Iranian Journal of Science and Technology, Transactions of Civil Engineering
https://doi.org/10.1007/s40996-018-0220-2

RESEARCH PAPER

A Study on the Optimization of the Performance of Type 1 Fuzzy Controller Based on the IDA Method

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Received: 2 September 2017 / Accepted: 11 December 2018

Abstract

In this paper, optimization of the design of a fuzzy-genetic controller was done through the IDA and ET analysis methods. Combination controllers versus classical control methods have the ability to handle nonlinear and complex problem, learnability, adaptability and robustness to errors. However, one of the main shortcomings of fuzzy Type-1 systems is ignorance of the uncertainties in the fuzzy rule base. Studies which have been conducted on the benchmark structures show that the training of controllers is generally based on the control of the index of damage in a particular earthquake. Controller performance in case of different loading conditions depends on the characteristics of the earthquake used in the training phase, and the controller performance, in other conditions, is not optimal. In this study, the results of the IDA and ET methods for training and designing controllers, as a solution for reducing the uncertainty in structural behavior and loading, were used. Also, the IDA method was used to evaluate the performance of controllers. Examining the strengths and weaknesses of controllers in a wider range of dynamic loading conditions through using the IDA method is applicable. Moreover, evaluation of the results based on a wider range of earthquakes with different maximum accelerations can be done through the IDA method. A benchmark building which was equipped with a MR damper was used in order to evaluate the proposed control method. The results of structural analysis in the proposed controller with uncontrolled structure response, and controlled structures under fuzzy controller that was trained under a special earthquake, were compared and evaluated. Numerical results show that controller training under ET-generated accelerogram in the proposed controller is more effective than other controllers and structural responses under different loading conditions will be optimized. The use of the proposed controller reduces damage in the structure by 15–20% in comparison with other controllers.

Keywords Fuzzy-genetic combination controller · Optimization of controller design · MR damper · Incremental dynamic analysis methods of IDA and ET

1 Introduction

In the last two decades, different studies on the behavior of structures against earthquakes and more familiarity with the nature of earthquakes show that the subject of control of structures was one of the main focuses of scholars. Reducing structural responses to enhance safety and providing conditions for serviceability are among the goals of researchers. To achieve these goals, the control tools are very significant. Structural control methods are classified into several categories including passive, active, semi-active and hybrid systems. In this research, reducing the damages to the structures against earthquakes by semi-active control method using MR damper and using the results of incremental analysis of structures were studied.

Spencer, Dyke et al. studied the MR damper and presented a model for its dynamic behavior. They compared their proposed dynamic model with existing idealized models as well as laboratory samples and showed that proposed models are suitable for analyzing and designing structures equipped with MR damper (Dyke et al. 1996a, b; Spencer et al. 1997). Carlson, Spencer, Yang et al. studied the dampers in real dimensions of the structures. They examined dampers in real dimensions, and they evaluated dynamic models of MR dampers (Carlson and Spencer 1996; Spencer et al. 1997; Yang et al. 2002). Different algorithms were proposed for controlling structures against earthquake with

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Published online: 16 January 2019

MR damper. Jansen et al. formulated four different classical control algorithms including the Lyapunov controller, bang–bang controller, modulated homogeneous friction algorithm and a clipped optimal controller for using with the MR damper algorithm. In their study, a 6-story frame that was equipped with this damper was controlled for the El Centro earthquake and the benefits of each of these algorithms were discussed (Jansen and Dyke 2000). In addition to classical methods, intelligent methods are also used to control the structures with this damper. Some of these algorithms, such as optimal control, pole positioning, H2, H∞, etc., are based on mathematical methods, and some others, such as fuzzy and neural algorithms, are intelligent algorithms.

By combining fuzzy control with some control algorithms, other methods can be created which is called combined control method. Fuzzy-modal control methods, slip-fuzzy control, fuzzy-neural control, genetic-fuzzy control, etc., are examples of combined control methods that were investigated by researchers in recent years. Some researchers, like Kim, Wang, Dounis, etc., investigated the combined control techniques; they combined control algorithms with fuzzy algorithms in order to optimize fuzzy parameters. The results revealed that fuzzy controllers combined with optimizing controller parameters perform better than fuzzy controllers (Dounis and King 2003; Alli and Yakut 2005; Schurter and Roschke 2001; Bathaei et al. 2017, 2018; Ramezani et al. 2017; Shariatmadar and Golnargesi 2014). The parameters of the fuzzy controllers can be determined by methods such as the expert knowledge or common algorithms for optimization. If a genetic algorithm is used to determine the fuzzy parameters of a genetic algorithm, the controller is called a genetic-fuzzy controller. Karamodin et al. used a genetic-fuzzy control method in order to control the benchmark structure. Relying on the capabilities of fuzzy controllers-like the ability to handle nonlinear and complex problems, training capability, adaptability and error-tolerance, they controlled the behavior of the benchmark structures. The comparison between their proposed controller and other controllers shows a significant decrease in the structure response in comparison with other controllers (Karamodin 2009). Baghban et al. controlled the behavior of a benchmark structure by means of a genetic-fuzzy controller. They compare their proposed controller performance with linear–quadratic–Gaussian (LQG) active controller and self-organizing fuzzy logic controllers (SOFLC) with active actuators. They showed that the combination genetic-fuzzy controller is quite effective in overall damage reduction for a wide range of motions, compared with the SOFLC and LQG controllers (Karamodin et al. 2011).

In studies on the benchmark structures, it can be seen that training of controllers is based on control of index of damage in a particular earthquake. On the other hand, the criterion for measuring the performance of controllers which are designed to reduce damages in a structure is generally based on the judgment of a limited number of earthquakes. The results of studies on the fuzzy controllers show that one of the weaknesses of fuzzy type-1 systems is to consider uncertainties in the fuzzy rule base. Therefore, in this study, genetic-fuzzy type-1 controller was studied and optimized. In this paper, the optimization of controller parameters is based on the training under the influence of a wide range of earthquakes that were carried out. The IDA method is used for training and designing controllers as a new solution in order to reduce the uncertainty in the behavior of the structure and loading. On the other hand, it was revealed that the use of IDA and ET methods to evaluate the performance of controllers will lead to the evaluation of controllers based on the results of structural analysis under the influence of a wide range of earthquakes.

The analysis of structures based on the IDA method is one of the new methods of nonlinear analysis of structures. It involves subjecting a structural model to one (or more) ground motion record(s), each scaled to multiple levels of intensity, thus producing one (or more) curve(s) of response parameterized versus intensity level (Vamvatsikos and Cornell 2002). In the past, this method was generally used to study the behavior of structures. In this study, attempts were made to use the benefits and capabilities of nonlinear incremental analysis in the control of structures such as structural science. In this research, a new method of incremental analyzing called "endurance time (ET) method" was used. The principles of this method are based on the concepts of IDA method. In analyzing the ET method, an accelerogram that grows over time, which is actually representative of a wide range of earthquakes, is used to excite and analyze the structure. Studies on the method of endurance time were initiated by Estekanchi, and many researchers developed this method. In this novel procedure, an intensifying artificial accelerogram, termed as endurance time acceleration function or ETA, is applied to the structure and its various structural responses are monitored. They showed that artificial accelerograms could be representative of a wide range of earthquakes (Estekanchi et al. 2007).Among the scholars who studied the ET method are Hariri-Ardebili et al. (2013), Madarshahian et al. (2011), Jokar et al. (2004). In this paper, it was shown that ETA functions can be used to optimize the design of combined controllers.

