismic excitation, the structural responses were compared with the responses of passive-off and passive-on controllers.

Three objective functions are defined by equation.13. The working margin of applied voltage of each MR damper is assumed to be [0,1] V. A three-story benchmark-building is selected to illustrate the proficiency of TE_FC. The building specification is demonstrated in Table.2.

Table 2. The 3-story rehabilitated building mechanical properties

The mass of stories	5x105 Kgf
The stiffness of stories	2x104 kN/m
Overall damping coefficient (%)	1

A seismic near-fault with forward-directivity was chosen. The dynamic simulation with El-Centro time-history -was accomplished by MATLAB. Considering three objective functions, the TE_FC specify that one MR damper and sensor is required to be installed in the third story for seismic rehabilitation. The TE-FC administrates the output-force of MR- by providing electrical inducing current. The simulation results for each case of structural controllers are illustrated in Table.3. The rehabilitation demonstrates major reductions based on J1 and J2 indexes. These indexes are related to the RMS (Root-Mean-Square) of the displacement, inter-story drifts and absolute acceleration of stories. Results of J3 index are less favorable, because the importance of peak absolute acceleration contemplated to be less than displacement and velocity of stories. The performance of TE-FC is satisfactory and superior to passive-on with respect to all cases except J3. After seismic rehabilitation, the FC has been decreased the acceleration of first story as same as the PON. Based on several studies based on damage indexes, the priority factor of the reduction of structural responses during rehabilitation for acceleration, inter-story drift and displacement of stories is assumed to be 0.8, 2 and 1, respectively.

Table 3. Numerical-evaluation results for the 3-story rehabilitated building

	Peak Displacement (m)			Peak Drift (m)			Peak Acceleration (m/s2)		
Floor	1	2	3	1	2	3	1	2	3
POFF	0.0671	0.1212	0.1512	0.0671	0.0551	0.0321	7.3471	10.0292	12.8381
FC	0.0221	0.0381	0.0421	0.0222	0.0172	0.0142	5.0882	7.3432	7.6342
Objective Function		J1			J2			J3	
		29.6%			34.1%			65.8%	
PON	0.0241	0.0391	0.0471	0.0272	0.0181	0.0162	4.9831	7.4532	7.9251
Fitness values		J1			J2			J3	
		31.8%			38.8%			67.0%	

Based on author's knowledge, there are no published researches on optimal rehabilitation of low-rise or high-rise buildings with semi-active dampers by applying separate sensor distribution to administrate the control forces more efficiently. Fuzzy interference system was used in each floor, which the sensor was installed. Based on displacement and velocity of the floor, fuzzy system calculates the inducing electrical current, which should be sent to create magnetic field around each damper. TE agents is assumed the number and location of the dampers and their sensors, independently. The objective values of the population gradually improve with respect to J1, J2 and J3 indexes. To improve the probability of determining the global best solution in heuristic optimization, five independent TE algorithms were began simultaneously to avoid trapping in local best solution. Global best parameters were shared in each 50 iterations between five independent TE algorithms. To represent the efficiency of the TE-FC, a previously studied example was utilized. Two different cases are presented, in which the MR damper is utilized in a passive mode to inspect the behaviors of rehabilitated building in semi-active and passive cases. 'POFF' expresses the case which no electrical inducing current was transmitted to MR damper. 'PON' case is the case which maximum inducing current (3.0 Ampere) was sent to the MR damper. Furthermore, to investigate more precisely the obtained results were compared with clipped-optimal controller. Simulation results demonstrate the proficiency of TE-FC in Table 4.

Table 4. Peak responses of 3-story rehabilitated building [35] subjected to Elcentro earthquake

Structural Responses	Uncontrolled	Controlled			
		POFF	PON	Clipped Optimal structural controller	TE-FC
1st story displacement (cm)	0.34	0.16	0.11	0.12	0.11
3rd story displacement (cm)	0.76	0.43	0.35	0.41	0.38
Output Force of damper (KN)	0	2.97	4.26	4.17	3.98

Results represent that suggested TE-FC can achieve to a satisfactory level of performance in structural rehabilitation. The maximum displacement of top story in POFF, PON and clipped-optimal controller are attenuated to 43%, 54% and 46% of the uncontrolled responses. Simulation results demonstrate that TE-FC can attenuate the undesirable up to 53% as same as PON controller without consuming major electrical current and energy. Additionally, the maximum required control-force represents the efficiency of a structural controller. The passive mode may not be the most appropriated controller because it consumes the largest control forces. however, the PON strategy attenuates the peak of displacement in top story to 54%. The TE-FC applies 7% less peak forces of MR-damper in comparison with PON. The significant performance of the structural rehabilitation presented in table.4.

5.2. Case of Rehabilitations

Two different four and eight story benchmark-buildings have utilized to represent the proficiency of the suggested controller in structural rehabilitation. The first twenty second of the N-S component of El-Centro earthquake is utilized. The first rehabilitated case is a four-story benchmark building with the following specifications:

$$m_1 = 4x\,10^5 kgf \;, m_2 = m_3 = 3x\,10^5 kgf$$

$$m_4 = 2.5x\,10^5 kgf \;,\; \xi = 2\%$$

$$k_1 = 480\times 10^3 KN/m \;, k_2 = k_3 = 384\times 10^3 KN/m \;, \; k_4 = 336\times 10^3 KN/m \quad (13)$$

It was clear that less number of MR-dampers did not lead to appropriate response decrement in the structural control and more number of dampers will not necessarily be economic. The economic issues should be also discussed to enhance the quantity of MR dampers. A cost function should be applied to compute the optimal quantity of MR-dampers. For the four-story rehabilitated benchmark-building, the following fitness function was employed :

$$PF = (2\times j_1 + 1\times j_2 + 0.8\times j_3)\times(1+ND\times 0.1) \quad (14)$$

ND is the quantity of MR dampers, J1, J2 and J3 are indexes of structural responses, which were described in section 6.1. 100 initial agents are applied to determine optimal damper and sensor distribution. Nine iterations are required to determine the optimal distribution in four-story rehabilitated benchmark building:

$$Dp = [\ 0 \quad 0 \quad 1 \quad 3\ ] \ , \ Sp = [- \quad - \quad 4 \quad 4] \quad (15)$$

Where Dp and Sp are the matrix of damper and sensor distribution, respectively. It is rational to apply 200kN MR dampers one in the 3rd-floor and three in the 4th-floor of benchmark building. The number four which written in third column of SP matrix represented that the required sensor for the damper which was installed in third story should be installed in fourth story of building.

Table 5. Four-story benchmark building numerical simulation responses after rehabilitation

Floor		1	2	3	4
Quantity of dampers				1	3
The mean of damper force (kN)				60.0 kN	181.2 kN
Top-story Displacement (m)	Uncontrolled case	0.028	0.057	0.074	0.086
	Controlled case	0.012	0.022	0.027	0.032
	Percentage of Reduction	61%	62%	65%	64%
The peak of Drift (m)	Uncontrolled case	0.029	0.028	0.019	0.011
	Controlled case	0.012	0.010	0.009	0.006
	Percentage of Reduction	60%	64%	52%	49%
Top-story Acceleration (m/s2)	Uncontrolled case	8.27	12.23	13.19	16.15
	Controlled case	5.34	6.00	6.52	11.07
	Percentage of Reduction	35%	51%	51%	32%

The same conclusion was obtained for the column four as well. Thereupon, only one sensor should be installed in the fourth story and adequate for this structure. These sensors are independant from state sensors in the central control computer. Fig.5 exhibits the output-force of dampers which is installed in the 3rd and 4th floor of building. Fig.6 exhibits the time history of displacement and drift of the 4th story building. Furthermore, Table.5 illustrated the dynamic analysis responses. The second case of rehabilitation represents the eight-story benchmark-building by the following specification:

$$\begin{aligned}&m_1 = m_2 = 400\ ton\ ,\\ &m_3 = m_4 = m_5 = m_6 = m_7 = m_8 = 350\ ton\\ &k_1 = k_2 = k_3 = 3\times10^5\, KN/m\ \ , k_4 = k_5 = k_6 = 2.5\times10^5\, KN/m\ ,\\ &k_7 = k_8 = 1.8\times10^5\, KN/m\\ &\xi = 1\%\end{aligned} \tag{16}$$