2 Structural Model

In this paper, the 9-story structure that was designed by Ohtori et al., is used as a benchmark structure (Ohtori et al. 2004). The dimensions of this structure are 45.75 m by 45.73 m in plan and 37.19 m in elevation. The bays are

9.15 m on center, in both directions, with five bays each in the north–south (N–S) and east–west (E–W) directions. The lateral load-resisting system of building is comprised of steel perimeter moment-resisting frames (MRFs) with simple framing on the furthest south E–W frame. The interior bays of the structure contain simple framing with composite floors. The columns are made of 345 MPa steel. The columns of the MRF are wide flange. The levels of the 9-story building are numbered with respect to the ground level. The ninth level is the roof. Typical floor-to-floor heights (for analysis purposes measured from center-of-beam to center-of-beam) are 3.96 m. The floor-to-floor height of the basement level is 3.65 m, and the height of the first floor is 5.49 m. The bases of columns are modeled as pinned and secured to the ground. The seismic mass of the structure depends on the various components of the structure, including the steel framing, floor slabs, ceiling/flooring, mechanical/electrical partitions, roofing and the penthouse located on the roof. The seismic mass of the ground level is 9.65×10^5 kg, for the first level it is 1.01×10^6 kg, for the second through eighth levels it is 9.89×10^5 kg, and for the ninth level it is 1.07×10^6 kg. The seismic mass of the above ground levels of the entire structure is 9×10^6 kg. The first five natural frequencies of the 9-story benchmark evaluation model are: 0.443, 1.18, 2.05, 3.09 and 4.27 Hz. Specifications of beams and columns are presented in Fig. 1. Position of dampers, accelerometer sensors and controllers in benchmark building are shown in Fig. 2.

3 Magnetorheological Dampers (MR Dampers)

One of the tools that is used in the semi-active control method is the magnetorheological damper. In analytical and laboratory studies, this damper was very effective in controlling structures and it was taken into consideration by many researchers. In this paper, the MR damper is used to

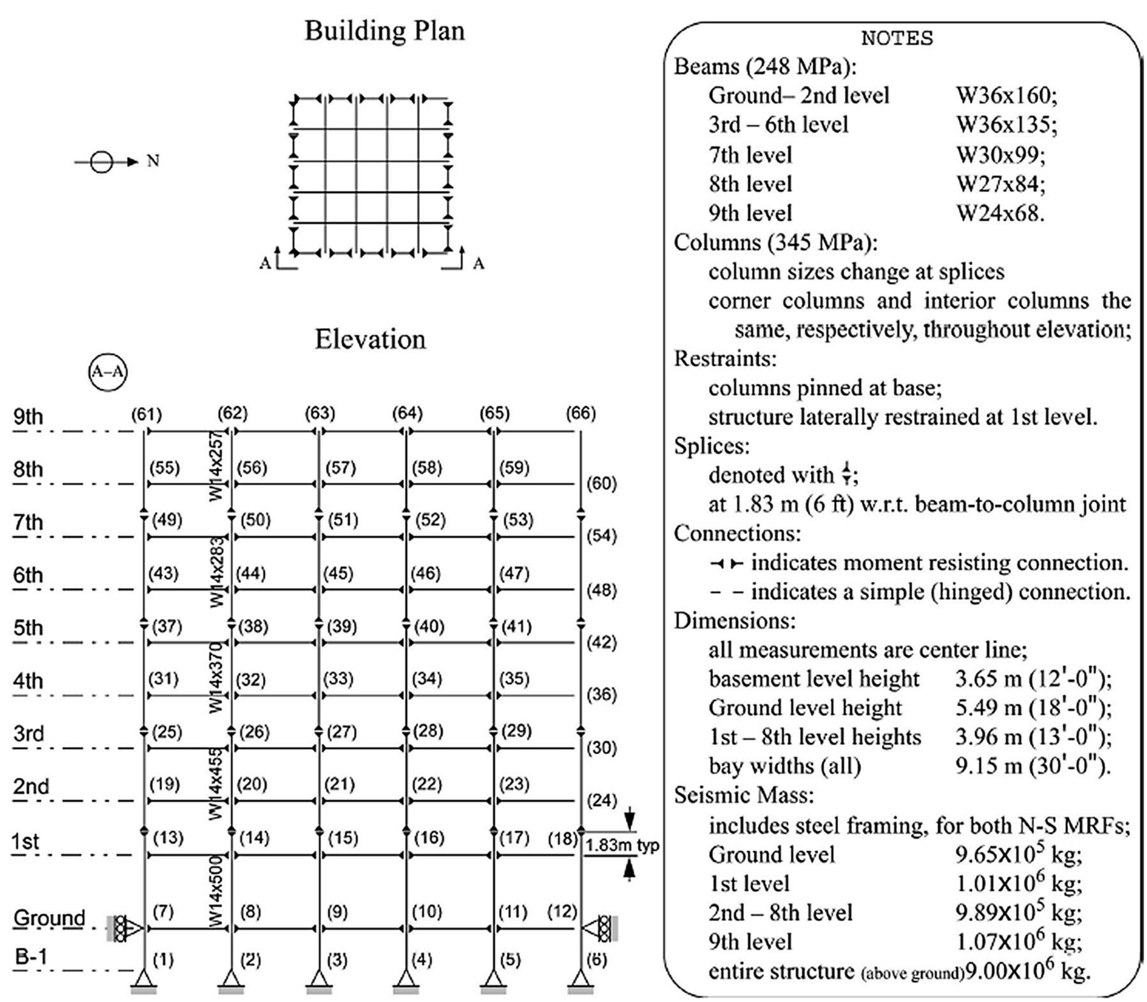


Fig. 1 9-Story benchmark building N–S MRF

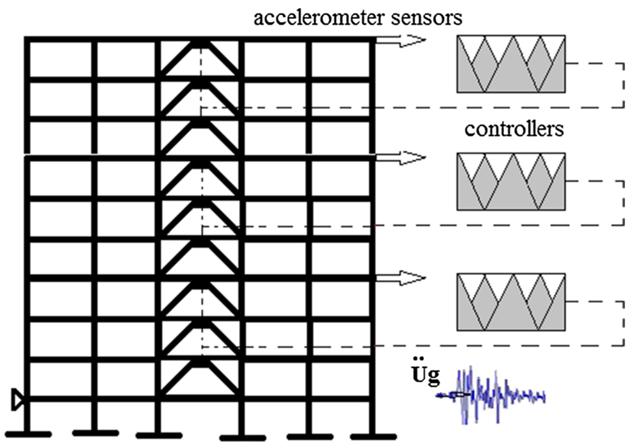


Fig. 2 Position of dampers, accelerometer sensors and controllers in benchmark building

control the structural behavior. This damper is usually composed of a cylinder, in which a liquid containing magnetized field with polarized particles is formed. Behavior of liquid MR is controlled by the magnetic field. In the absence of a magnetic field, the liquid flows through the fluid. But when it is under the influence of the magnetic field, it becomes a semisolid in a few milliseconds. The equations for dynamic model of MR damper can be written as shown below (Karamodin 2009):

$$\begin{aligned} f &= C_0\dot{q} + \alpha Z \\ \dot{Z} &= -\gamma|\dot{q}|z|z|^{n-1} - \beta\dot{q}|z|^n + A\dot{q} \\ \alpha &= \alpha(u) = \alpha_a + \alpha_b u \\ C_0 &= C_0(u) = C_{0a} + C_{0b}u \\ \dot{u} &= -\eta(u - v) \end{aligned} \tag{1}$$

In these equations, q is the relative displacement of the damper, and z is a variable that shows the dependence of the response to its history. By setting parameters, it is possible to determine the tilt of linear behavior and curvature of the passage from the linear behavior to yield. Parameters and variables are adjustable by use of a controller. In these relations, u is the output of the dielectric current circuit, which is determined by the following dynamic equation in terms of the input voltage of the circuit. In this study, the damper parameters are selected to have a maximum capacity of 1000 kN when $V_{\max}$ is 10 V.

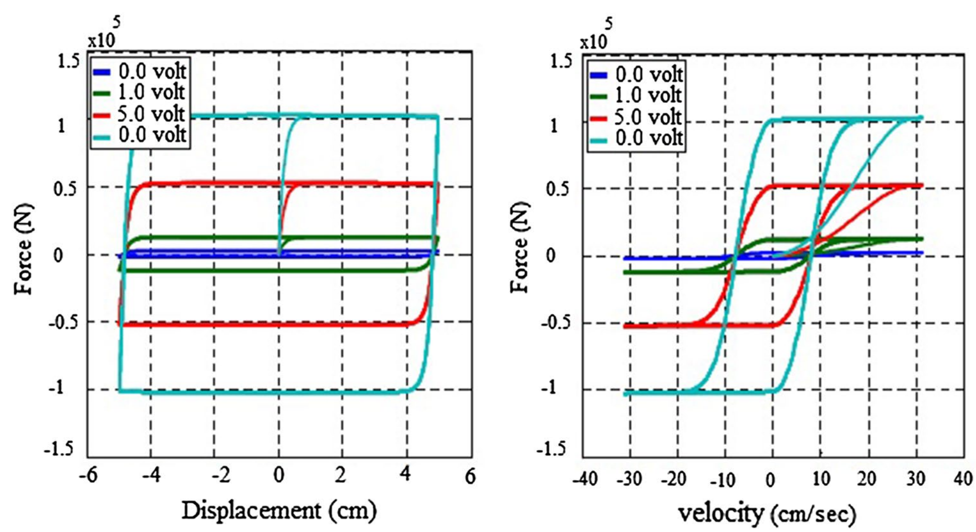
$\alpha_b = 4.9616 \times 10^5$ N/(cm V) $\alpha_a = 1.0872 \times 10^5$ N/cm $\beta = 3$ cm^{-1}
$C_{ob} = 44$ N s/(cm V) $C_{oa} = 4.4$ N s/cm $A = 1.2,\ n = 1$
$\gamma = 3$ cm^{-1} $\eta = 50$ s^1

Figure 3 shows an example of diagrams of forces–displacement and force–velocity of this damper. These diagrams show the response of the damper under the influence of a constant voltage and a sinusoidal displacement with 1 Hz frequency and 5 cm range.

4 Fuzzy Logic Controllers

The theory of fuzzy control presented by Zadeh which is based on the theory of fuzzy systems (Zadeh 1965), attracted the attention of many researchers in controlled structures. This method, by applying a series of rules, solved the need for precise mathematical modeling of the structure. The advantages of this control algorithm in comparison with the classical algorithms are having strength against uncertainties and errors in the various parts of the control system like: data, loads, structural model and measurements. Another important feature of this method is the ability of using it in nonlinear systems. Due to the nature of nonlinear behavior of structures and the ability of fuzzy control algorithms in dealing with nonlinear problems, this tool can be used to control the structures. Another advantage of this method

Fig. 3 A sample of force–displacement and force–velocity diagrams of MR damper



in comparison with other control methods is using human knowledge and experience in the design of the controller and the possibility of adapting the control system.

To design a fuzzy system, input, output, membership functions and fuzzy rules should be determined. These parameters can be optimized by the knowledge of experts or by conventional methods. In this research, the general structure of the system, including the input and output variables, the number and type of membership functions and fuzzy rules, has been determined based on Karamodin (2009) study. The input values are equal to the acceleration response and the velocity of the structure. Output values are equal to the amount of force applied to the structure. Optimization of parameters and rules based on the minimization of the target function (damage of structure based on Park and Ang index) was performed by genetic algorithm. Controller training is performed under ET analysis. In fact, with the use of artificial accelerograms of ET, a wide range of possible earthquakes participated in this process.

5 Incremental Dynamic Analysis

Incremental dynamic analysis (IDA) is a parametric analysis method that is used to evaluate the performance of structures under the earthquake loads and has attracted the attention of the researchers. As shown in Fig. 12, in this method, a structure is under the influence of various earthquakes with various intensities, and the results of the analysis are presented as a curve. The curves are the response of each structure to earthquakes with different seismicity. In these graphs, indicators such as displacement, velocity, storey drift, acceleration of the structure, etc., can be considered as a response of the structure. By studying the obtained diagrams, a comprehensive assessment of the behavior of structure can be made, under the influence of far field and near field earthquakes with different intensities. Thus, by knowing the behavior of the structure, it is possible to consider some ways to control its behavior. Despite its time-consuming process and its difficulty, the specific information of IDA curves can justify the use of this method. Bertero, for the first time in his research, referred to the concept of incremental analysis (Bertero 1977). Then, many researchers used this method in their research; some of these researchers are Luco and Cornell (2007), Nassar and Krawinkler (1991), Psycharis et al. (2000), Mehanny and Deierlein (1999), De Matteis et al. (2000). Extensive research on the IDA method was carried out by Vamvatsikos, and the capacity and reliability of structures under various earthquakes were evaluated. Their research is a complete reference to the method of production, summarization and interpretation of IDA graphs (Vamvatsikos and Cornell 2002). The Fema (2000) report also used this method as a method for determining the final capacity of a structure failure (Fema 2000).

6 Endurance Time Method

Endurance time (ET) method, which is based on Sharif University of Technology in Iran, is a new method of seismic analysis. In this procedure, structures are subjected to a specially designed intensifying accelerogram and their endurance time is measured based on the time interval, during which they can resist the imposed dynamic actions. Structural response is investigated over time and is evaluated according to the corresponding response to different levels of excitation intensity, strengths and weaknesses and structural performance (Estekanchi et al. 2007).