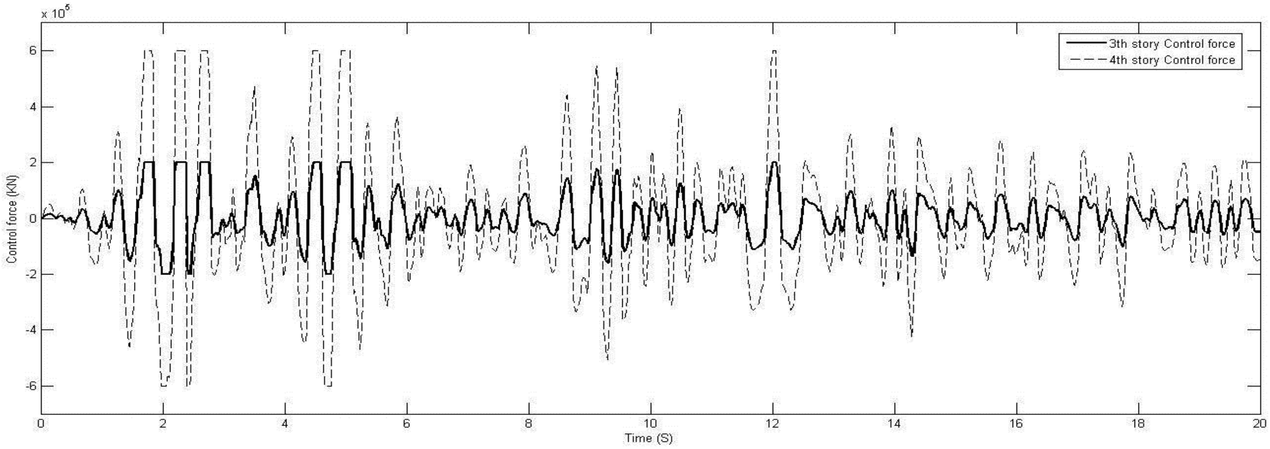


Fig.5. The output control force in third and fourth floor of four-story rehabilitated building

For the eight-story benchmark-building the following fitness function was utilized:

$$PF = (2\times j_1 + 1\times j_2 + 0.8\times j_3)\times(1 + ND\times 0.07) \tag{17}$$

ND is the quantity of MR dampers, J1, J2 and J3 are indexes of structural responses, which were described in section 6.1. The TE could specify the quantity and distribution of the dampers and sensors. Four fitness functions PF, J1, J2 and J3 indexes, to find the optimal and cost effectiveness distribution. The TE-FC applies 60 initial agents and reaches to the optimum solution after eleven iterations.

The optimal distribution for eight-story rehabilitated building is:

$$\begin{aligned}Dp &= [0\ \ 2\ \ 1\ \ 2\ \ 2\ \ 0\ \ 2\ \ 0]\\ Sp &= [-\ \ 1\ \ 8\ \ 3\ \ 6\ \ -\ \ 8\ \ -]\end{aligned} \tag{18}$$

Where Dp and Sp are the matrix of damper and sensor distribution, respectively. Two-200kN MR-damper should be installed in the 2nd, one in the 3rd, two in the fourth, two in the fifth and two in the seventh floor of structural system.