The concept of the ET method can be well explained by using a hypothetical test of shaking table. As shown in Fig. 4, three different structures with unspecified characteristics are located on a seismic table, which is randomly vibrated. The intensity of vibration gradually increases. At the start of the test, all three structures are stable until the range of vibrations is low. As time goes on and the intensity of excitation increases, first the structure A (at $t = 8$ s), then the structure C (at $t = 13$ s) and finally the structure B (at $t = 18$ s) are destroyed. By performing this simple test, it can be concluded that the structure A, which is applied to the dynamic excitation, has the lowest endurance and the weakest performance. The structure B, which lasts for a long time, has the best performance (Estekanchi et al. 2007).

If the dynamic excitation is applied, in direct agreement with the dynamic excitation caused by the earthquake, it can be expected that the structure B has the ability to withstand more severe earthquakes than the A and C structures. In other words, by performing such a test, it is possible to estimate the seismic performance of the structures. In addition, if the acceleration function was calibrated it meets the design requirements, so a minimum acceptable durability time for practical application in the design stage can be determined. In this method, the following simple concepts are used to develop an applied analytical tool.

The practical application of the ET Method is dependent on the generation of intensifying acceleration functions that by using the results of the analysis leads to an acceptable estimation of the earthquake in the structure. For this purpose, the concept of the response spectrum can be effectively used in the excitation functions of the ET. These functions are designed to be used as numerical optimization techniques so that the acceleration response spectrum from them at any given time is proportional to the target acceleration spectrum. The acceleration and displacement

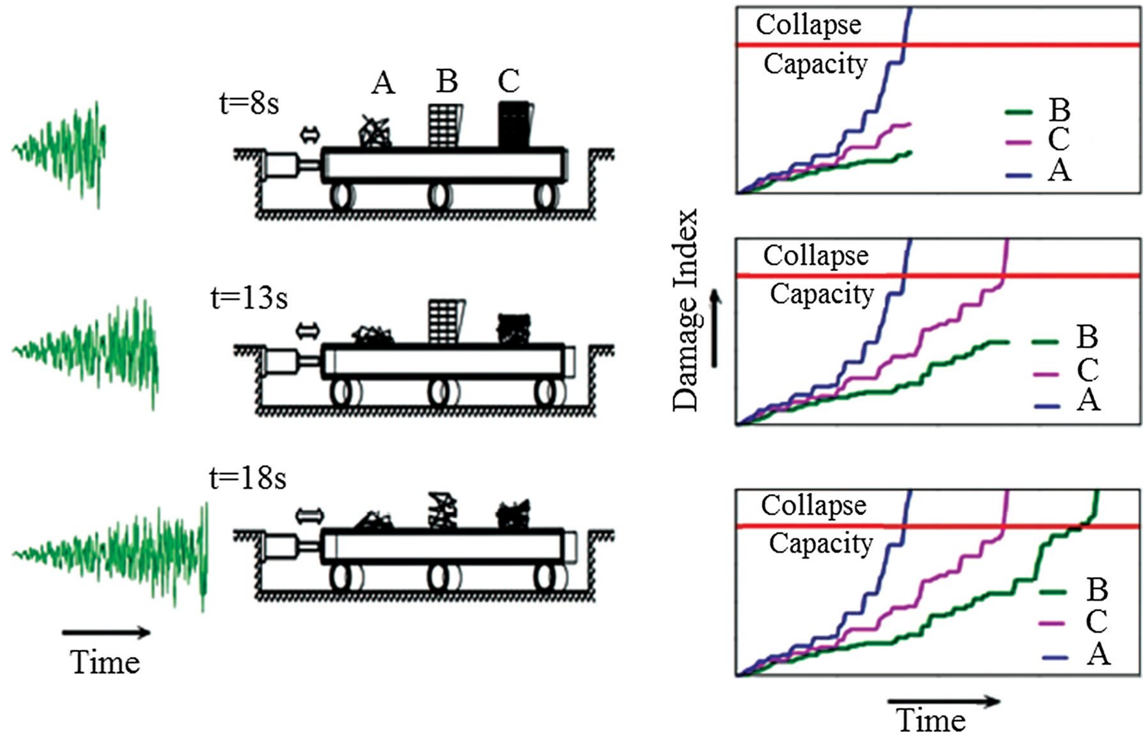


Fig. 4 A schematic introduction of the endurance time method (Estekanchi et al. 2007)

response spectrum are obtained by using Eq. (2) (Nozari and Estekanchi 2011):

$$S_u S_{\mathrm{uc}}(T,t) = \frac{t}{t_{\mathrm{Target}}} S_{\mathrm{ac}}(T) \times \frac{T^2}{4\pi^2}$$
$$S_u S_{\mathrm{ac}}(T,t) = \frac{t}{t_{\mathrm{Target}}} S_{\mathrm{ac}}(T) \tag{2}$$

In Eq. (2), t, T, $S_{\mathrm{ac}}(T)$, $S_{\mathrm{uc}}(T, t)$ and $S_{\mathrm{ac}}(T, t)$ are, respectively, time, periods of free vibration, codified acceleration spectrum, target response displacement and acceleration in the endurance time functions. t_{Target} is the target time (equal to 10 s in this study), which is equal to the time when the scale factor is equal to the base one. It is complicated for an analytical method to find the acceleration that satisfies the above conditions. Therefore, the present problem can be related to the optimization problem according to Eq. (3) (Riahi et al. 2011):

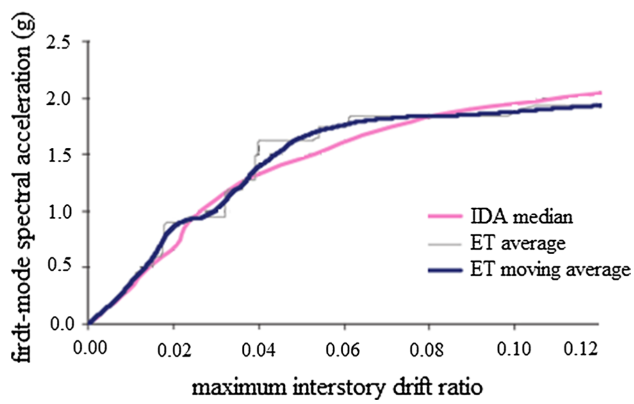


Fig. 5 Comparison of the results of the analysis obtained from the ET and IDA method (Riahi et al. 2011)

has yielded satisfactory results. Reducing the volume of computations as well as good match analysis results under

$$\mathrm{Minimize}\,\mathrm{F}\left(a_g\right) = \int_0^{T\max} \int_0^{t\max} \left\{ \left[S_a(T,t) - S_{\mathrm{ac}}(T,t)\right]^2 + \alpha\left[S_u(T,t) - S_{\mathrm{uc}}(T,t)\right]^2 \right\} \mathrm{d}t\,\mathrm{d}T \tag{3}$$

Considerable research was done in the field of verifying the results of nonlinear and linear analyses under accelerograms produced by the ET method. Researchers argued that the use of accelerograms produced by this method has yielded satisfactory results. Reducing the volume of computations as well as good match analysis results under ET accelerograms with IDA graphs is other advantage of this method (Riahi et al. 2011). Figure 5 shows an example of the matching results of the analysis obtained from the ET and IDA method. In this paper, ET accelerograms, as a summary of several accelerograms, have been used in the design and training of proposed controllers.

7 Numerical Study

By studying researches on controllers used in benchmark structures, it is usually observed that data from a particular earthquake are used to train controllers. Selection of a specific accelerogram in the training process may increase the uncertainty in the behavior of the structure under loading conditions. In the next part, as an example, the behavior of a benchmark structure, in which controller is trained under a special earthquake, was investigated.

According to the ASCE rules for analyzing the time history of a structure, it is necessary to use the mean values of the structure response under the influence of at least 7 accelerogram series. For this purpose, in this paper, 7 accelerogram series is used from the 20 sets of records used in the FEMA440 that were recorded on type C soil. The selection of accelerograms is made so that their spectrum is more in line with the response spectrum of the Iranian National Building Code (INBC) standard 2800. Then, the selected accelerograms are scaled so that the level below their pseudo-acceleration spectrum would be equal to the level below the spectrum of the INBC standard 2800. The range of the period for this scale is from 0 to 5 s. The characteristics of the accelerograms are given in Table 1.

The specifications of the benchmark structure are presented in Sect. 2. In each floor, a number of MR dampers with a capacity of 1000 KN are installed in order to control the structure. The number of these dampers in the first to third floor is 3, 2 and 2, and in the fourth to ninth floor is 1. Accelerometer sensors are installed to measure the response of the structure at the level of the roof of the third, sixth and ninth floors. A controller is considered for each of the dampers of the first to third floor, the fourth to the sixth floor and the seventh to the ninth floor. The input of each controller is acceleration, and the relative displacement of the floors is between the two sensors. The design of control parameters of the first three floors is based on minimizing the overall damage to these three floors. This damage is obtained from the weighted average of the damages of the respective floors. The weight of this average is the energy absorbed in each floor. For the second three floors and the third three floors, the same controller of the first three floors is used.

The controller used in this system is a fuzzy-genetic controller. For the fuzzy controller, fixed numbers of rules are selected with a specific pattern and all of its parameters are trained by the genetic algorithm. The general form of rules, input and output parameters are shown in Fig. 6 and Table 2. The surface of fuzzy rules is presented in Fig. 7.

Membership functions in this fuzzy controller are considered Gaussian. In this controller, the membership functions are not common among all the rules, and each law has its own membership functions. Each membership function has two parameters such that C is its mean and σ is the variance of it. Thus, with respect to the two inputs and the output, each rule has six parameters associated with membership functions. Moreover, the operator of the combination of input variables in the introduction of each rule is considered to be parametric, so that for the AND operator the parameter $t=1$ and for the operator OR the parameter $t=2$ is considered.

Choosing the right number of rules is especially important because too many or too few rules will reduce the efficiency of the fuzzy system. On the other hand, choosing the right number of rules is difficult. Here, to solve this problem, for each rule a parameter (ω) is considered as a weight factor. This parameter varies from 0 to 1. With increasing or decreasing the degree of participation of the rules, the operation of the system will be changed. In this way, in practice, the number of rules is also optimized. According to these materials, each rule has eight parameters. By choosing twenty laws above, there will be a total of 160 parameters, which should be optimized by GA. All of these parameters are encoded in real numbers in GA. The range of changes in the input and output variables is, respectively, − 10 to 10

Table 1 Characteristics of 7 ground motions used in this study

Record no.	Record name	Earthquake name	Year	Magnitude (Richter scale)	Duration (s)	Time sampling (s)	Scale factor
1	LADSP000	Landers	1992	7.5	50	0.02	3.64
2	LPAND270	Loma Prieta	1989	7.1	39.9	0.005	2.61
3	LPGIL067	Loma Prieta	1989	7.1	39.9	0.005	2.21
4	LPLOB000	Loma Prieta	1989	7.1	39.9	0.005	2.29
5	LPSTG000	Loma Prieta	1989	7.1	39.9	0.005	1.44
6	MHG06090	Morgan Hill	1984	6.1	29.9	0.005	1.84
7	NRORR360	Northridge	1994	6.8	40	0.02	1.07

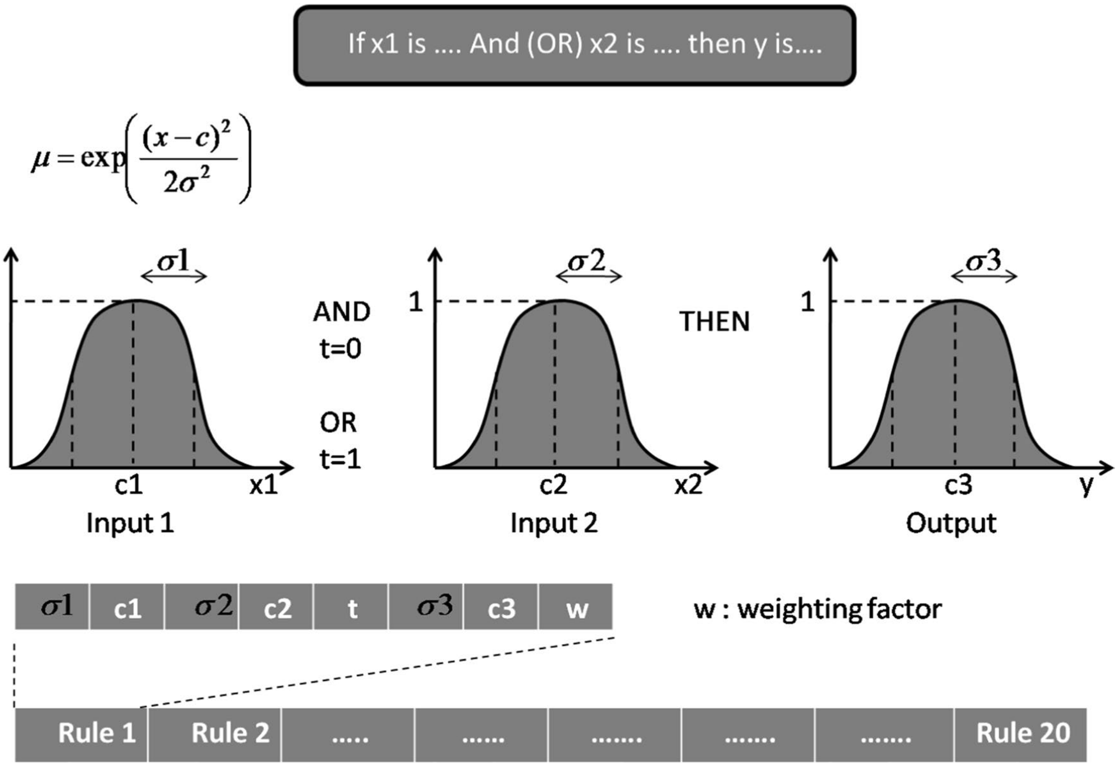


Fig. 6 General form of rules, input and output parameter of fuzzy-genetic controller