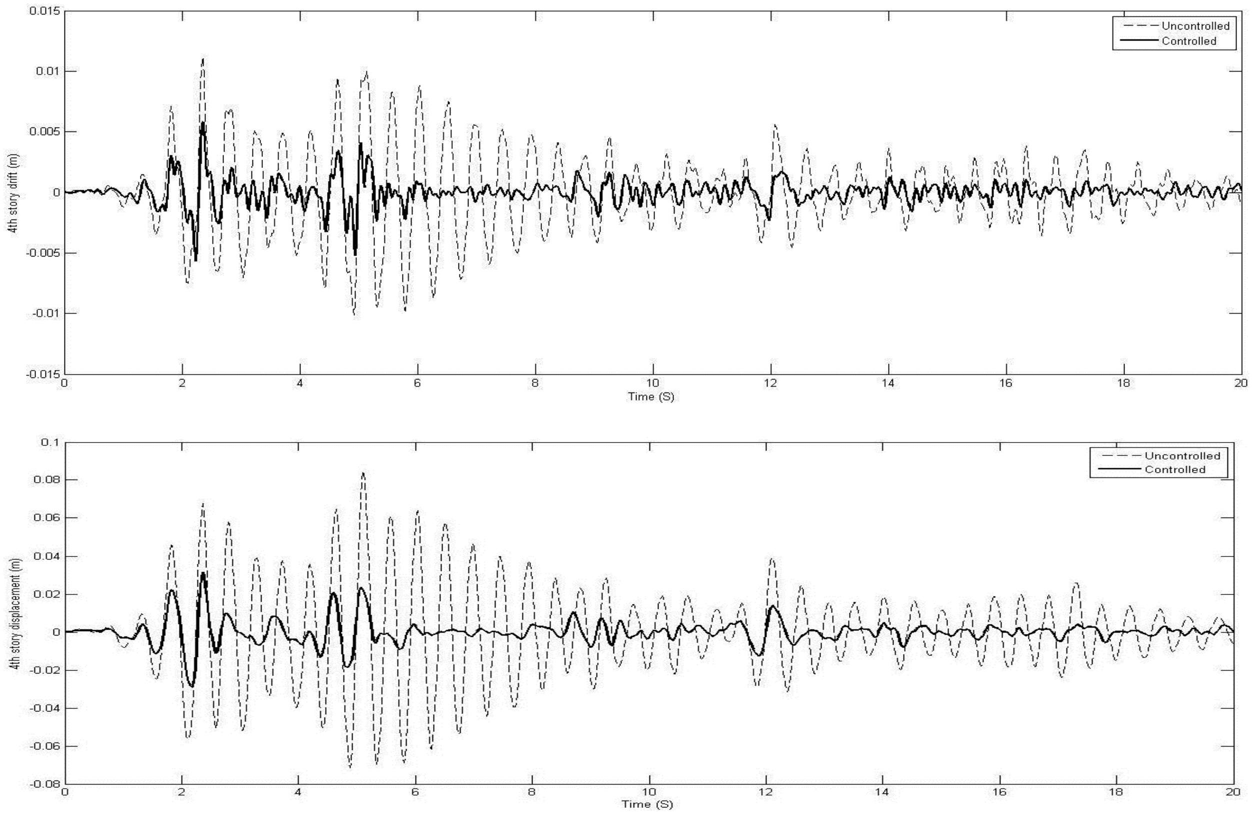
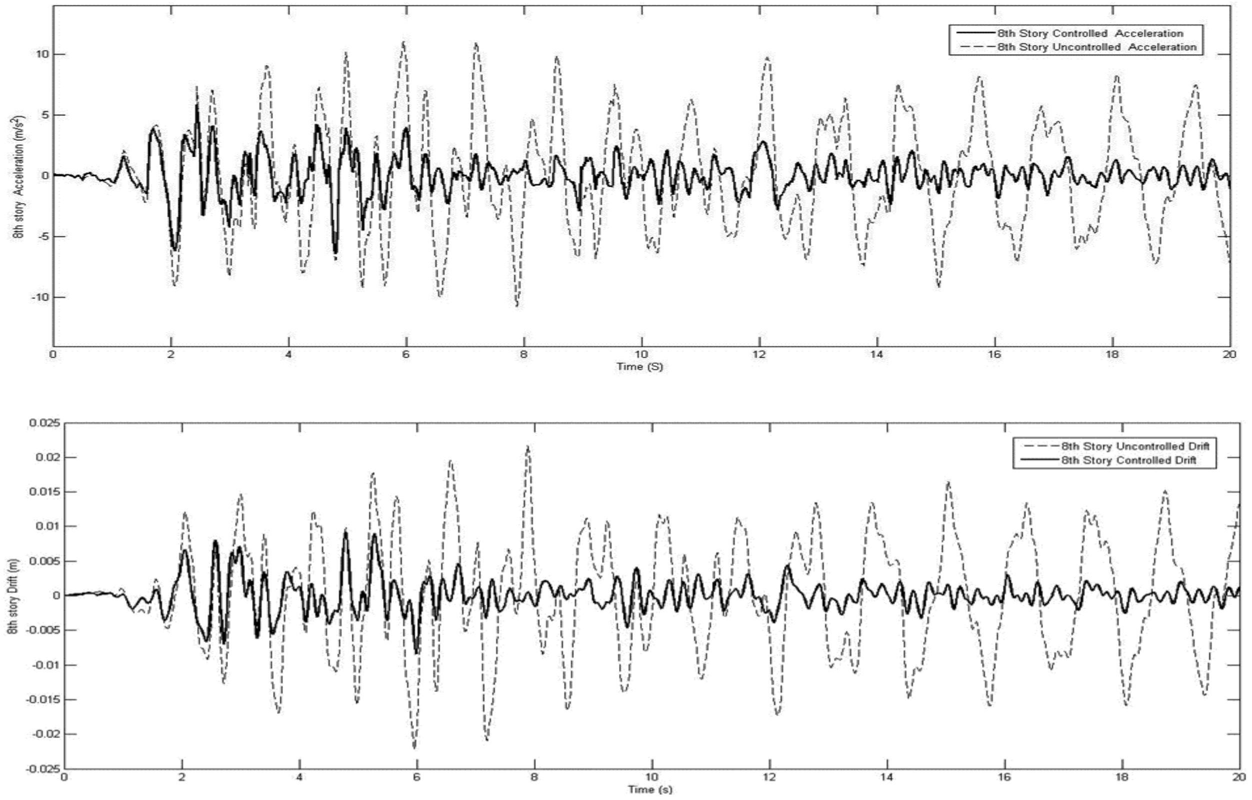