Table 2 Rules, input and output parameters of fuzzy-genetic controller

	σ_1	c_1	t	σ_2	c_2	σ_3	c_3	ω
Rule 1	0.6934	−5.993	1	0.6041	5.76	0.5607	6.483	0.50253
Rule 2	0.7296	5.079	1	0.6272	8.394	0.6587	9.252	0.35643
Rule 3	0.69	−9.66	0	0.5046	−9.266	0.5351	6.387	0.43417
Rule 4	0.9008	−4.304	0	0.908	7.12	0.6348	6.531	0.66591
Rule 5	0.6087	−4.38	1	0.9759	2.957	0.5543	8.788	0.92538
Rule 6	0.7953	−5.991	1	0.861	−7.46	0.8505	9.181	0.59002
Rule 7	0.8803	−1.848	0	0.7224	9.577	0.73	5.14	0.73231
Rule 8	0.5938	2.146	0	0.766	6.96	0.7491	6.266	0.81611
Rule 9	0.5494	6.263	1	0.7335	9.75	0.618	7.55	0.69814
Rule 10	0.5411	−6.5	0	0.6864	3.529	0.8782	6.244	0.97343
Rule 11	0.7238	−8.353	0	0.8949	−6.075	0.9055	5.093	0.06234
Rule 12	0.5502	5.926	0	0.902	5.01	0.627	5.32	0.86370
Rule 13	0.5669	5.041	0	0.924	9.37	0.704	8.27	0.68654
Rule 14	0.5711	−3.868	0	0.6261	5.051	0.724	4.03	0.13429
Rule 15	0.7286	−8.738	1	0.6071	7.107	0.969	0.211	0.83873
Rule 16	1.784	2.249	0	0.7246	−9.473	0.9068	6.414	0.42391
Rule 17	0.5668	−6.126	1	0.7276	9.633	0.6972	9.767	0.43984
Rule 18	0.7293	5.758	0	0.6412	−9.488	0.8023	4.426	0.46020
Rule 19	0.779	2.56	1	0.964	3.428	0.8142	8.8	0.62805
Rule 20	0.6866	3.876	0	0.7475	8.453	0.695	0.1726	0.98242

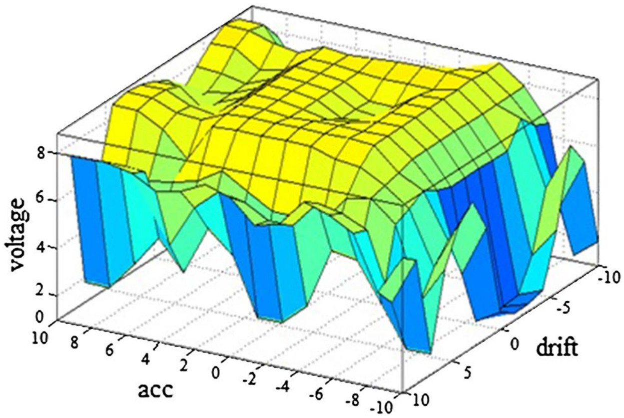


Fig. 7 The surface of fuzzy rules

and 0–10. Accordingly, the lower and upper limits are input and output variables and are, respectively, − 10 to 10 and 0–10. Accordingly, the lower and upper limit is considered for parameters as $c1$ and $c2$, − 10 and 10 and for $c3$, 0 and 10. Also, the lower and upper limits of the parameters б are 0.5–2. The parameters t and ω are encoded in real numbers between 0 and 1. For t, numbers smaller than 0.5–0 and numbers greater than 0.5–1 have been converted. The number of members in the genetic algorithm is 20 members. Primary members are selected randomly. To generate the new member, the elite member would be moved to the new generation without any changes. Other members of the new generation would be produced with migration and mutation operators. 80% of these members are migrated with the migration operator, and 20% are generated by the mutation operator. For the mutation operator, the Gaussian mutation method is used. This controller is coded in the MATLAB environment, and its parameters are optimized by the GA algorithm.

In the first step, the fuzzy-genetic controller in the benchmark structure is trained on the basis of different earthquakes. Each structure, equipped with a trained controller, is analyzed under the influence of 7 selected accelerograms. The Park and Ang damage index is used to assess damages. The damage of each structure is shown in Tables 3, 4, 5, 6, 7, 8 and 9.

Careful observation of Tables 3, 4, 5, 6, 7, 8 and 9 indicate that, in all earthquakes, the use of controllers significantly reduces the damage of structures compared to uncontrolled structures. In all cases, the damage to the structure under a particular earthquake shows that the controller is also designed based on that particular earthquake shows the greatest decrease compared to the situations where the controller training is based on other earthquakes.

For example, as shown in Table 5, a structure whose controller was trained under the Loma 2 earthquake reduces the structural damage to a 19.22% control without a controller. However, if the controller of the same structure is trained under the earthquakes of Lander, Loma 1, Loma 2, Loma 3, Morgan and Northridge, in the Loma 2 earthquake analysis, the damage is decreased to 16.56%, 14.11%, 9.3%, 13.44%, 14.79% and 13.56%, respectively. This result is obvious and predictable. Because the structure is more successful in response to an earthquake whose controller is already trained under the same earthquake. However, as it can be seen, the reduction in degree of damage, in structures that are under different loads of earthquake, is unpredictable. The behavior of the structure is heavily dependent on the earthquake that the controller

Table 3 Comparison of damage index of uncontrolled and controlled structure (trained by Lander earthquake)

	Lander	Loma 1	Loma 2	Loma 3	Loma 4	Morgan	Northridge	Mean
Control	0.176	0.2037	0.136	0	0.1692	0.273	0.296	0.179129
Uncontrol	0.324	0.262	0.163	0.116	0.262	0.4166	0.4162	0.279971
Percent	45.68%	22.25%	16.56%	100.00%	35.42%	34.47%	28.88%	36.02%

Table 4 Comparison of damage index of uncontrolled and controlled structure (trained by Loma 1 earthquake)

	Lander	Loma 1	Loma 2	Loma 3	Loma 4	Morgan	Northridge	Mean
Control	0.178	0.2	0.14	0	0.163	0.277	0.292	0.178571
Uncontrol	0.324	0.262	0.163	0.116	0.262	0.4166	0.4162	0.279971
Percent	45.06%	23.66%	14.11%	100.00%	37.79%	33.51%	29.84%	36.22%

Table 5 Comparison of damage index of uncontrolled and controlled structure (trained Loma 2 earthquake)

	Lander	Loma 1	Loma 2	Loma 3	Loma 4	Morgan	Northridge	Mean
Control	0.18	0.2	0.132	0	0.161	0.265	0.29	0.175429
Uncontrol	0.324	0.262	0.163	0.116	0.262	0.4166	0.4162	0.279971
Percent	44.44%	23.66%	19.02%	100.00%	38.55%	36.39%	30.32%	37.34%

Table 6 Comparison of damage index of uncontrolled and controlled structure (trained by Loma 3 earthquake)

	Lander	Loma 1	Loma 2	Loma 3	Loma 4	Morgan	Northridge	Mean
Control	0.181	0.213	0.148	0	0.173	0.295	0.307	0.188143
Uncontrol	0.324	0.262	0.163	0.116	0.262	0.4166	0.4162	0.279971
Percent	44.14%	18.70%	9.20%	100.00%	33.97%	29.19%	26.24%	32.30%

Table 7 Comparison of damage index of uncontrolled and controlled structure (trained by Loma 4 earthquake)

	Lander	Loma 1	Loma 2	Loma 3	Loma 4	Morgan	Northridge	Mean
Control	0.176	0.2008	0.1411	0	0.154	0.273	0.2874	0.176043
Uncontrol	0.324	0.262	0.163	0.116	0.262	0.4166	0.4162	0.279971
Percent	45.68%	23.36%	13.44%	100.00%	41.22%	34.47%	30.95%	37.12%

Table 8 Comparison of damage index of uncontrolled and controlled structure (trained by Morgan earthquake)

	Lander	Loma 1	Loma 2	Loma 3	Loma 4	Morgan	Northridge	Mean
Control	0.1765	0.2055	0.1389	0	0.1565	0.2567	0.2818	0.1737
Uncontrol	0.324	0.262	0.163	0.116	0.262	0.4166	0.4162	0.279971
Percent	45.52%	21.56%	14.79%	100.00%	40.27%	38.38%	32.29%	37.96%

Table 9 Comparison of damage index of uncontrolled and controlled structure (trained by Northridge earthquake)

	Lander	Loma 1	Loma 2	Loma 3	Loma 4	Morgan	Northridge	Mean
Control	0.1783	0.2047	0.1409	0	0.162	0.275	0.274	0.176414
Uncontrol	0.324	0.262	0.163	0.116	0.262	0.4166	0.4162	0.279971
Percent	44.97%	21.87%	13.56%	100.00%	38.17%	33.99%	34.17%	36.99%

is trained and designed for. As shown in the results, the difference in the reduction of damage in the various training accelerograms in some cases will be up to two times higher. As an example, it can be seen in Tables 5 and 6 that, if the controller of the two structures were trained, respectively, under the Loma 2 and Loma 3 earthquakes, under the same loading conditions (Loma 2 earthquake accelerogram effect), the damage in the structure would be decreased to 9.2% and 19.02%, respectively. This difference in the amount of damage reduction shows the intensity of the behavior of controlled structure behavior as controller training.

In the process of training controllers, the selection and use of accelerograms, the characteristics of which are likely to be similar to the earthquakes on the structure, is very important. The ET-generated accelerograms, which contain the characteristics of a wide range of earthquakes, can be used as a suitable solution. In this way, the optimization of the controller parameters is done by training under the influence of a wide range of earthquakes. In this study, as a new idea, the structure controller was trained based on the ET accelerograms. For this paper, the endurance time acceleration functions called ETA20e01-03, which are in line with the average of the selected earthquakes, are used. Figure 8 shows an example of a function of acceleration of the ETA20e01-03 accelerogram series.

As shown in Fig. 9, these functions are produced in such a way that the spectrum of these series of acceleration functions in tenths of a second is proportional to the average range of accelerograms of the selected set after applying the initial scale coefficients. The optimization process for the ETA20e01-03 acceleration function, for 200 points with a period of 0–5 s and for 20 points with a period of 5–50 s, was performed (Riahi et al. 2011).

Then, the controlled structure was analyzed under actual earthquakes, in which the artificial accelerogram was generated based on them. The results of these analyses are shown in Fig. 10. The eight diagrams shown in Fig. 10 belong to eight different structures, in each of which controllers are trained under seven actual accelerograms and ET artificial accelerogram. Each of these graphs refers to the average damage response of the structure under the 7 accelerograms. (In fact, each graph is a summary of 7 IDA graphs.)

By comparing the results of the analysis on the structure with the proposed controller and other structures, it can be seen in Fig. 10 that the proposed controller reduces damages by 15–20%, compared to other controllers, at different load levels. This means that instead of training the controller

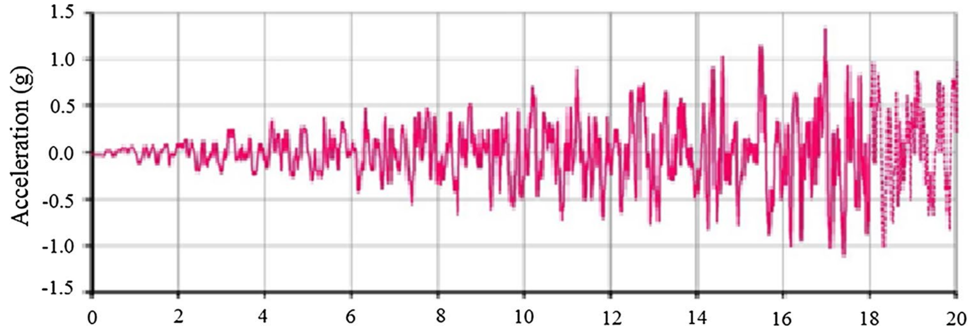


Fig. 8 A typical intensifying acceleration function (Riahi et al. 2011)

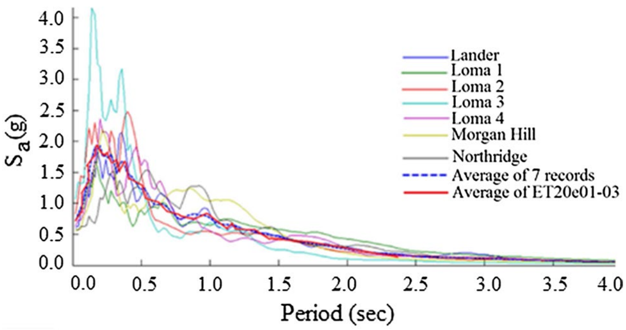


Fig. 9 Acceleration spectra of ground motions used to generate ETA20e series (Riahi et al. 2011)

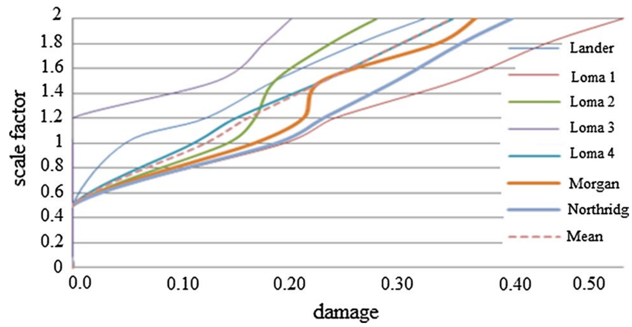


Fig. 11 Comparison of structural response for 7 scaled accelerograms and ETA20e01-03

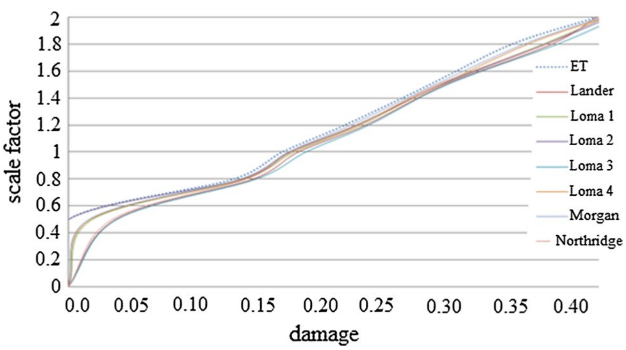


Fig. 10 Comparison of the results of the analysis for 7 scaled accelerograms and ETA20e01-03

under a particular earthquake, a more efficient controller can be provided with a controller under the ET accelerograms training.