Fig.6. Four-floor time history of displacement and drift of four-story rehabilitated building



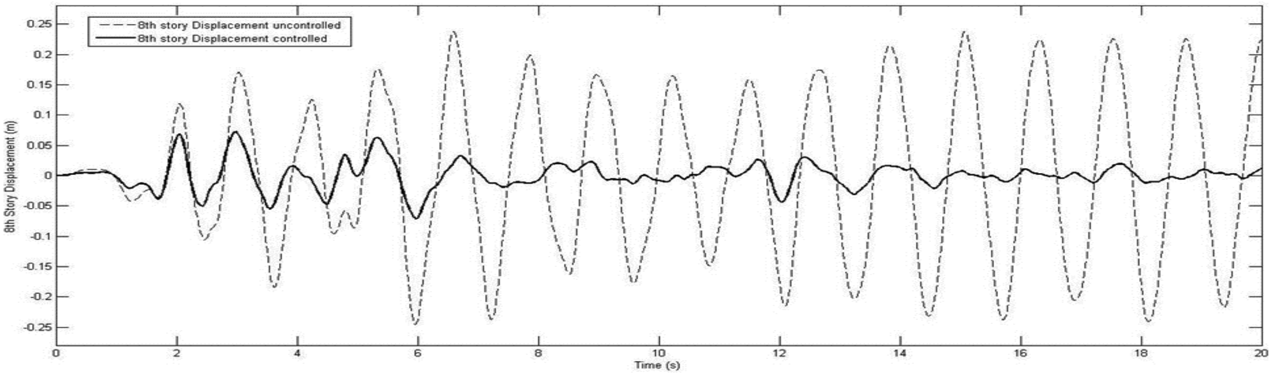


Fig.7. The 8th floor displacement, velocity and acceleration results in eight-story rehabilitated building

The number eight which written in seventh column of SP matrix represented that the required sensor for the damper which was installed in seventh story should be installed in eight story of building. In the case of other columns the same conclusion was acquired Thereupon, their sensors should be installed in the 1st, 8th, 3rd, 6th and 8th floor of rehabilitated building, respectively. These sensors are independant from state sensors in for central control computer. It could be summarized that four sensors are adequate for 8th story benchmark building. Figure.7 presents the time history of displacement, velocity and acceleration of structural responses. Figure.8 exhibits the control forces of 3rd, 5th and 7th floor. The suggested TE-FC and optimal distribution of MR-dampers and their sensors decreased the undesired drift, displacement and acceleration benchmark building. To represent the reliability, robustness and effectiveness of the TE-FC, the mean decrement ratios for the El-Centro were investigated in Table.6. Results reveal that suggested optimal Thermal Exchange-fuzzy controller (TE-FC) could compute the optimal distribution and optimal control force. At the same time, TE-FC could optimize the quantity and distribution of MR-dampers in structural system. TE-FC was capable of attenuating the maximum displacement, drifts and acceleration of building to about 72.7%, 67.8% and 31.3% of uncontrolled mean displacement, respectively. Consequently, TE-FC demonstrates its ability to effectively decreased based on the simulation and numerical results.