In Fig. 11, a comparison is made between the results of the IDA analysis of the controlled structure under the 7 accelerograms and the accelerogram ETA20e01-03. The controller of this structure is trained in ET accelerograms. The graphs of Fig. 11 show the structure response to the ET accelerograms which is within the structure response graphs at 7 selected accelerograms. Therefore, in addition to designing the controller and using the ET accelerograms, this accelerogram can be used as the representative of the 7 selected accelerograms. By checking the curvature of the graphs of Fig. 11, it can be seen that the behavior of the controlled structure in different earthquakes with different peak ground acceleration and the process of structural response change under different accelerograms are unpredictable.

On the other hand, considering that the design and operation of the controllers and the behavior of the structures are influenced by the type and intensity of the selected earthquakes, the evaluation of the behavior of the controlled structures is much more complicated than the uncontrolled structures. However, in previous studies, the performance of controllers was generally evaluated as well as the behavior of structures was subjected to a limited number of earthquakes. Therefore, in this research, the need of using a wide range of earthquakes with a maximum of accelerations is emphasized in the form of IDA methods.

As pointed out in the IDA analysis method, drawing IDA graphs requires repeated analyses, under the influence of various earthquakes at maximum accelerations. Although the data obtained from these analyses are very useful, these analyses are time-consuming and overwhelming, and the large volume of data from the IDA analysis complicates the interpretation of the results of the analysis. Therefore, in order to analyze, design and evaluate controllers in control science, there is a need for an alternative method for analyzing IDA by maintaining its useful properties. The analysis of ET method can be a good alternative to IDA development analyses. Figure 12 shows a comparison between the results of structural analysis under ET artificial accelerograms and the results of IDA analysis. Controller of structure is trained under ET accelerogram.

As can be seen in Fig. 12, there is a good agreement between the graphs derived from the ET-accelerated analysis and the mean response of the structures under the 7 selected accelerated analyses. Therefore, in future studies, one may use ET incremental accelerograms to reduce the size of the calculations, save time on the analysis of the structures and more realistic evaluation of the performance of the controllers.

8 Conclusions

By studying researches on benchmark structures, it was found that the criterion for measuring the performance of proposed controllers is generally based on a limited number of earthquakes. Also, the training, optimization and design of many controllers in past researches were based on a specific earthquake at a specific damage level. On the other hand, the criterion for measuring the performance of controllers which are designed to reduce damages in the structure is also based on the judgment of a limited number of earthquakes. In this study, as a new idea, damage control is based on judgment of a wide range of earthquakes, with different maximum acceleration. In this way, the controller parameters based on training were optimized by a wide range of earthquakes. Also, the available method of control for a wider range of earthquakes was validated. In this way, their strengths and weaknesses are examined in a wider range of dynamic loading conditions. In fact, in this paper, in order to reduce the uncertainty in the behavior of the structure and the uncertainty in loading, the modern analytical methods of IDA and ET are used to train and design controllers. By investigating the IDA curves and the incremental analyses, the following results can be obtained:

1. The results of analyses indicate that the behavior of controlled structures, like uncontrolled structures, varies in different earthquakes and accelerations. On the other hand, since the type and intensity of the selected earthquakes have a great influence on the design and operation of the controllers and consequently on the behavior of the structures, the evaluation of the behavior of the controlled structures is much more complicated than the uncontrolled structures. This complexity in structural behavior explains the need of using the analytical methods in structural control science, like structural science. It is shown in this paper that by checking IDA analysis curves, controllers can be compared to a wider range of earthquakes. Thus, more realistic judgments can be made of the strengths and weaknesses of the controllers. However, in previous studies conducted by researchers, the performance evaluation of controllers was restricted to a limited number of earthquakes.
2. The results show that when a controller of a structure is trained with the help of a specific accelerogram, the reaction of the structure in the face of that particular earthquake is always satisfactory and predictable. However, the amount of damage reduction in the structures in which the selected earthquake is different for the trained stage earthquake, is unpredictable and the structural behavior is heavily dependent on the accelerogram that the controller is trained and designed for. As the results show, the damage reduction in two structures that the controller of which is trained and designed under two different earthquakes, can vary up to two times in the face of the same loading conditions. Moreover, the performance of two-component controllers depends largely on how the controller is trained and the type of selected earthquake in the training phase.

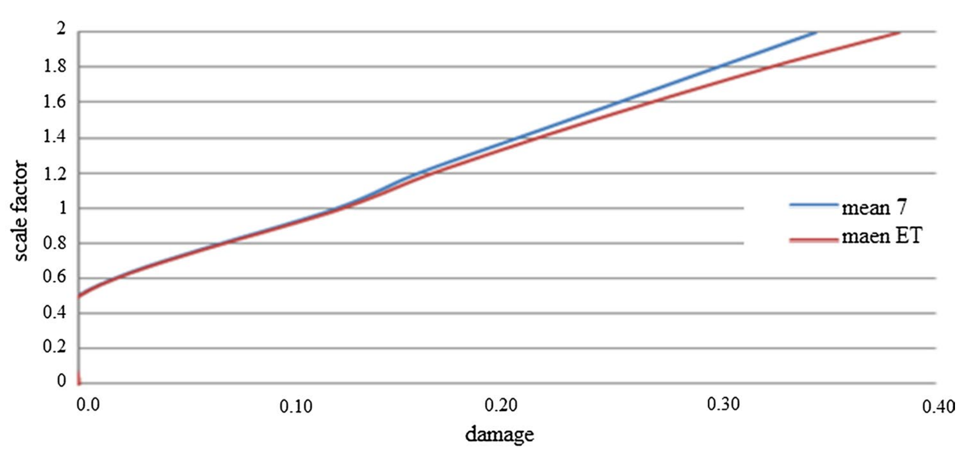


Fig. 12 Comparison of the mean of structural responses for 7 scaled accelerograms and ETA20e01-03

3. Numerical results show that the participation of a wide range of earthquakes, with various accelerations, in controller training phase can improve the performance of controllers. In fact, training of controller under ET accelerograms in the proposed controller is more effective than other controller (trained under a particular earthquake) and the structural responses will be more optimal. The use of the proposed controller will reduce the damage by 15–20% in the structure compared with other controllers at different levels of risk.
4. By comparing the graphs obtained from the analysis of structures under ET accelerograms and the results of IDA analysis, there is a good agreement between their results. Therefore, ET accelerograms can be used to analyze and evaluate controllers. Using ET accelerograms instead of conducting a wide range of IDA analyses can reduce the amount and cost of performing analysis to several times by maintaining the useful properties of IDA analysis.

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