Table 6. The Numerical simulations of rehabilitation in 8th-story benchmark building

Floor			2	3	4	5	6	7	8
Quantity of dampers			2	1	2	2	0	2	0
The mean of damper force (kN)			129.9	66.7	129.9	134.3	0	135.1	0
Top-story Displacement (m)	Uncontrolled case	0.042	0.082	0.112	0.146	0.178	0.204	0.228	0.246
	Controlled case	0.011	0.021	0.029	0.039	0.047	0.056	0.066	0.073
	Percentage of Reduction	73%	74%	74%	73%	74%	73%	71%	70%
The peak of	Uncontrolled	0.043	0.039	0.034	0.039	0.039	0.035	0.038	0.023

Drift (m)	case								
	Controlled case	0.011	0.011	0.011	0.014	0.012	0.011	0.013	0.009
	Percentage of Reduction	73%	73%	69%	64%	69%	69%	67%	60%
Top-story Acceleration (m/s2)	Uncontrolled case	5.02	6.51	7.97	9.18	7.73	7.39	10.07	11.05
	Controlled case	4.89	5.74	5.18	4.81	4.74	5.70	5.20	6.32
	Percentage of Reduction	3%	12%	35%	48%	39%	23%	48%	43%

The compatibility in designing of the suggested TE-FC to account for any variation in the excitation contents online via FC controller creates it more reliable and effective structural controller in seismic rehabilitation. To represent the efficiency of the suggested TE-FC controller in rehabilitation, the uniform dampers and sensors distribution is contemplated in eight story building. The TE optimization algorithm suggests nine 200kN MR dampers should be applied in this building. For a better comparison, the number of dampers is considered constant in both benchmark building.

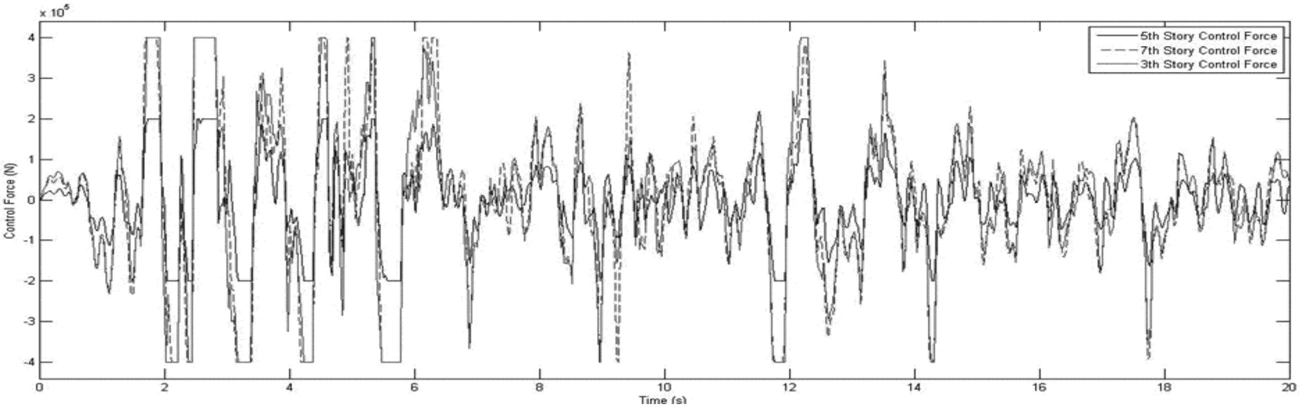


Fig.8. Applied control force in the 3rd, 5th and 7th story of eight-story rehabilitated building

The sensors are installed in the story of their own dampers, to study the effect on optimal damper placement more precisely without any optimization process.Thus, the uniform distribution for sensors and dampers in eight-story building is:

$$Dp = [1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 2]$$
$$Sp = [1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8] \tag{19}$$

Table.7 represents the robustness and effectiveness of the suggested method in rehabilitation of eight-story building. The mean decrement ratios (optimally controlled to uniformly controlled displacement, drift and acceleration ratio) are compared.

Results reveal that TE-FC can compute the optimal distribution and optimum control force. At the same time, TE-FC leads to excessive response reductions in comparison with uniform damper distribution by applying the same number of dampers. TE-FC demonstrates the optimally distribution capability to significantly attenuating the maximum displacement and drifts of building to about 20 and 14 of uniformly distribution controlled average responses after rehabilitation. Minor reduction percentage in acceleration responses is achieved.

Table 7. Efficiency of TE-FC rehabilitation in 8th-story benchmark building

Floor		1	2	3	4	5	6	7	8
Quantity of dampers		-	2	1	2	2	-	2	-
The mean of damper force (kN)			129.9	66.7	129.9	134.3		135.1	
Top-story Displacement (m)	Uniform controlled	0.010	0.025	0.035	0.048	0.058	0.068	0.083	0.092
	TE-FC Controlled	0.011	0.021	0.029	0.039	0.047	0.056	0.066	0.073
	Reduction Percentage (%)	10	19	21	23	23	21	20	26
The peak of Drift (m)	Uniform controlled	0.010	0.013	0.013	0.015	0.014	0.012	0.014	0.011
	TE-FC Controlled	0.011	0.011	0.011	0.014	0.012	0.011	0.013	0.009
	Reduction Percentage (%)	10	18	18	8	16	11	11	19
Top-story Acceleration (m/s2)	Uniform controlled	4.98	5.92	5.87	5.79	5.35	6.02	6.24	6.52
	TE-FC Controlled	4.89	5.74	5.18	4.81	4.74	5.70	5.20	6.32
	Reduction Percentage (%)	2	3	13	20	11	6	20	1

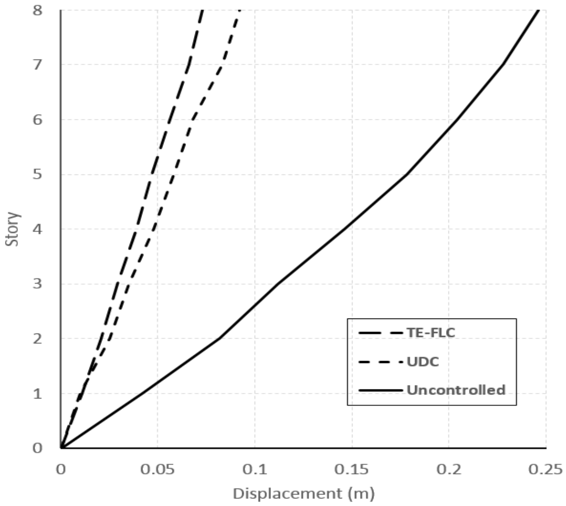


Fig.9. Maximum floor displacement in TE-FC controlled, uniformly distribution controlled (UDC) and uncontrolled cases.

The capability of TE-FC in optimizing the acceleration response reduction is 8% more than uniform damper distribution. Figure.9 gives the maximum floor displacement in TE-FC controlled, uniformly distribution controlled (UDC) and uncontrolled cases of

8th-story building. It could be summarized that suggested TE-FC with optimal distribution of actuators and their sensors decreased the undesired drift, displacement and acceleration responses to the suitable magnitudes. Based on numerical results and simulations, TE-FC could be utilized as a controller in seismic control of structural buildings. Moreover, the compatibility in designing of the suggested TE-FC to consider the variation in the excitation content online via FC creates it more robust, reliable and efficient for seismic rehabilitations.

6. Conclusions

The effect of intelligent semi-active thermal exchange-fuzzy controller in structural rehabilitation is investigated by attenuating seismic responses of structural systems. A novel TE (Thermal Exchange) is utilized to optimize the MR damper and their sensor distribution for the reduction of undesirable responses. An effective TE-FC is administrated the electrical inducing current of the installed MR-dampers. Several numerical simulation and results were accomplished to illustrate the proficiency of Thermal Exchange-fuzzy controller (TE-FC) in structural rehabilitations. The results of TE-FC represent significant performance with respect to responses reduction after rehabilitation. The optimal quantity and the distribution of dampers and their sensors were determined with the least computational effort and in a reasonable time-delay. In low-rise buildings, the evaluations illustrate that installation of dampers and the sensors on the upper stories will lead to proper responses. In high-rise buildings, numerical results depict that the distribution of dampers should be distributed all over the building to mitigate the undesirable responses. The efficiency of optimal arrangement of dampers and sensors over uniformly distribution of damper and sensors is also presented. Consequently, the economical properties and maintenance cost could be minimized indirectly by optimizing the number of dampers. The compatibility of designing of the suggested TE-FC to account for the variation in the excitation magnitude and content in time via FC controller makes it more reliable, robust and effective for seismic structural rehabilitation. Therefore, the economical and rehabilitation properties of the semi-active controller could be optimized simultaneously.

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